Ballistic limit curves for cylindrical projectiles impacting dual-wall spacecraft systems

K. Hu¹ and W.P. Schonberg²
¹Mechanical Engineering Department, University of Missouri-Rolla, Rolla, U.S.A.
²Civil Engineering Department, University of Missouri-Rolla, Rolla, U.S.A.

Abstract

Ballistic limit curves are presented for a variety of cylindrical projectile shapes impacting a typical dual-wall spacecraft wall configuration. These curves are compared against the ballistic limit curve for spherical projectiles impacting the same dual-wall system. All curves are drawn using the results of numerical simulations of the high speed impact process. It is found that the ballistic limit curves for all of the cylindrical projectiles lie beneath the curve for spherical projectiles, that is, cylindrical projectiles have more penetrating capability than comparable spherical projectiles. The implication is that if spacecraft wall systems are designed using spherical projectile-based ballistic limit curves, the design can be highly non-conservative.

1 Introduction

Ballistic limit curves (BLCs) for dual- or multi-wall spacecraft wall systems impacted by spherical projectiles have been developed for a variety of impact conditions (see, e.g., [1]). These curves are used to optimize the design of spacecraft wall parameters (material, thickness, etc.) so that the walls can withstand high speed on-orbit impacts by meteoroids and pieces of orbital debris. Considerable work has been done to validate these BLCs through laboratory testing. However, meteoroids and orbital debris particles can take any shape. Morrison [2], and more recently Piekutowski [3], has shown that non-spherical projectiles can be more damaging than equal mass spherical projectiles
under the same impact conditions. As a result, orbital debris protection systems designed using currently available spherical projectile-based BLCs can be non-conservative.

This paper presents the results of a study whose objective was to develop BLCs for a typical spacecraft dual-wall configuration impacted by non-spherical projectiles. Specifically, BLCs are presented for cylindrical and disk-like projectile shapes. The response of the dual-wall system to impacts by these projectiles is obtained using the AUTODYN software package. Ballistic limit curves are drawn as lines of demarcation between regions of rear-wall perforation and no perforation in two-dimensional spherical projectile diameter-impact velocity space. The various BLCs obtained are compared against a baseline spherical projectile-based BLC and to each other to determine which of the non-spherical projectile shapes considered herein is the most dangerous from a rear-wall perforation perspective.

2 AUTODYN modeling of the impact event

2.1 Material properties and modeling algorithms

The BLCs of non-spherical projectiles in this paper were developed using data derived from numerical simulations of high speed impact events performed using the AUTODYN software package. In all of the simulations, the same material models and modeling strategies were used. Material parameters, etc. were based on the results of a normal impact parameter sensitivity study conducted by Hayhurst, et al, and reported in [4].

Because of the large deformations of the projectile and the bumper that result from the initial impact, the projectile and the bumper were modeled using the SPH module. SPH is a gridless technique so it does not suffer from the problems associated with grid tangling that can occur in large deformation events. In all cases, materials were modeled using the shock EoS, the Johnson-Cook strength model, and the principal stress failure model.

2.2 Projectiles shapes and dual-wall target setup

Four non-spherical projectile shapes were considered in this study: long and short cylinders (L/D ratios of 5:1 and 2:1, respectively); and, long and short disks (L/D ratios of 1:2 and 1:5, respectively). In all cases, the projectiles were made of AL6061-T6. Figure 1 below shows a sketch of the projectiles considered herein.

![Figure 1: Projectiles shapes](image)
The dual-wall configuration considered in this study is illustrated in Figure 2 below: a 0.12 cm thick AL6061-T6 bumper is placed 10 cm ahead of a 0.32 cm thick AL6061-T6 rear wall.

![Figure 2: Dual wall Configuration](image)

2.3 Analysis procedure

For each non-spherical projectile, impact simulations were conducted at impact velocities ranging from 1 to 13 km/s. At intervals of 2 km/s, a series of simulations were run wherein projectile mass was increased to where the projectile (or ensuing debris cloud) was able to perforate the rear wall. In this way we were able to draw BLCs between regions of rear wall perforation and no-perforation in 2-D projectile mass-impact velocity space. In order to make the various BLCs so obtained comparable to a spherical projectile-based curve, non-spherical projectiles mass-velocity curves were converted into equivalent spherical diameter-velocity curves based upon an equal mass consideration.

The actual BLCs for the non-spherical projectiles considered herein were obtained by adjusting some of the parameters and constants in the equations for a spherical projectile-based BLC [1]. Those parameters and constants were manipulated to make the curve appear to give the best fit to the simulation results. Once these curves were available, we were able to evaluate the effects of projectile shape on perforation ability.
3 Results and discussion

3.1 Ballistic limit curves

Figure 3 below presents the BLCs for the four non-spherical projectile shapes considered in this study as well as the BLC for a spherical projectile. As can be seen from this figure, projectile shape can have a significant effect on its penetrating ability. We also see that the sphere proved to be the least dangerous shape compared with the non-spherical projectiles considered in this study. The long and short cylinders show the highest penetrating ability below impact velocities of 6.5 km/s. When impact velocity is over 7.5 km/s, the long cylinder and the flattest disk exhibit the highest perforating ability.

Finally, it is also interesting to note that the BLC for the long cylinder (i.e. L/D=5:1) is missing a key feature that is commonly associated with BLCs for dual-wall systems under high speed impact – it does not have the hump as the impact velocity transitions from ordnance to hydrodynamic velocities. The other non-spherical projectiles do show this hump, although at velocities that can be significantly different from those associated with spherical projectile impacts.

![Figure 3: Ballistic limit curves for cylindrical projectiles](image)

3.2 Debris cloud characteristics

As was seen in Figure 3, non-spherical projectiles showed a very different penetrating ability when compared to spherical projectiles of comparable mass. Further analysis reveals that this is most likely the result of the different debris cloud shapes that evolve after the initial impact on the bumper. Figures 4 and

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5a-d show the debris cloud shape at comparable times for a spherical projectile and the four non-spherical projectiles considered in this study. All of the projectiles had the same initial mass (equal to that of a spherical projectile with a 5 mm diameter) and the same impact velocity (7 km/s).

Figure 4: Spherical Projectile Impact (D=5mm, V=7 km/s, time=6.14 μs)

The view of the spherical projectile debris cloud in Figure 4 shows the following major features: an expanding bubble of bumper debris moving forward; an ejecta veil, consisting almost entirely of bumper fragments, moving rearward, was ejected from the front side of the bumper; and, projectile debris fragments located inside and at the front of the bumper debris bubble. These projectile fragments are often considered to be the most significant feature of the debris cloud in terms of potential for rear wall damage. A detailed discussion of the shapes of these fragments and effects of their impacts on the rear wall has been presented in [5]. AUTODYN models are apparently quite capable of being able to correctly reproduce the shapes of debris clouds following high speed spherical projectile impacts [6]. The shape of the debris clouds shown in Figures 5a-d (i.e. following the impacts of cylindrical projectiles) also match very well the radiographs of debris clouds created under similar impact conditions (see, e.g., [7]).
Figure 5a: Cylinder Impact (L/D=2:1, V=7km/s, time=5.93 µs)

Figure 5b: Cylinder Impact (L/D=5:1, V=7km/s, time=6.07 µs)
In the case of the impact of a cylinder with L/D=2:1, Figure 5a shows a conical leading edge consisting mainly of bumper fragments with apparently no intact solid particle remaining. In addition, the whole body of the projectile was fragmented by the impact on the bumper. This is because the short cylinder is not long enough to withstand the damage caused by the interaction of the strong shock and rarefaction waves created by the initial impact. As a result, the short cylinder debris cloud is very similar to that created following a spherical projectile impact. However, as can be seen in Figure 2, it possesses more perforation ability than that created by the impact of a sphere projectile: in addition to having a big “hump” from 6.5 to 10 km/s, the short cylinder’s BLC as a whole moves “forward” and “downward” as compared to the BLC for a spherical projectile.

In the case of the impact of a cylinder with L/D=5:1, Figure 5b shows that the rear part of the projectile remained intact following the initial impact. In fact, for all impact speeds between 1 and 13 km/s we found that there was always an intact part of the projectile remaining. Although the leading portion of the long cylinder is fragmented, the trailing portion remains solid. Apparently in this case the projectile is long enough to withstand the action and interaction of the strong shock and rarefaction waves. This also explains why the BLC for a cylindrical projectile with L/D=5:1 has no “hump” feature: the portion of the cylinder that is not fragmented by the initial impact on the bumper becomes, in effect, a solid projectile that impacts and perforates the rear wall of the system. It is as if the dual-wall were effectively a simple single-wall structure. Single-wall BLCs are monotonically decreasing functions, much like the BLC of the long projectile in Figure 3. From these observations we conclude that, for the projectile shapes considered in this study, the long cylinder is the most dangerous shape from perspective of rear wall perforation: a dual-wall configuration offers little or no improvement in protection against rear wall perforation by long cylindrical projectiles.

For the disk shape projectiles, Figure 5d shows that the debris cloud formed by the short disk (L/D=1:5) contained a long columnar structure inside the external bubble of debris. This columnar structure stretched from the bumper to the rear wall; its front end appears to contain an intact solid part of projectile. These characteristics match those evident in the radiograph results presented in [5]. For the long disk (i.e. L/D=1:2), Figure 5c shows that the number of fragments and droplets within the columnar rod was much less than in the case of the short disk (L/D=1:5), which make it less penetrating. This is also evident in Figure 3, where the short disk’s BLC is well below that of the long disk. Furthermore, the hump is much smaller than that in the long disk’s BLC, which means the dual-wall system has less protective ability as the disk L/D decreases.
Figure 5c: Disk Impact (L/D=1:2, V=7km/s, time=6.10 μs)

Figure 5d: Disk Impact (L/D=1:5, V=7km/s, time=6.10 μs)
4 Summary

Ballistic limit curves have been presented for a variety of cylindrical projectiles impacting a typical dual-wall configuration. These curves have been compared against the ballistic limit curve for spherical projectiles impacting the same wall system. It is found that the ballistic limit curves for all of the cylindrical projectiles lie beneath the curve for spherical projectiles, that is, cylindrical projectiles have more penetrating capability than comparable spherical projectiles. Therefore, caution is urged if spherical projectile-based ballistic limit curves are used to design orbital debris protection systems. In such cases, the design can be highly non-conservative.

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