

Optimum structure of Whipple shield against hypervelocity impact

M Lee

Professor, Department of Mechanical Engineering, Sejong University
98 Kunja-Dong, Seoul 143-747, Korea

E-mail: mlee@sejong.ac.kr

Abstract. Hypervelocity impact of a spherical aluminum projectile onto two spaced aluminum plates (Whipple shield) was simulated to estimate an optimum structure. The Smooth Particle Hydrodynamics (SPH) code which has a unique migration scheme from a rectangular coordinate to an axisymmetric coordinate was used. The ratio of the front plate thickness to sphere diameter varied from 0.06 to 0.48. The impact velocities considered here were 6.7 km/s. This is the procedure we explored. To guarantee the early stage simulation, the shapes of debris clouds were first compared with the previous experimental pictures, indicating a good agreement. Next, the debris cloud expansion angle was predicted and it shows a maximum value of 23 degree for thickness ratio of front bumper to sphere diameter of 0.23. A critical sphere diameter causing failure of rear wall was also examined while keeping the total thickness of two plates constant. There exists an optimum thickness ratio of front bumper to rear wall, which is identified as a function of the size combination of the impacting body, front and rear plates. The debris cloud expansion-correlated-optimum thickness ratio study provides a good insight on the hypervelocity impact onto spaced target system.

1. Introduction

Understanding and controlling large plastic deformation problems such as hypervelocity impact/penetration (roughly $V > 2$ km/s) events are of great importance for protection of space vehicles and satellite system as well. This is because the external walls are exposed to impacts from meteoroid or space debris [1]. Characteristics of debris clouds produced by hypervelocity impact of aluminium spheres with thin aluminium plates were described using flash radiographs [2]. For protection, one uses dual-plate shields [3, 4] or multishock shields [5]. For a practical purpose, ballistic limit curves were generated using expensive experiments of more than 200 shots and they are generally used for a validation of numerical predictions [6]. Many numerical activities have been taken to reproduce the ballistic limit curves [7-9].

In this paper, detailed evolution of the debris clouds are first captured numerically for various ratios of bumper to impacting sphere diameter ($0.063 < t/D_s < 0.630$). The main purpose of this is to investigate the effect of this ratio on the extent of debris cloud expansion, which seems to be an important factor for threat to rear wall structure. From the author's knowledge, this information is, if ever, rarely given. Once the debris clouds are well captured, a second plate (t_w) is placed with some spacing, while keeping the total thickness ($t + t_w$) unchanged. Then the protection capability was examined by estimating the critical sphere diameter (D_c) as a function of thickness ratio of front to



real plates (t/t_w). To do this, a series of simulations using the Smooth particle Hydrodynamics (SPH) code, which we recently developed, has been conducted. The impact velocity considered was 6.7 km/s at normal incidence. The numerical predictions are compared with the widely used empirical equations. The existence of an optimum thickness ratio t/t_w has been proposed.

2. Smooth Particle Hydrodynamics (SPH)

Lucy [10], Gingold and Monaghan [11] first introduced the Smooth Particle Hydrodynamics (SPH) in space science areas. SPH is an interpolation method to calculate values and derivatives of continuous field properties by using discrete points which are located completely arbitrary. Because of the significant advantages over conventional grid based Lagrange scheme (no mesh distortion problem), SPH scheme was adopted and applied to the computations of large deformation problems [12, 13]. Johnson et al. [14], and Hayhurst et al. [15] presented algorithms for axisymmetric geometry. These are much similar in that they consider each particle as torus ring geometry. However, uniqueness of the cylindrical SPH code we developed recently is that it can be migrated from a Cartesian coordinate version in a simple way [16].

3. Hypervelocity impact simulations

The major purpose of this study is to demonstrate the existence of an optimum thickness ratio of two spaced thin plates showing a best protection capability. The following is the methodology taken in this study. First of all, an accurate prediction of the debris clouds is crucial. This is because the late stage simulation of debris clouds impact onto rear wall structure mainly relies on how well the debris clouds are captured. The second part is to analyze the effect of a change in the t/D_s ratio on the extent of debris clouds expansion. This is required for the following reason. To reduce threat of real wall, it is necessary for the front bumper to spread the debris clouds as possible as it can, and to fail the impacting body into fine dense fragments. This is only achievable if the front bumper plate is not too thin, and not too thick due to limitation on the total thickness of two plates. Naturally the final part is to find an optimum thickness ratio of two spaced thin plates demonstrating a best ballistic limit.

3.1. Modeling

A series of SPH simulations has been conducted for impact of an aluminum (2017-T4) sphere on a single aluminum (6061-T6) plate at normal incidence. Then two spaced plates problem was carried out. All was performed in two-dimensional axisymmetric domains. The impact velocity is 6.7 km/s \pm 0.06 km/s. The sphere diameter is 9.53 mm in all cases. The front plate thickness considered here ranged from 0.6 ($t/D_s = 0.063$) to 6 mm ($t/D_s = 0.63$). We tried to maintain a consistent mesh resolution system. For the plate, particle size varies from 0.15 mm to 0.2 mm such that the plate is packed with from 4 to 30 particles across the thickness. The radial extent of the plate is 50 mm which is approximately 10 times of the impacting sphere radius. The size ratio of sphere particle to plate particle is around one, to be comparable sizes. The constitutive response for 6061 T6 Aluminium was represented by the Johnson-Cook model.

3.2. Shapes of debris cloud

We like to validate the numerical model by comparing with previous experimental debris cloud pictures. At the same time, it is necessary to be able to predict the effect of a change in the t/D_s ratio on the debris cloud shapes. To do this, we considered seven cases, 6 cases ($0.063 < t/D_s < 0.424$) from the experiment [2] and one extra case ($t/D_s = 0.63$). Figures 1 and 2 shows one case of comparison between predictions and experimental debris pictures. In general, the agreement is fairly excellent. As observed in the previous experiment [2], three major features of the cloud are well captured; an ejected veil, an expanding bubble of bumper debris, and the internal structure composed of a front, disk-like center, and rear element.

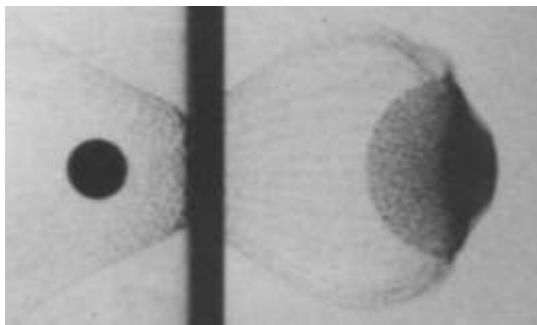


Figure 1. Debris clouds from experiment [2] for $t/D_s = 0.102$, $V = 6.72$ km/s, time = $7.3 \mu s$

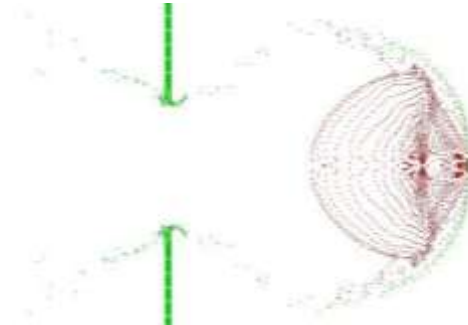


Figure 2. Simulated result for the same case with the experiment in Fig. 1.

3.3. Expansion angle of debris clouds

Figure 3 shows the typical shape of debris clouds. The extent of debris clouds can be estimated by using the initial sphere radius, the maximum debris radius and the axial distance between locations of the initial sphere center and the maximum debris radius as,

$$\tan(\theta) = \frac{(R_{debris} - R_s)}{L} \quad (1)$$

To provide some information on the evolution of expansion angles, the data for the case of $t/D_s = 0.084$ are summarized in table 1. It can be seen that the expansion angle does not change much during the evolution, which is not surprising. In this study an average angle is used. In figure 4, the predicted expansion angles of debris clouds are shown for various t/D_s ratios. As the t/D_s ratio increases, the expansion of debris clouds becomes significant. For 6.7 km/s, it reaches a maximum angle of 23 degrees at $t/D_s = 0.23$. With further increase, the expansion angle starts to decrease. The existence of a maximum expansion angle is not surprising. For low t/D_s , the resistance of front plate is not enough and for high t/D_s , the plate becomes a thick target.

For $V < 7$ km/s (available speed range in test), the previous experimental study found that the debris clouds expansion is very sensitive to impact velocity [2]. For $V > 7$ km/s, however, the current numerical study shows that the radial expansion is not significant, only 4 degrees increase from 6.7 km/s to 9 km/s. Consequently, the axial expansion becomes substantial while the radial expansion becomes saturated.

Having validated the predictive capability of the current numerical model for the debris cloud evolution stage, we are now ready to pay attention to two-spaced-plates impact problem. The performance can be governed by the following factors. The front plate is able to spread the energy of an impacting sphere into debris clouds as wide as it can. The debris must be composed of a cloud of finely divided fragments. Furthermore, the rear wall is to be thick enough to provide good resistance. Hence maximum protection is expected to be obtainable for $t/D_s < 0.234$, as indicated as “potential optimum bumper thickness ratio” in figure 4, but this ratio cannot be too small. This is the subject of the next section.

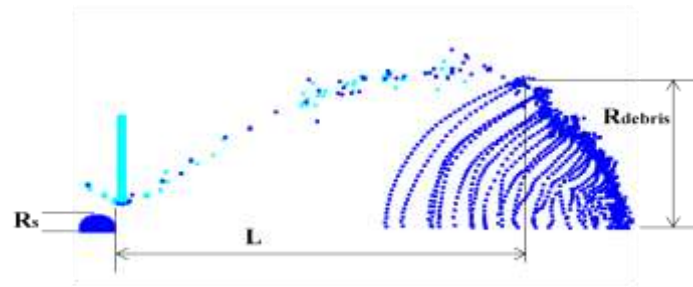


Figure 3. Definition of expansion angle of debris clouds.

Table 1. Debris cloud expansion angle evolution after impact, $V = 6.68 \text{ km/s}$, $t/D_s = 0.084$.

Computational Cycles	Angle (degree)	Average angle
6,000	11.06	11.56
9,000	11.55	
12,000	11.78	
15,000	11.69	
18,000	11.72	

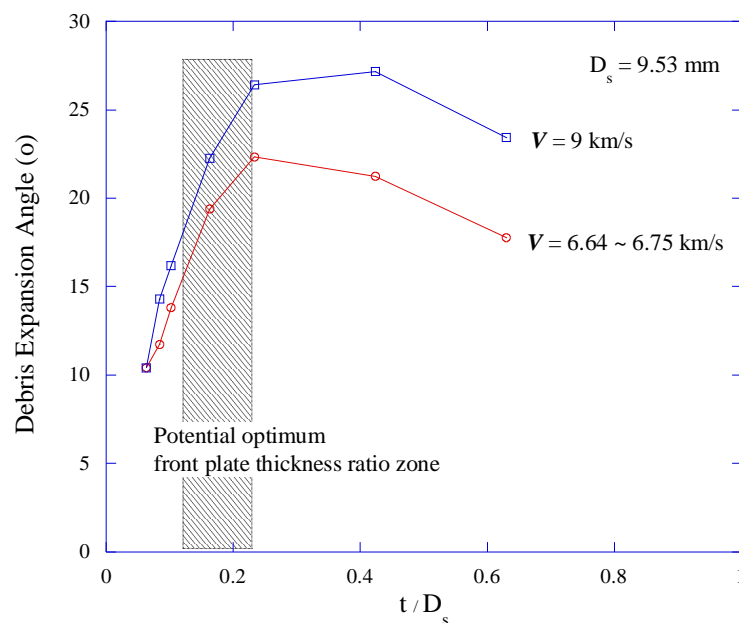


Figure 4. Expansion angle of debris clouds vs. thicknesses ratio of aluminum front plate to sphere diameter, $D_s = 9.53 \text{ mm}$, $V = 6.7 \pm 0.06 \text{ km/s}$, and 9 km/s .

3.4. Expansion angle of debris clouds

By placing a second plate with a spacing of 120 mm to the previous single plate setup, two-spaced-plates (Whipple shield) has been examined as a protection system. This spacing was popular and used in the previous several studies. The total thickness of two plates was fixed at 4.8 mm. The front plate

(bumper) thickness ranged from 0.6 to 2.2 mm, while the real wall thickness from 4.2 to 2.6 mm. The radial extent of the rear wall is 250 mm which is 5 times of the front plate in order to cover the debris clouds impact. A series of SPH simulations has been conducted at normal incidence. The same impact velocity of 6.7 km/s is used. Again we tried to maintain a consistent mesh resolution system even to the real wall. As the real wall is thicker than the front wall, a minimum of 11 particles and a maximum of 21 particles were generated across the thickness. The number of particles was around 20,000.

The critical sphere diameter is found to be around 6 mm for the impact velocity of 6.7 km/s as shown in figure 5. In the current simulations, the resolution of the critical diameter is ± 0.2 mm. The critical diameter is defined as the ballistic limit, which is just able to cause failure of the rear plate. The prediction reveals the existence of an optimum thickness ratio of front to real walls, in which the critical diameter becomes a maximum value. It occurs at $t/t_w = 0.48$, corresponding to $t/D_s = 0.163$ for the size combination considered in this study.

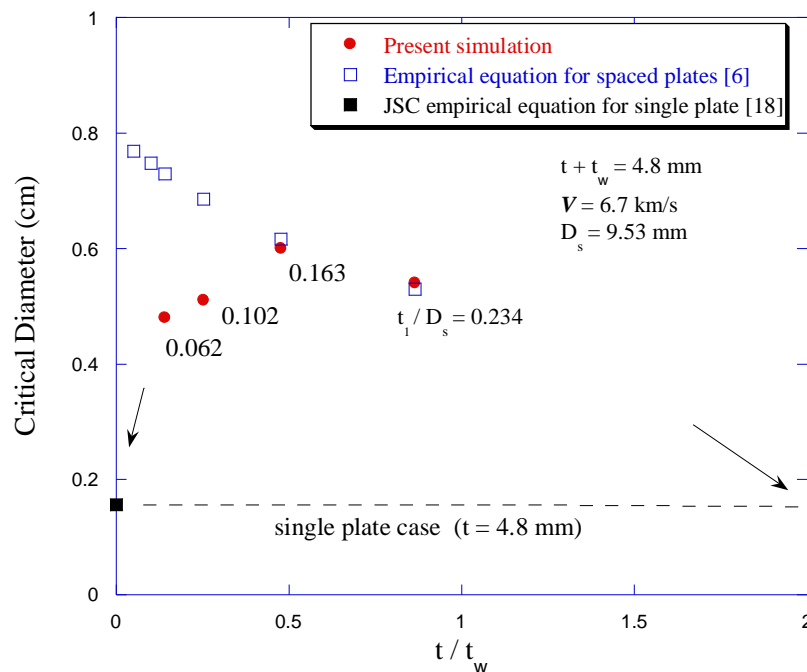


Figure 5. Critical sphere diameter vs. thickness ratio of front to real walls for $t + t_w = 4.8$ mm, $D_s = 9.53$ mm, $V = 6.7 \pm 0.06$ km/s

For a comparison purpose, the results predicted by the generally used semi-empirical damage equations [6] are also included in figure 5. It can be seen that the empirical correlation matches with the current simulations only for $t/t_w > 0.48$. For this region, as the front plate thickness increases, the critical diameter decreases, which seems to be reasonable. As a limiting case, if $t_w = 0$, the two spaced plates impact problem becomes a single plate case. Then the critical diameter becomes a small value, $D_c = 1.55$ mm obtained from a previous empirical equation [17]. This should be true for the other region $t/t_w < 0.48$. As another limiting case, if $t = 0$, it also becomes a single plate problem, and the critical diameter should be $D_c = 1.55$ mm. The current numerical model predicts this trend, approaching the single plate impact result for both extreme cases, while the empirical equation does not. Note that the critical diameter for the single plate case was already well estimated in the previous work using the current numerical model [18]. It seems that the empirical equations are not applicable to very low t/D_s .

4. Conclusion

The hypervelocity impact of an aluminum sphere onto two spaced aluminum plates has been examined using a new in-house code of Smooth Particle Hydrodynamics (SPH) scheme. The numerical formulations are first described with an emphasis on the unique migration technique from a Cartesian coordinate into axi-symmetric coordinate. The impact velocity considered is 6.7 km/s.

The debris clouds have been well captured for various ratios of front plate thickness to sphere diameter by comparing with previous experimental pictures. The debris expansion angle reaches a maximum value of 23 degrees. This occurs at $t/D_s = 0.23$.

The protection capability of two spaced plate target system has been estimated at constant total thickness of 4.8 mm. The predicted critical sphere diameter becomes a maximum value at the optimum thickness ratio of $t/t_w = 0.48$. On the other hand, the empirical equations could not reveal the existence of an optimum thickness ratio. The current numerical study provides a good insight on the hypervelocity impact onto spaced thin plate target system by correlating the extent of debris clouds expansion, such that it could be valuable for design concerns.

Acknowledgements

This work was supported by the Research fund of Survivability Technology Defense Center of Agency for Defense Development of Korea.

References

- [1] Angel Y G and Smith J P 1993 *Int. J. Impact Eng.* **14** 25
- [2] Piekutowski A J 1993 *Int. J. Impact Eng.* **14** 73
- [3] Kinslow R 1970 *High Velocity Impact Phenomena* Academic Press, New York
- [4] Zukas J A, Nicholas T, Swift H F and Curran D R 1982 *Impact Dynamics* Wiley, New York
- [5] Cour-Palas B G and Crews J L 1990 *Int. J. Impact Eng.* **10** 135
- [6] Christiansen E L and Kerr J H 2001 *Int. J. Impact Eng.* **26** 93
- [7] Hayhurst C J, Livingstone IHG, Clegg R A, Destefanis R and Faraus M 2001 *Int. J. Impact Eng.* **26** 309
- [8] Palmieri D, Faraus M, Destefanis R and Marchetti M 2001 *Int. J. Impact Eng.* **26** 579
- [9] Hu K and Schonberg W P 2003 *Int. J. Impact Eng.* **29** 345
- [10] Lucy L B 1977 *Astrophys. J.* **82** 1013
- [11] Gingold R A and Monaghan J J 1977 *Mon. Not. R. Astron. Soc.* **181** 375
- [12] Libersky L D and Petschek A G 1990 *Lect. Notes Phys.* **395** Springer, Berlin
- [13] Johnson G R, Petersen E H and Stryk R A 1993 *Int. J. Impact Eng.* **14** 385
- [14] Johnson G R, Stryk R A and Beissel S R 1996 *Comput. Methods Appl. M.* **139** 347
- [15] Hayhurst C J and Clegg R 1997 *Int. J. Impact Eng.* **20** 337
- [16] Lee M and Cho Y J 2011 *J. Strain Anal. Eng.* **46** 879
- [17] Hayashida K B and Robinson J H 1991 NASA TM-103565, NASA, George C. Marshall Space Flight Center
- [18] Lee M and Cho Y J 2011 *J. Mech. Sci. Technol.* **25** 2457