PRELIMINARY STUDY ON CONFIGURATION OF TRIPLE-WALL SHIELD WITH OBLIQUE MIDDLE WALL

WEN Xue-zhong, KE Fa-wei, HUANG Jie, CHEN Ping, MA Zhao-xia, LIU Sen

Hypervelocity Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang, P.R. China Email: HAI@cardc.cn

ABSTRACT

Spacecraft shield configuration is important in protecting the spacecraft from damages caused by small size space debris impact which could not be monitored. Improving the performance of the shield without increasing its weight and size has been a significant subject in the space debris shield research. Based on the fact that the ballistic limit of oblique impact is higher than that of normal impact, this paper introduces the "N" configuration to improve the shield performance with the oblique middle wall. According to the design, the middle layer of a triple-wall configuration was placed obliquely. The shield performances of this configuration and a parallel triple-wall configuration with the same areal density were compared and analyzed by 3D numerical simulation and hypervelocity impact tests. These results verified the validity of the introduction of oblique middle wall in improving the shield performance. The improvement is more notable with higher impact velocity.

Key words: Hypervelocity impact, Shield configuration, Angle effect

1 INTRODUCTION

There are a lot of space debris around the spacecraft orbit. The spacecraft will be damaged when the debris impact it, and it may fail or even breakup under the sever conditions. Therefore, spacecraft shield is important in protecting the spacecraft from damages caused by impact of small size space debris which could not be monitored. It is the important component for the safety of on-orbit spacecraft. Improving the performance of the shield configuration has been a significant subject in the space debris shield research.

Whipple shield configuration was proposed by Whipple in 1948, who firstly came up with the thought of breaking projectile and the method of dispersing the impact energy by space distance. Compared with the single plate with same areal density, Whipple shield configuration improves the ballistic limit when the projectile is broken (i.e. the impact velocity is higher than 3.0km/s). Up to now, several kinds of shield configurations have been developed for a further improvement of ballistic limit based on Whipple shield configuration, such as advanced Whipple shield configuration [1], stuffed shield configuration [2], and multi-shock shield configuration [3]. The thoughts of new configurations are still breaking projectile adequately, dispersing the impact energy in bigger area, and absorbing more debris energy.

It can be found that the ballistic limits of all kinds of shield configurations under normal impact are lower than that of oblique impact in most velocity range [4]. Based on this, the ballistic limit may be improved by inclining the middle layer of shield configuration, which was certified by the corrugation shield configuration proposed by Schonberg W in 1990. The ballistic limit of corrugation shield configuration was improved greatly under oblique impact for the restriction of corrugation combination layers on the impact debris. However, there is no evident difference between corrugation configuration and non-corrugation configuration under normal impact except the distribution range of debris impact is relatively small [1].

This paper presents the design of the "N" configuration to improve the shield performance with the introduction

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of oblique middle wall, based on the fact that the ballistic limit of an oblique impact is higher than that of a normal impact. The rear plate damages of the “N” configuration and the parallel triple-wall configuration with the same areal density were compared and analyzed by 3D numerical simulation and hypervelocity impact tests.

2 OBLIQUE DESIGN OF MIDDLE LAYER OF SHIELD CONFIGURATION

The bigger the impact angle, the bigger the ballistic limit of shield configuration when the other impact conditions are same. This conclusion can be drawn from the ballistic limits of several kinds of shield configurations presented in [4]. However, the ballistic limit of oblique impact is smaller than that of normal impact in the midrange velocity, which is also embodied in the test results of reference [5]. The reason is that the breaking degree of projectile under oblique impact is lower than that of normal impact with the same impact velocity.

Therefore, inclining the middle layer of multi-layer configuration is proposed in the paper for improving the performance of shield configuration in the high velocity range. And the performance of shield configuration in the midrange velocity can be further improved if the breaking effect is not weakened. The “N” configuration (shown in Fig. 1) is rebuilt by inclining the second plate of the parallel triple-wall configuration (shown in Fig. 2) with some angle. When the “N” configuration is impacted by projectile, the projectile is broken adequately, and the debris generated by projectile impacting the first plate can be further dispersed by the second plate. Therefore, the performance of “N” configuration can be improved.

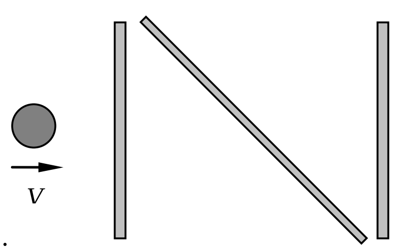


Figure 1. “N” Configuration

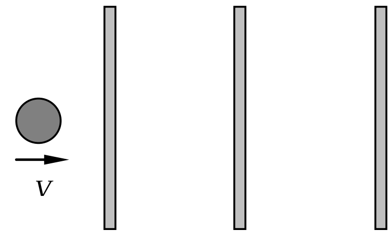


Figure 2. Parallel Triple-wall Configuration

The rear plate damages of the “N” configuration and the parallel triple-wall configuration with the same areal density and impact conditions were compared and analyzed by 3D numerical simulation and hypervelocity impact tests to compare the performances of the two configurations. The probability of improving the performance of shield configuration with inclined middle layer would be validated.

3 HYPERVELOCITY IMPACT RESULTS AND ANALYSIS

Figure 3. Hypervelocity Impact Range

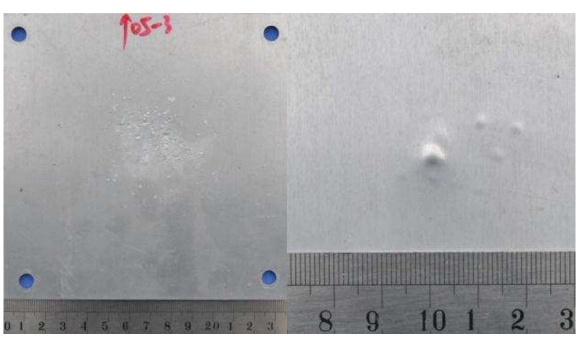
The test was carried out on the hypervelocity impact range (shown in Figure3) of China Aerodynamics Research and Development Center. The projectiles are Al-2024 sphere. The targets include “N” configuration and the parallel triple-wall configuration with same areal density. The two configurations are composed of the same materials with the same area density and space. The parallel triple-wall configuration is composed of Al-2024 aluminum plates with the thickness of 1mm, Al-1100 aluminum plates with the thickness of 1mm, and Al-2024 aluminum plates with the thickness of 2mm along the impact direction. And the distances of between adjacent plates are 50mm. The middle plate of the “N” configuration is Al-1100 aluminum plates with the thickness of 1mm, which is inclined by 36.8 ° compared to the first plate, and the center distance between adjacent plates are also 50mm.

Some test results are shown in Fig. 4 and the test conditions are shown in Tab 1. On the condition that the projectile diameter is 4mm with the impact velocity of about 3km/s, there is only one bump with the diameter of 4mm on the rear of the third plate of the “N” configuration. However, there is one bump with the diameter of 5mm and four bumps with the diameter of 2mm on the rear of the third plate of the triple-wall configuration. These can be seen from Fig. 4.a and Fig. 4.b.

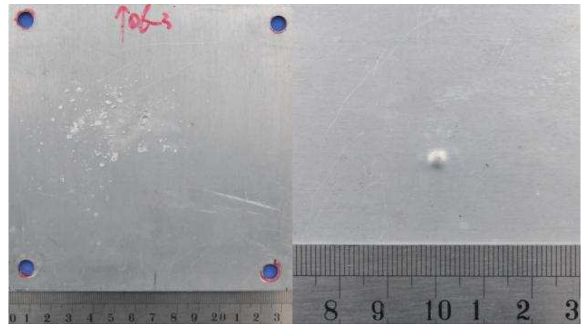
On the condition that the projectile diameter is 5mm with the impact velocity of about 4.8km/s, there is small deformation in the 30mm×50mm region on the rear of the third plate of the “N” configuration, and there is one bump with the diameter 4mm and several small bumps in the deformation area. On the rear of the third plate the triple-wall configuration, there is one big bump with the diameter of 40 mm and several small bumps on the big bump. These can be seen from Fig. 4.c and Fig. 4.d.

Table1 Test conditions

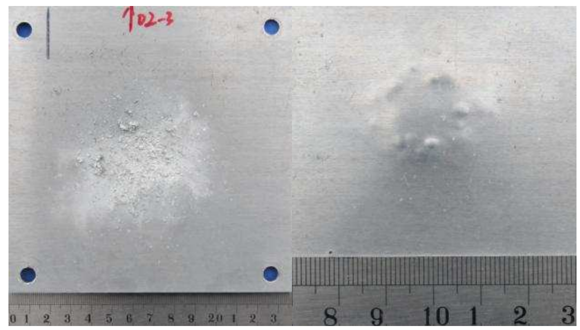
NO.	configuration	projectile	impact velocity
1	parallel	Φ 4mm	2.96km/s
2	“N”	Φ 4mm	3.00km/s
3	parallel	Φ 5mm	4.79km/s
4	“N”	Φ 5mm	4.85km/s



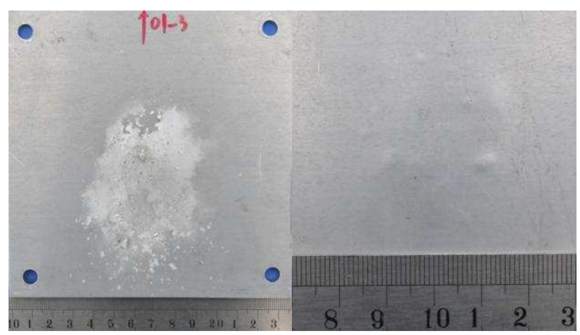
a. Front And Rear Of Third Wall Of Parallel Triple-wall Configuration（V=2.96km/s）



b. Front And Rear Of Third Wall Of “N” Configuration（V=3.00km/s）



c. Front And Rear Of Third Wall Of Parallel Triple-wall Configuration（V=4.79km/s）



d. Front And Rear Of Third Wall Of “N” Configuration（V=4.85km/s）

Figure 4. Damage Comparison Of Third Plate Of Two Configurations

Compared with the parallel triple-wall configuration, the damage area of the “N” configuration’s rear plate is larger, however, the damage degree is reduced significantly. Especially, the damage degree is reduced more evidently with the velocity increased.

4 NUMERICAL SIMULATION AND ANALYSIS

4.1 Numerical Simulation

The 3-D models of shield configuration and projectile were founded with SPH (smoothed particle hydrodynamic) by using the finite element software of AUTODYN. The models were symmetrical along Z axis. The state equation of shock was used in projectile and target. The strength model of JOHNSON_COOK was used in the first and third aluminum plate, and the strength model of Steinberg Guinan was used in the middle aluminum plate.

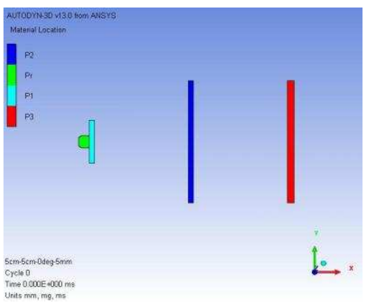


Figure 5. Simulation Model Of Parallel Triple-wall Configuration

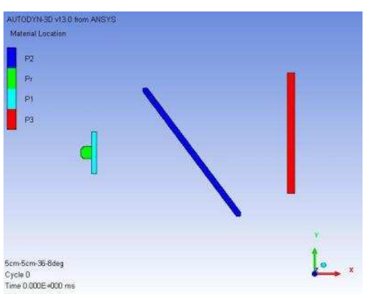
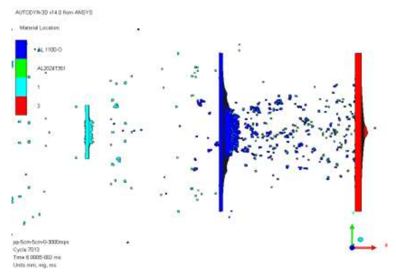


Figure 6. Simulation Model Of "N" Configuration

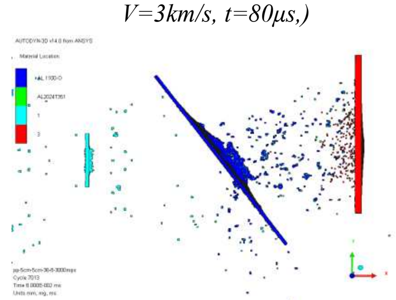
The simulation models of the two configurations were shown in Fig. 5 and Fig. 6, the thickness of the three plates and their space were some to the above targets used in the test. Considering the calculation scale and time, the dimensions of three aluminum plates are 20mm×10mm, 60mm×30mm and 60mm×30mm for the parallel triple-wall configuration along the impact direction. The dimensions of three aluminum plates are 20mm×10mm, 80mm×40mm and 60mm×30mm for the "N" configuration.

4.2 Analysis Of Simulation Results

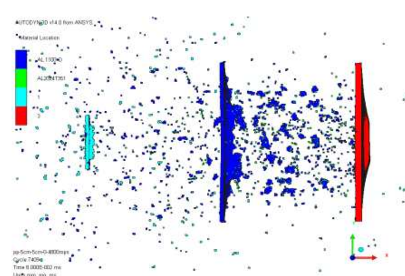
The simulation results under the same impact conditions with the above test are shown in the Fig. 7. *Φ*, *V* and *t* denote the projectile diameter, impact velocity and calculation time respectively in the Fig. 7. It could be seen from the simulation results that the damage area of the "N" configuration's rear plate is smaller than that of the parallel triple-wall configuration. However, its damage degree is increased with higher bump. The simulation results are consistent with the above test results.



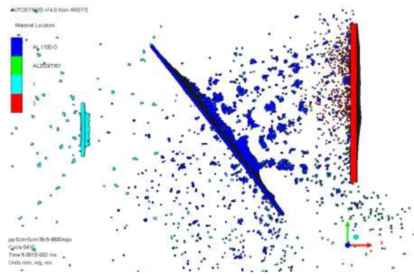
a. Parallel Triple-wall Configuration (Φ=4.0mm, V=3km/s, t=80μs,)



b. "N" Configuration (Φ=4.0mm , V=3km/s, t=80μs)



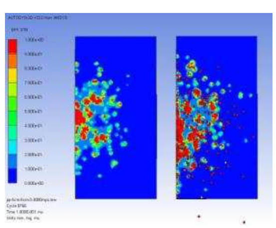
c. Parallel Triple-wall Configuration (Φ=5.0mm, V=4.8km/s, t=80μs)



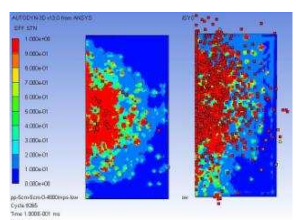
d. "N" Configuration (Φ=5.0mm, V=4.8km/s, t=80μs)

Figure 7. Simulation Results Under Same Impact Conditions With Above Test

For the two configurations, comparisons of the rear plate strain of the simulation results were shown in the Fig. 8 under the 4 groups of velocities ranged from 3km/s to 7km/s. The first image in every group corresponds to the rear plate of the parallel triple-wall configuration, and the second corresponds to that of the "N" configuration. It can be seen from the Fig 8 that the strain range of the rear plate of the parallel triple-wall configuration is smaller with more intensive area than that of the "N" configuration under the same impact conditions.



a



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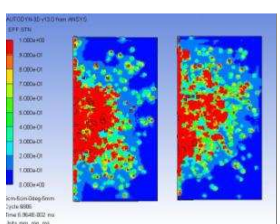

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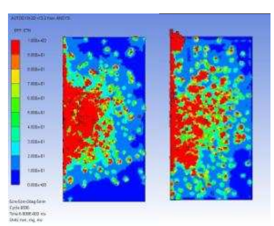

d

Figure 8. Comparisons Of Rear Plate Strain Of Simulation Results For Two Configurations(a. Φ =4mm,V=3km/s,t=100μs; b. Φ =5mm,V=4.8km/s t=100μs; b. Φ =5mm,V=4.8km/s t=100μs; c. Φ =5mm,V=6km/s t=70μs;d.Φ =5mm,V=7km/s,t =60μs)

The following conclusions were obtained by the simulation results. Under the same impact conditions of velocities ranged from 3km/s to 7km/s, the strain area of the "N" configuration's rear plate was larger with lower damage degree than that of the parallel triple-wall configuration because the debris energy on the rear plate was reduced and dispersed by the inclined plate of the "N" configuration. Especially, the projectile was broken more adequately and the effect was more evident with the impact velocity enhanced.

There were two reasons that caused the "N" configuration with inclined middle plate to reduce the damage degree of the rear plate. Firstly, the impact debris was dispersed by the inclined middle plate in bigger area, which was more evident with the impact velocity enhanced. The impact energy on the rear plate was dispersed more effectively, so the damage degree of the rear plate was reduced significantly. Secondly, the center distribution of the impact debris that passed through the second aluminum plate was deviated from the ballistic axis because of the inclined middle plate, which increased the flight distance and dispersing time of debris. So the damage degree of the rear plate was reduced. In addition, there was angle effect between the middle plate and the rear plate, the debris impact area on the rear plate became bigger, the impact energy of debris on the rear plate was dispersed more effectively, so the damage degree of the rear plate was reduced significantly.

In the above analysis, the damage of the debris ricocheted by the inclined middle plate on the rear plate was not considered. However, the ricocheted debris had small damage on the rear plate because the included angle between its velocity direction and the normal direction of the rear plate was small. Moreover, the protection on the ricocheted debris could be realized easily by regulating the configuration properly, such as increasing the number of the thinner middle plate and realizing catenation on configuration.

CONCLUSION AND PROSPECT

The following conclusions were obtained by comparing and analyzing the simulation results and test results for the two configurations.

(1) The inclined middle plate of several layers configuration can reduce and disperse the debris energy on the rear plate, which offered a new method to improve the performance of shield configuration.

(2) Under the impact conditions of this paper, the damage degree of the “N” configuration’s rear plate was lower compared with the parallel triple-wall configuration. Especially, the effect was more evident with the velocity increased.

(3) The results verified that the inclined middle plate can improve the performance of multi-layer shield configuration, and the performance of shield configuration is improved more evidently under high velocity range.

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