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# DESIGN VERIFICATION OF WHIPPLE BUMPER SHIELDS FOR PROTECTING SMALL SPACECRAFT FROM HYPERVELOCITY IMPACTS DURING FAST FLY-BYS TO DUSTY OBJECTS

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## ABSTRACT

*JAXA provides a 24U-class daughtership "B1" to ESA's Comet Interceptor (CI) mission for fast flyby observation of a long-period comet or an interstellar object. The spacecraft must survive in the dusty environment with a lightweight impact bumper shield at an encountering velocity of up to 70 km/s, which is too fast to be reproduced by ground experimental facilities. We designed a three-layered Whipple bumper with hydrocode simulations that were confirmed to reproduce the successful survival of Giotto's bumper shield for the Comet Halley flyby in 1986. The ballistic limit curve (BLC) calculations showed that the impact damage could be stopped on the second layer at the maximum mass and velocity for the mission with a maximum mass of 34 mg and maximum velocity of 70 km/s, based on the EDCM 4.1 dust model. Our hydrocode calculations were consistent with the protection performance of real-scale impact experiments at 1.0-6.5 km/s by employing Japanese AFRP as intermediate layers. This result will open a new era for fast flyby exploration of small spacecraft to dusty objects. This is a summary of the refereed paper of the same title in preparation for submission [1].*

Keywords: Comet Interceptor, Whipple bumper shield, Hypervelocity impacts, Hydrocodes, Ballistic limit curves, AFRP

## 1. BUMPERS FOR HYPERVELOCITY FLY-BYS TO DUSTY OBJECTS

As deep space exploration diversifies their destinations in frontiers of the Solar System, fast fly-by investigations of celestial bodies are getting more popular for small spacecraft with fewer resources, in contrast to legacy orbiter/lander configurations with full resources. Such small spacecraft must be protected from hypervelocity impact damages by microparticles when they fly by dusty objects such as plumes ejected from sub-surface oceans of icy satellites, planetary rings, and cometary coma of long-period comets as well as potentially interstellar objects.

At present, ESA is developing an F-class mission called Comet Interceptor which aims to conduct a flyby observation of a long-period comet or an interstellar object [2]. Both targets must be first discovered and then determined their intercepting orbits by the spacecraft after its launch planned in 2029 and during the parking orbit operation at the Sun-Earth Lagrange 2 region. JAXA provides one of the two daughtership called the "B1" spacecraft of a 24U cubesat form factor in a total mass of around 30 kg. It will be piggybacked by the "A" mothership provided by ESA. The B1 spacecraft must survive in the dusty environment [3] with a dedicated impact bumper shield during the closest approach (CA) for fast flyby observations of the target object at an encountering velocity up to 70 km/s, which is too fast to be reproduced by impact experimental facilities on the ground.

How can we design such a bumper then? First, we must establish a design proposal based on hydrocode simulations with Ansys Autodyn® [4], estimating the protection performance by ballistic limit curve (BLC) evaluation [5, 6], and assessing the validity of the BLC results in a reproducible velocity and mass ranges for ground impact experiments. The basic design plan was formulated by the mission definition review (MDR) and system definition review (SDR) of the B1 spacecraft in 2022, and specifications for manufacturers were presented in 2023.

ESA's Giotto mission to Comet Halley in 1986 was the only successful example of past space missions that conducted a fast fly-by investigation to a cometary coma at the equivalent encountering velocity (i.e., 68.4 km/s) [7]. The Giotto spacecraft employed a dedicated Whipple bumper shield [8, 9] based on numerical simulations and extrapolation of slower impact experiments to withstand a cometary dust impact of the maximum mass of 0.1 g. Its dual-sheet bumper shield was composed of the first Al layer of 1-mm-thick and a thicker intermediate layer combined with 7.5-mm-thick epoxy Kevlar, 5-mm-thick polyurethane foam, and 2-mm-thick epoxy Kevlar separated by 23 cm of the stand-off distance [10, 11]. Epoxy Kevlar is a type of Aramid Fibre-Reinforced Plastics (AFRP) and is lightweight and high in strength compared to metallic alloys [12, 13, 14]. Thus, we employ the AFRP product manufactured in Japan for the intermediate layers of our bumper shield.

## 2. CI-B1 BUMPER REQUIREMENTS

To design dust impact bumpers for any spacecraft, one should consider at least the following criteria:
(1) Dust flux model near the comet to be explored,
(2) Relative impact velocity between cometary coma/dust tail and dust trail,
(3) Relative relationship between comet coma/dust-tail-dust trail impact angle and spacecraft attitude,
(4) Protected parts, area, and temperature environment of the spacecraft exterior such as thrusters, solar array paddles (SAP), antennas, and other parts that extend beyond the system envelope
(5) Probability of No Failures (PNF) for the designated mission duration,
(6) Allowable damage modes such as physical breakdown, attitude disturbance, collisional plasma generation, and dark current inflow,
(7) Resource allocation to bumper functions including mass, area, power, data volume, etc.

**TABLE 1:** PARAMETER REQUIREMENTS OF THE COMET INTERCEPTOR B1 SPACECRAFT BUMPER SHIELD

| Parameters | Requirements |
|---|---|
| Max. Dust Impact Velocity | 70 km/s |
| Dust Impact Locations | Any locations on the bumper |
| Max. Dust Impact Angle Offset | Within ±3° from the vertical vector of the bumper |
| Max. Dust Mass | $3.4 \times 10^{-5}$ kg (34 mg). This is 4.9 mm diameter if cometary grain density is 570 kg/m$^3$. |
| Number of Max. Dust Impact(s) | 1 |
| Shielding Capability | Interior of the spacecraft can be maintained normally (physically and electromagnetically) |
| Probability of Non-Failure | >0.7 |

For the Comet Interceptor B1 (CI-B1) spacecraft, volume, mass and resource allocation to the bumper is more difficult than Giotto. The maximum distance from the first layer to the spacecraft exterior is 100 mm and the total mass should be ~5 % of the wet spacecraft mass (<< 2 kg) including the design margin. Its bumper protection area must be in the plane of the spacecraft velocity vector and the total protection area of the main spacecraft body is 0.107 m$^2$, taking into account of attitude control uncertainty, except SAP, cameras, and magnetometer boom. We also assume that the reference comet dust environment model is ESA's Engineering Dust Coma Model (EDCM) Version 4.1 [15]. In contrast, the closest approach distance (CA) between the spacecraft and comet nucleus is calculated from a cumulative probability distribution (e.g., the probability of getting inside CA is 1%) as 420 km during the entire fly-by period in the EDCM 4.1 model environment. Table 1 summarizes the parameter requirements of the CI-B1 bumper shield.

## 3. BUMPER DESIGN PROCEDURES

No ground-based impact experiment facility can reproduce the 34 mg x 70 km/s mass-velocity range. In addition, impact experiments of equivalent momentum achieved by larger mass x lower velocity alone cannot consider melting, sublimation, ionization, and phenomena that may occur at extremely high velocities.

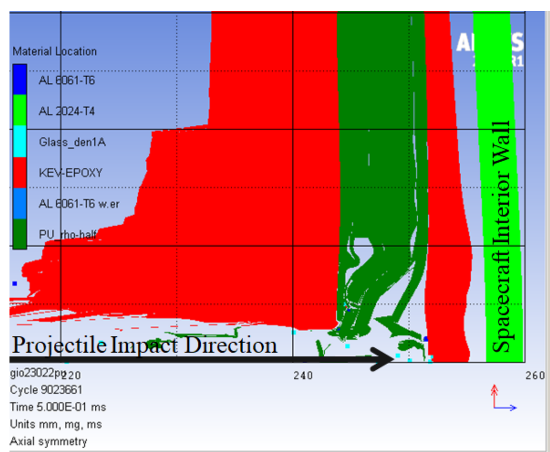


**FIGURE 1:** AUTODYN RESULTS OF PROTECTING THE SPACECRAFT INTERIOR BY GIOTTO BUMPER AFTER 0.5 MILLISECONDS OF A HALLEY DUST IMPACT AT 70 KM/S

Thus, we initially developed the hydrocode simulation condition for the Ansys Autodyn® program that could reproduce the performance outcome of the Giotto bumper shield with the EDCM 4.1 cometary dust environment model applied to Comet Halley and the determined orbit of the Giotto spacecraft at its closest approach. Giotto survived the Halley flyby because no impact dust penetrated both the bumper and the inner wall of the spacecraft, and deformation of the spacecraft's inner wall did not cause a fatal failure inside the spacecraft. In our Autodyn calculations, the first A6061-T6 layer was penetrated by a cometary dust impact at the maximum mass x maximum velocity range while impact-induced debris from the first layer continued to damage the intermediate layers but the damage did not reach the spacecraft interior (Figure 1).

After successfully reproducing the protection performance of Giotto's Whipple bumper shield, we measured the various physical parameters of the Japanese AFRP products to better adjust the Autodyn calculations. Then, we applied this new number of layers, thickness, standoff distance, and material combination with the Autodyn calculations to obtain the ballistic limit curve (BLC) for the CI-B1 Whipple bumper shield design (Table 2 and Figure 2).

**TABLE 2:** THICKNESSES AND STAND-OFF DISTANCES OF THE CI-B1 BUMOER DESIGN

| Distance from S/C Interior Wall (mm) | Bumper Layer (Materials and Thickness) |
|---|---|
| 99.0-100.0 | First (A6061-T6, 1.0 mm) |
| 27.0-29.0 | Second (AFRP, 2.0 mm) |
| 6.0-8.0 | Third (AFRP, 2.0 mm) |
| 5.5-6.0 | Fourth Layer (A6061-T6, 0.5 mm) |

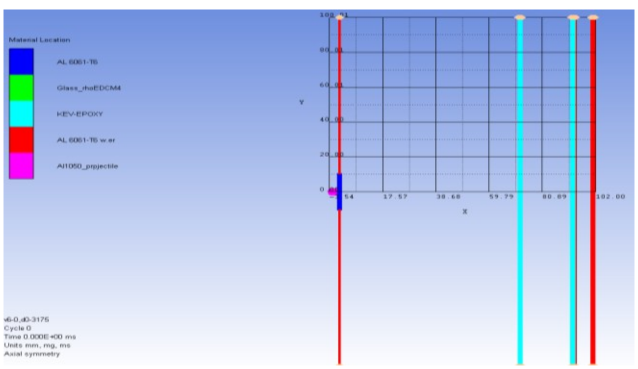

**FIGURE 2:** CI-B1 BUMPER DESIGNED BY THE AUTODYN

## 4. EXPERIMENTS AND HYDROCODE COMPARISON

Next, we performed hypervelocity impact experiments at normal angle on a prototype model of the multiple-layered bumper shield from sub-km/s up to 6.5 km/s as the fastest extend of two-stage light gas guns (TS-LGG), including the most severely damaged range around 2-3 km/s, at Hosei University, JAXA/ISAS, the University of Kent at Canterbury, and Cranfield University [15, 16, 17]. We kept the same projectile property as the maximum particle mass of 34 mg. Then, we evaluated the consistency of the experimental results with the BLC calculation results at the same velocity ranges by Autodyn. Figure 3 shows an impact result of the third and fourth layers on the AFRP bumper at 70 km/s. Damages on spacecraft mean that the spacecraft interior cannot function properly due to penetration of the spacecraft's inner wall just below the bumper, back spallation from the inner wall, or inflow of dark current due to hypervelocity impact-induced plasma plume. In the simulation of Figure 3, no physical damages inside the spacecraft were seen.

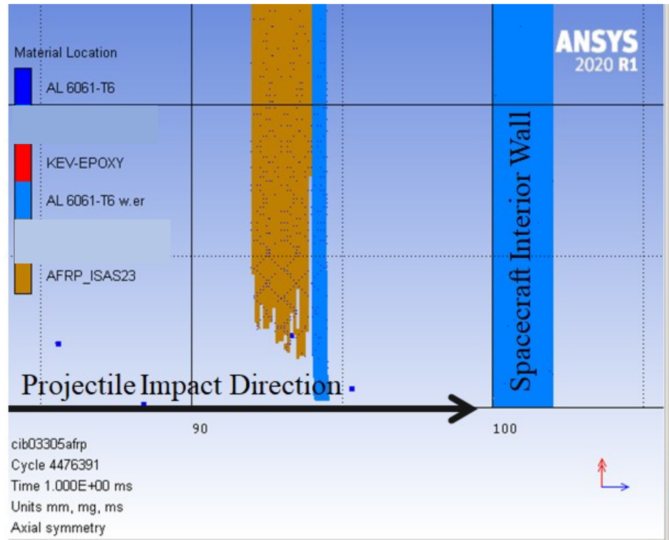


**FIGURE 3:** AUTODYN RESULTS OF PROTECTING THE SPACECRAFT INTERIOR BY CI-B1 BUMPER AFTER 1 MILLISECONDS OF A LONG-PERIOD COMET DUST IMPACT AT 70 KM/S

## 5. RESULTS AND DISCUSSION: BUMPER DESIGN BEYOND THE LIMITS OF IMPACT FACILITIES

According to earlier studies of Whipple bumper shield durability, the most severe damages within the bumper occur at a relatively lower velocity range where the impactor still survives intact after penetrating the intermediate layers of the bumper. Such velocity ranges exist around 1-3 km/s for the case with the A6061-T6 first layer; thus, we can investigate the damage level with a single impact shot by TS-LGG experiments to compare with the Autodyn simulations in the same velocity range.

Figures 4-9 report a comparison between high-speed imagery of TS-LGG impact experiments and the Autodyn simulations at each velocity range of ~2 km/s, ~4 km/s and ~6 km/s, together with impact damages seen by each bumper layer for the TS-LGG experiments. Physical deformation of the fourth layer was found for the ~ 2km/s impact. At ~4 km/s, the impactor was fragmented through the first and second layers penetrated but the damage was stopped at the third AFRP layer. The damaged area of the second layer became larger as impact velocity increased to ~6 km/s but the bumper protected the third layer and beyond.

Our Autodyn simulations reproduced the sequential development of impact damages well all the experimental cases; therefore, our BLC plots of the Whipple bumper shield using the Japanese AFRP layers should be consistent with actual impacts in space at a faster velocity than what laboratory experimental facilities can achieve. It is judged that the design of the CI-B1 bumper with similar impact conditions can also be performed by this method.



 

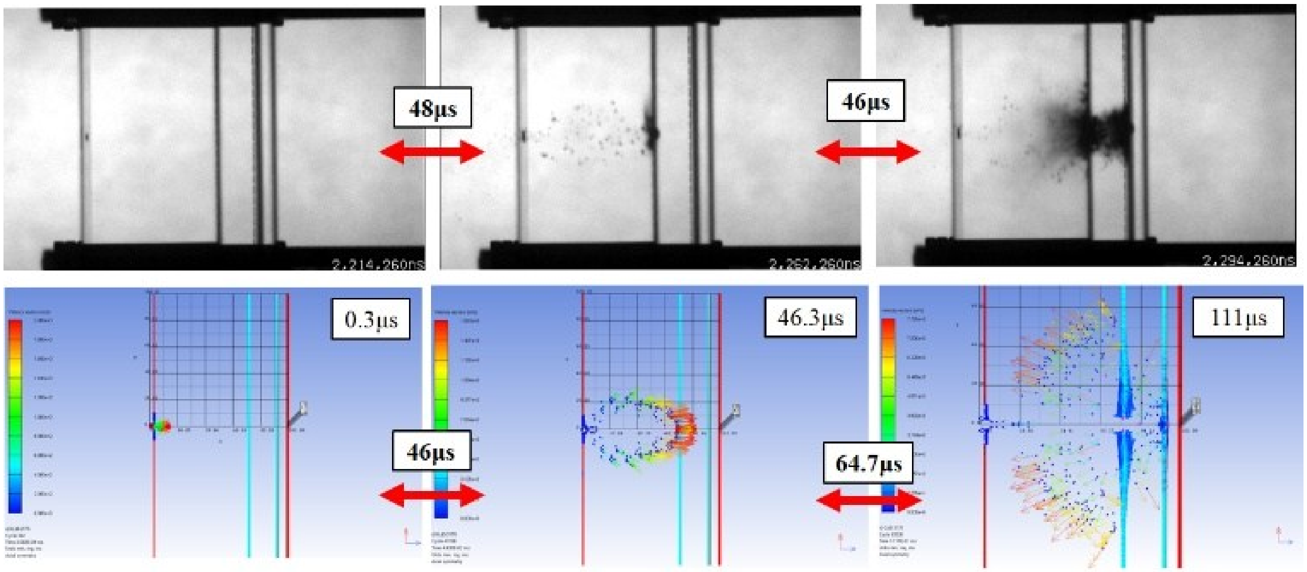


**FIGURE 4:** COMPARISON BETWEEN TS-LGG EXPERIMENT AND AUTODYN SIMULATION FOR THE CI-B1 BUMPER AT ~2 KM/S

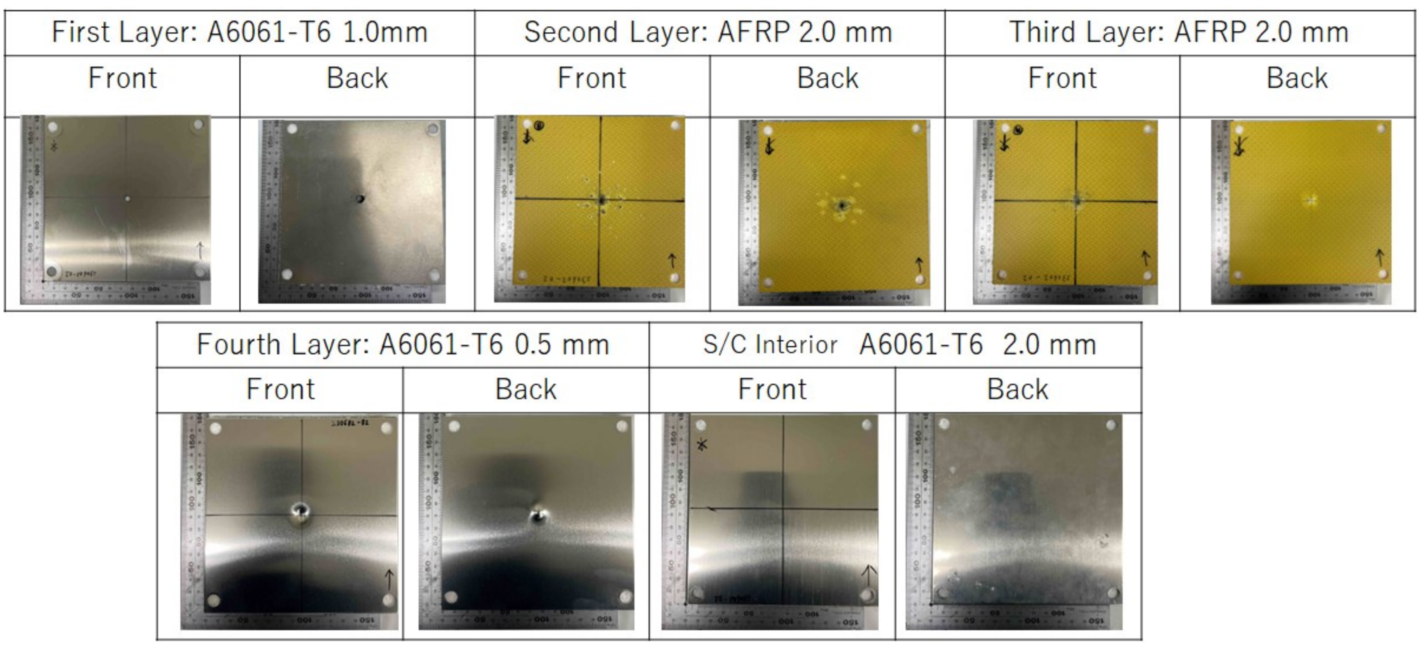


**FIGURE 5:** IMPACT DAMAGES WITNESSED BY EACH LAYER OF THE CI-B1 BUMPER AT ~2 KM/S

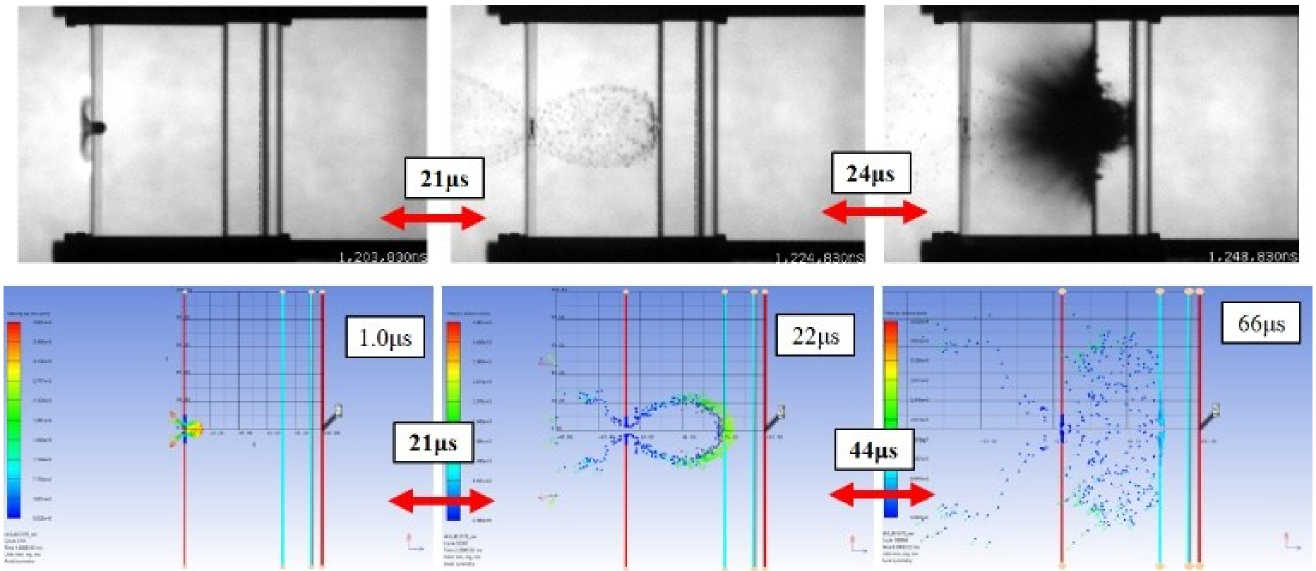


**FIGURE 6:** COMPARISON BETWEEN TS-LGG EXPERIMENT AND AUTODYN SIMULATION FOR THE CI-B1 BUMPER AT ~4 KM/S

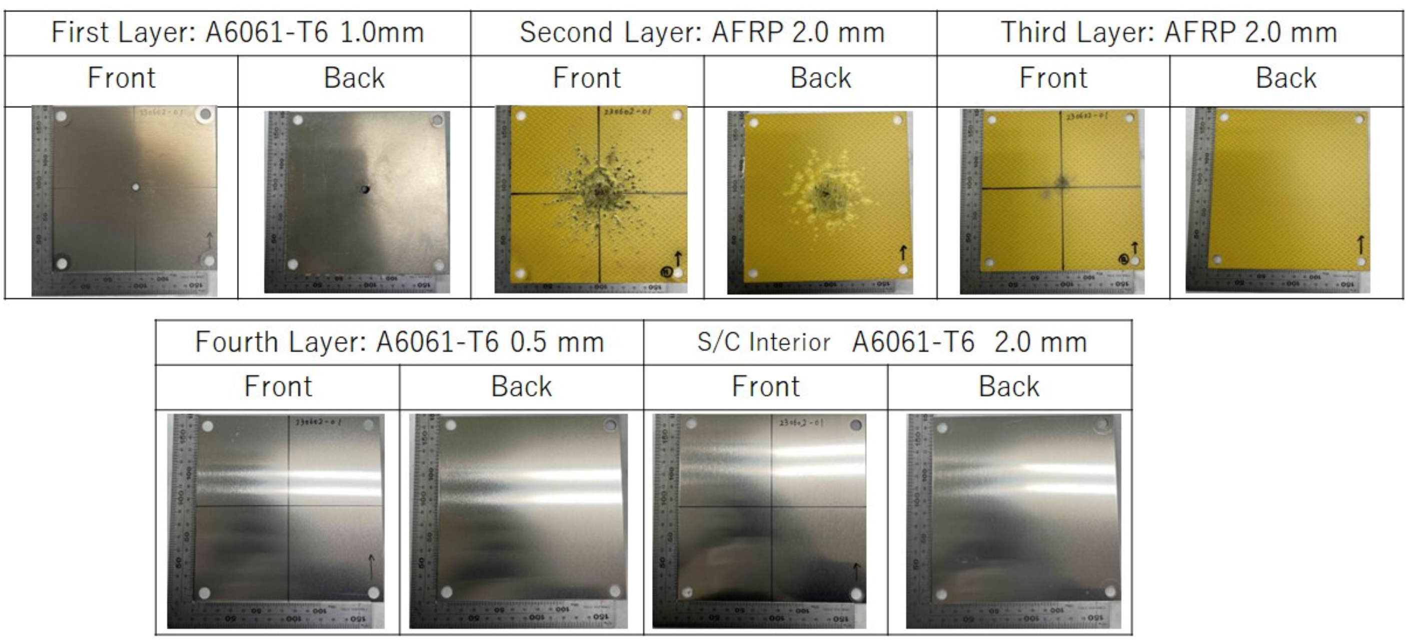


**FIGURE 7:** IMPACT DAMAGES WITNESSED BY EACH LAYER OF THE CI-B1 BUMPER AT ~4 KM/S

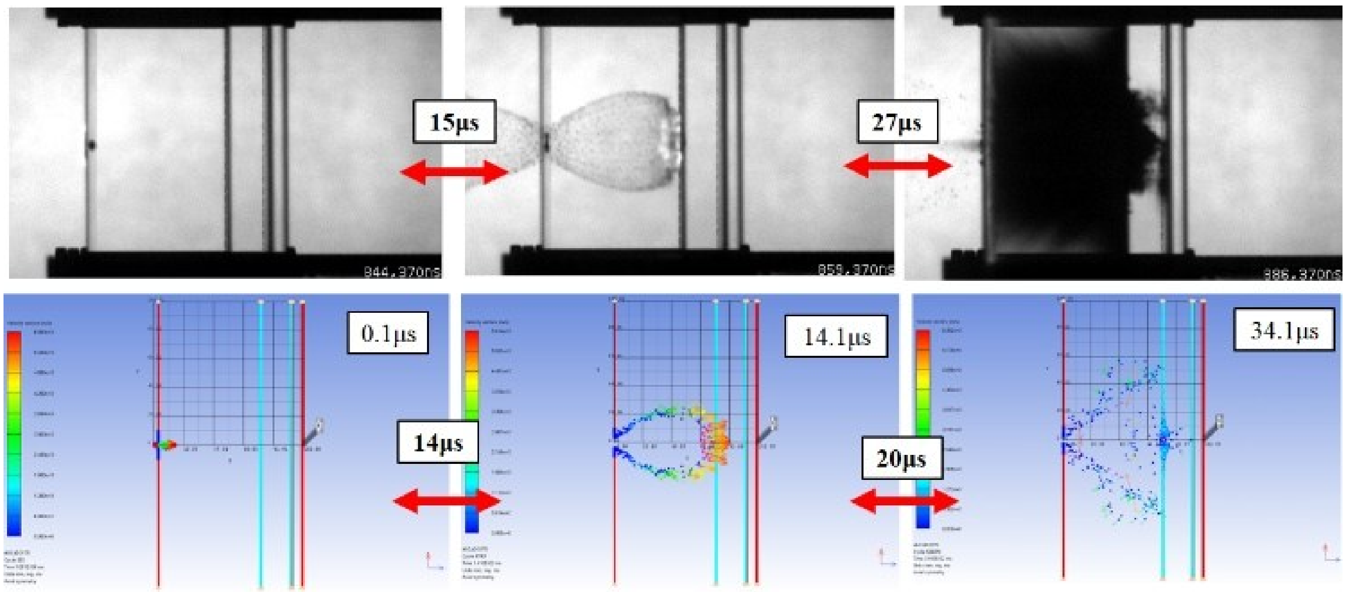


**FIGURE 8:** COMPARISON BETWEEN TS-LGG EXPERIMENT AND AUTODYN SIMULATION FOR THE CI-B1 BUMPER AT ~6 KM/S

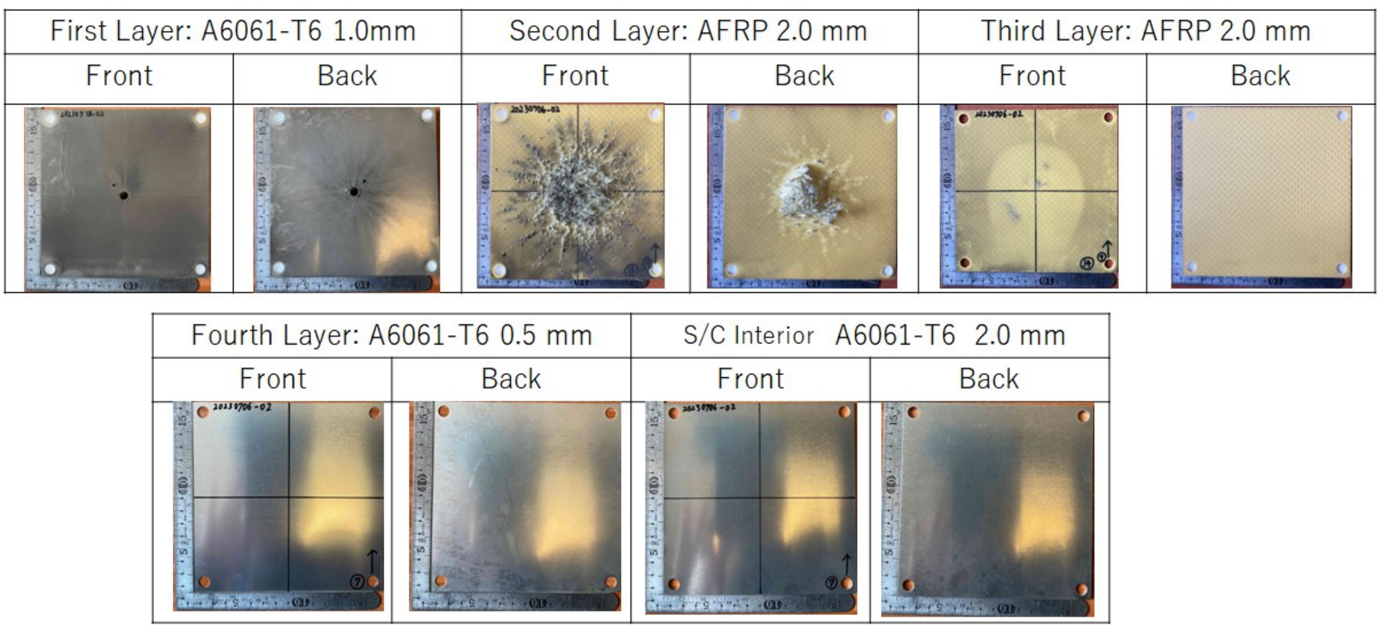


**FIGURE 9:** IMPACT DAMAGES WITNESSED BY EACH LAYER OF THE CI-B1 BUMPER AT ~6 KM/S

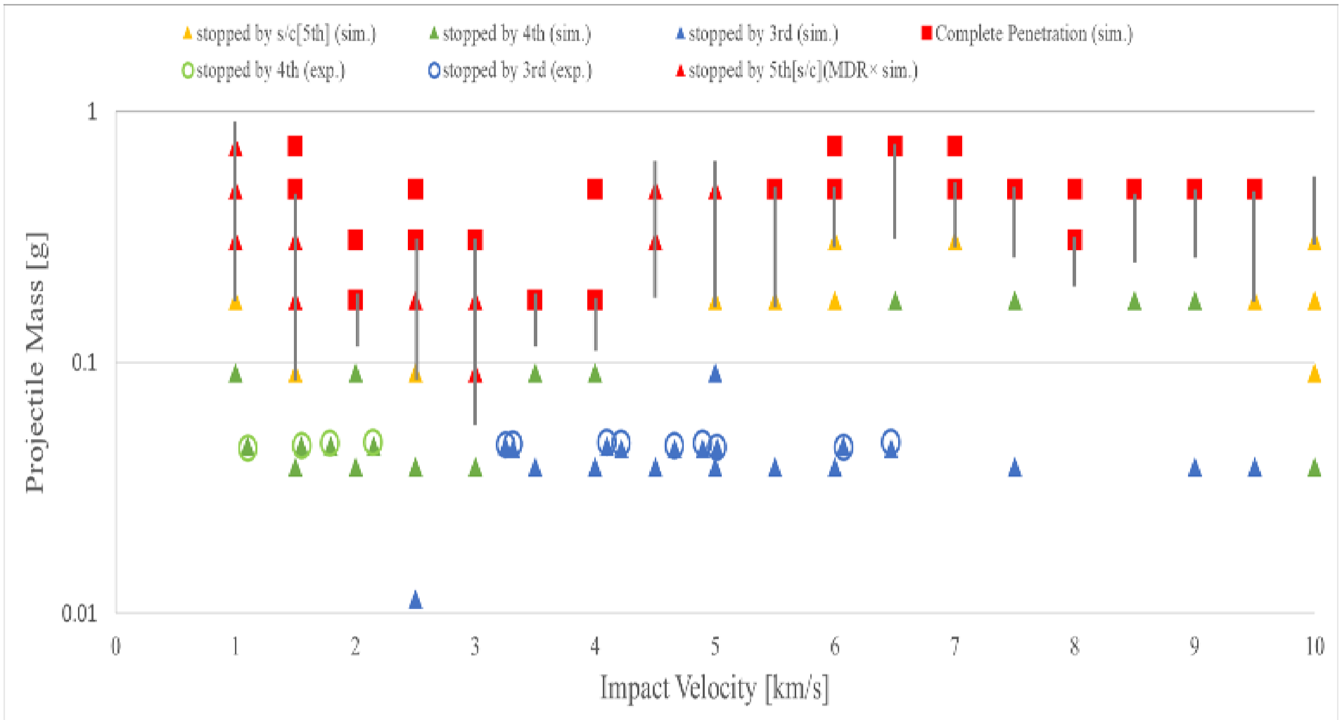


**FIGURE 10:** BALLISTIC LIMIT PLOTS OF THE CI-B1 BUMPER FOR BOTH EXPERIMENTS AND SIMULATIONS AT 1-10 KM/S

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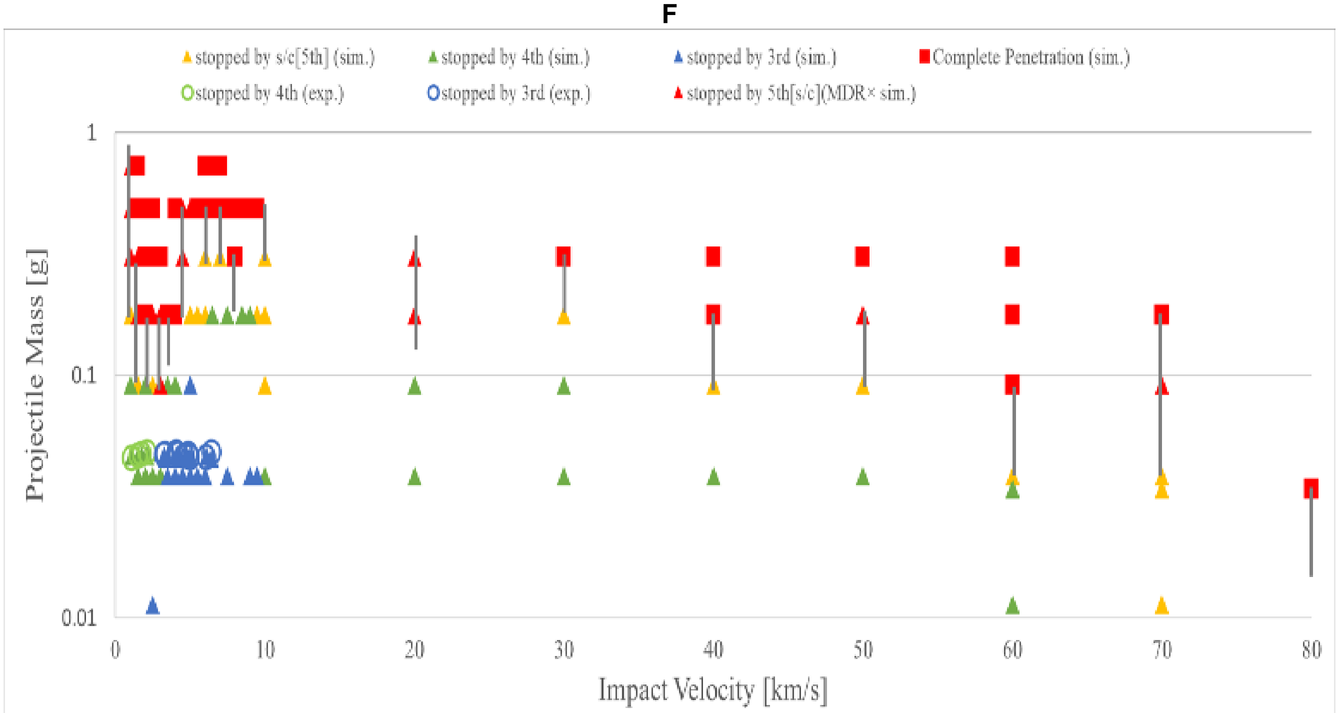


**FIGURE 11:** BALLISTIC LIMIT PLOTS OF THE CI-B1 BUMPER FOR BOTH EXPERIMENTS AND SIMULATIONS AT 1-80 KM/S

We calculated the Autodyn and plotted the BLC results at a diverse velocity range of 1-80 km/s by the CI-B1 Whipple bumper with the AFRP layers (Figures 10, 11). Consequently, we confirmed that no spacecraft interior failure occurred by impacts of a hollow glass bead sphere of 34 mg as the maximum cometary dust analogue at 1-80 km/s conditions. This allows us to conduct a numerical-simulation-based design of lightweight Whipple bumper shields for micro-spacecraft against hypervelocity dust impacts at a velocity beyond the performance limit of the ground experiment facilities.

## 6. CONCLUSION

In this study, we conclude the following points.

(1) The Autodyn simulation, which handles the CI-B1 bumper design, has been validated by reproducing the successful survival of Giotto's Whipple bumper shield for the Comet Halley flyby.

(2) The BLC was evaluated by the protection performance of the spacecraft interior behind the bumper from impacts with a maximum mass (34 mg) and maximum velocity (70 km/s) of cometary dust based on ESA's cometary environment model with a PNF>0.7.

(3) The CI-B1 bumper structure was designed to meet the resource constraints within a height of less than 100 mm and ~5% of the total mass of the spacecraft (<< 2 kg).

(4) The CI-B1 bumper was designed as a three-layered stuffed Whipple structure, and BLC calculations showed that the damage could be stopped on the second layer at the maximum mass and velocity for the Comet Interceptor mission.

(5) The BLC calculations were consistent with the protection performance of real-scale impact experiments (maximum mass x1.0-6.5 km/s) using Japanese AFRP.

We now can open a new era for fast flyby exploration of small spacecraft to dusty objects and the Comet Interceptor mission will be the first step.


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