BALLISTIC LIMIT OF ALAMIDO FIBER FABRIC STACKING FOR SUB-MILLIMETER DEBRIS IMPACT

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1. Introduction

For a satellite in low earth orbit, the impact of sub-millimeter space debris is a serious problem. Debris flux in low earth orbit calculated by MASTER-2009 is shown in Fig. 1. The vertical axis shows cumulative numbers of debris through a 3 km cube in low earth orbit for 5 years. This means debris impact probability of a 3 km cube satellite operated in low earth orbit for 5 years. When the debris diameter is 2.5 mm, the cumulative number is over 1. In this case, an impact of debris of 2.5 mm diameter can occur during the satellite operation. Because the average impact velocity of debris is over 10 km/s, the impact of even such a small particle can cause critical damage to a satellite. To show philosophy and procedure of debris protection design for a satellite, JAXA has prepared standards and a handbook[1)]. Important components related to satellite life and mission success are recommended to be installed inside the satellite structure. However, this is impossible for some components, e.g., expandable structures and wire harnesses. They are made of materials that are vulnerable to debris impact, and their damage can cause loss of control or mission failure. To protect these components, a flexible debris bumper is required. In this study, fabrics made of alamido fiber are investigated as flexible bumpers.

Alamido fiber fabric has been known to have high protection ability against impacts. There are many studies on low-velocity impacts on alamido fiber fabrics[2–6)]. Alamido fiber fabrics are also known to be useful for protection against high-velocity impacts. It is used as a part of the Staffed Whipple Bumper installed on the International Space Station[7)]. However, data on sub-millimeter debris impact on alamido fiber fabrics are not sufficient to justify their use as debris bumper shields. The purpose of this study is to obtain the ballistic limits of alamido fiber fabrics against sub-millimeter debris impacts. As alamido fiber fabric, clothes made from Kevlar produced by DuPont were investigated by hyper impact experiments and numerical simulations.

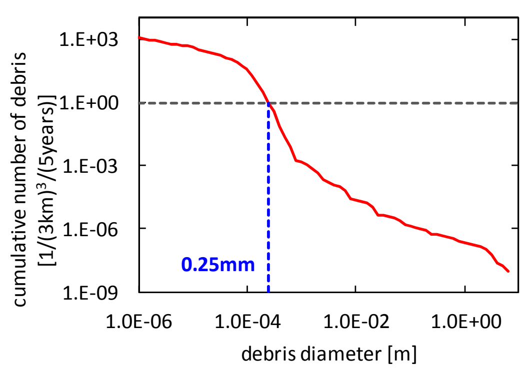

Fig. 1 Debris flux through 3 km cubic in low earth orbit

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2. Hypervelocity Impact Experiment

2.1. Experimental Condition

Tested Kevlar clothes are listed in Table 1. All clothes were plain weave. Fabric density means the number of warp and woof yarns per inch. A higher value of fabric density is found in finer textiles. Two types of Kevlar fiber were compared: K29, which is a normal type, and K49, which is high-modulus type. The tensile strengths of both fibers are approximately 3,000 MPa, but their tensile moduli are 71 GPa (K29) and 112 GPa (K49). The stacked clothes are installed as shown in Fig. 2. The thickness of stacked clothes was approximately 10 mm. There was no standoff between the fabrics and the aluminum alloy plate. The top and bottom edges of the target were fixed.

Hypervelocity impact experiments were performed using a two-stage light gas gun at the Institute of Space and Astronautical Science (ISAS) of JAXA. According to the flux of 0.1–1 mm debris calculated using a debris environment model, alumina impacts most frequently on a spacecraft. Its average impact velocity is approximately 10 km/s. However, a feasible velocity for the two-stage light gas gun was only 7 km/s. Currently, there is no device capable of stably accelerating sub-millimeter solid spheres to 10 km/s. Therefore, this study used steel as the projectile material. The impact pressure was therefore increased owing to the increased projectile density. To investigate the damage caused by sub-millimeter debris impact, steel spheres 0.15, 0.3, and 0.5 mm in diameter were used as projectiles. The projectiles were launched in a scatter-shot. Many projectiles were put into a sabot and accelerated at the same time.

Table 1 Tested Kevlar fabrics

ID	Fiber	Thickness (mm)	Areal density (g/m^3)	Fabric density (yarn/inch)
T710	K29	0.43	319	24x24
T120	K49	0.08	58	34x34
T328	K49	0.33	217	17x17

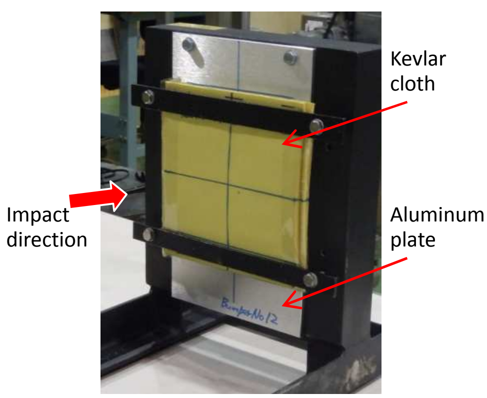

Fig. 2 Target setting

2.2. Experimental Result

The total data numbers obtained from the impact experiments are listed in Table 2. Kevlar clothes after the impact experiments are shown in Figs. 3–5. The projectiles perforated the 1st layer, and then they broke up. In the middle layer, the fragment clouds were stopped, and impacted yarns in the fabric were deformed.

In this study, the ballistic limit was defined as non-perforation by the projectile fragments, as shown in Fig. 6. From the ballistic limit layers

Table 2 Total data number of impacting projectiles

Fabric ID	Projectile diameter (mm)	Average impact velocity (km/s)	Data number
T710	0.15	6.11	51
T710	0.3	5.89	10
T710	0.5	5.81	9
T120	0.15	5.95	53
T120	0.3	6.23	22
T120	0.5	6.17	11
T328	0.15	6.14	131
T328	0.3	6.27	31
T328	0.5	6.13	14

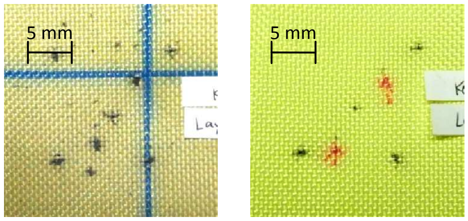

Fig. 3 Impacted T710 cloth, 0.3 mm projectiles, 5.88 km/s: (left) 1st layer. (right) 7th layer

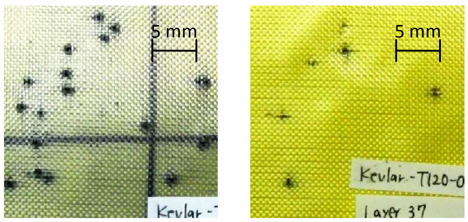

Fig. 4 Impacted T120 cloth, 0.3 mm projectiles, 6.22 km/s: (left) 1st layer. (right) 37th layer

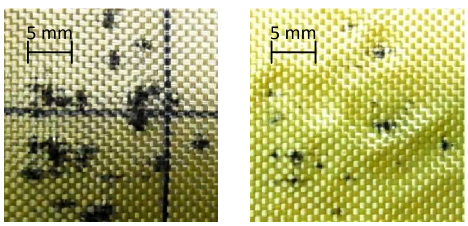

Fig. 5 Impacted T328 cloth, 0.3 mm projectiles, 6.24 km/s: (left) 1st layer. (right) 10th layer

of the fabrics, the ballistic limit thickness was calculated by the thickness per layer. The relationship between the projectile diameter and the ballistic limit thickness is shown in Fig. 7. The value of 3σ was used for the error bars. The ballistic limit thicknesses of the fabrics made from high-modulus fiber (K49) were smaller than normal fiber (K29) fabric. If the fiber is the same, stacking many thin fabric layers is effective in improving protection capability.

3. Numerical Simulation

3.1. Simulation Condition

Numerical simulations were performed for a normal type cloth (T710). The simulation code was AUTODYN-2D with axial symmetry and Lagrangian method with the numerical erosion.

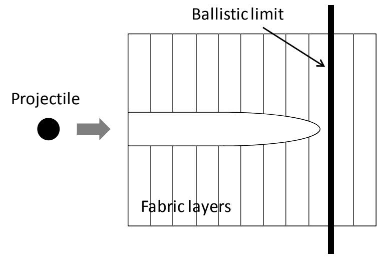

Fig. 6 Definition of ballistic limit thickness

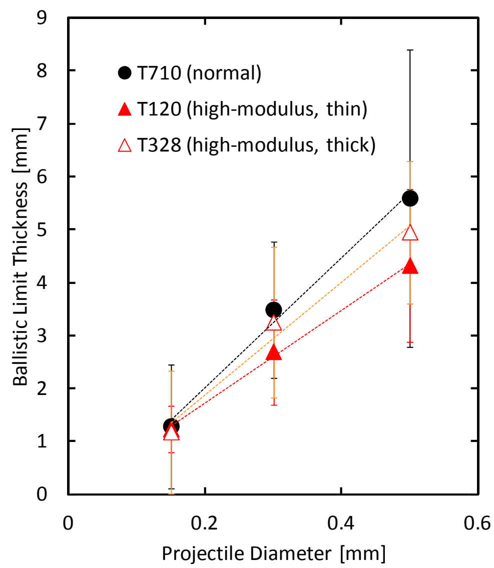

Fig. 7 Ballistic limit thickness obtained from experimental results

From previous research on impact simulations of Kevlar clothes, the followings were assumed[2–6].

- The fabric is in-plane isotropic (ignoring weave).
- Out-of-plane elastic modulus is 1/100 of in-plane.
- Shear modulus is 1/100 of in-plane elastic modulus.
- Poisson effect is ignored.

As material models, Orthotropic and Elastic were used as the equation of state and strength model. The density of the cloth was calculated by the areal density of the cloth divided by the thickness per layer. Each layer was modeled as a part.

To decide a failure threshold, the failure strain was varied 0.15–0.30. The simulation results were shown in Fig. 8. The steel sphere of 0.3 mm diameter impacted on Kevlar target staked 20 layers at 6 km/s. In the experiment, the ballistic limit was 6–9 ply in this condition. If the failure strain was 0.15, the ballistic limit calculated by the simulation showed in good agreement with the experiment. Therefore, the failure strain was decided as 0.15.

3.2. Simulation Result

By using the above condition, the ballistic limit of Kevlar cloth against alumina impacts was calculated. The projectile diameter and the impact velocity were varied in the range of 0.01–2 mm and 1.5–15.0 km/s. The Kevlar clothes were stacked 1, 5, and 10 ply.

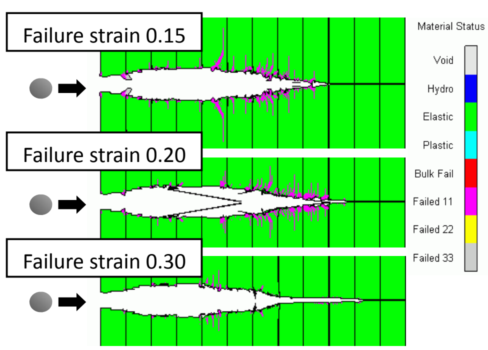

Fig. 8 Numerical simulation with failure strain of 0.15–0.30, 0.3 mm steel projectile, 6 km/s

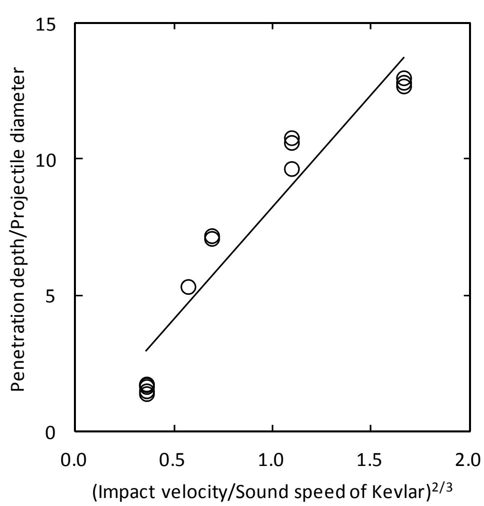

Fig. 9 Penetration depth calculated from numerical simulation

From non perforation results, penetration depth was calculated as shown in Fig. 9. The horizontal axis shows 2/3 power of the impact velocity, v_p normalized by the sound speed of Kevlar fiber, c. The vertical axis shows the penetration depth, p normalized by the projectile diameter, d_p. The penetration depth found to be proportional to 2/3 power of the impact velocity. The following equation was obtained from Fig. 9.

$$p / d_p = 8.25 \left(v_p / c \right)^{2/3} \qquad (1)$$

Next, the penetration depth was assumed as the ballistic limit thickness of Kevlar cloth, and then the ballistic limit equation was obtained. The simulation results and the ballistic limit curves are shown in Fig. 10. The curves show in good agreement if the impact velocity is over 5 km/s. Because the projectile material is the same in this study, Eq. (1) means that the penetration depth is proportional to the impact energy. In low velocity impact, it is known that momentum of a projectile contributes to damage than kinetic energy. Therefore, low velocity damage was considered to be not expressed by Eq. (1).

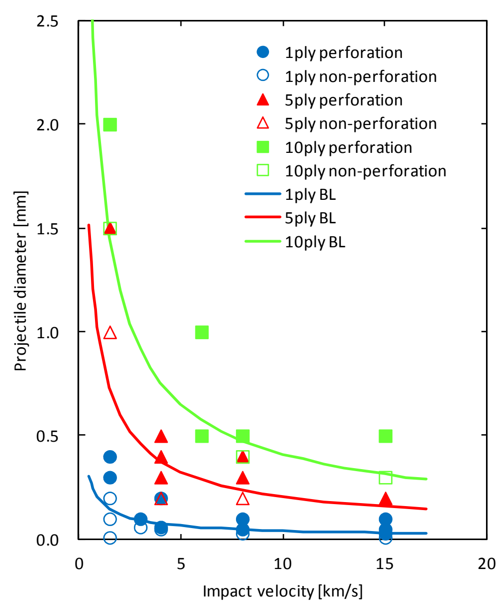

Fig. 10 Comparison of simulation results and ballistic limit curves

4. Summary

To investigate the ballistic limit of Kevlar clothes against sub-millimeter debris, hypervelocity impact experiments and numerical simulations were performed. From the experimental results, it found that protection capability of the high-modulus Kevlar cloth was better than the normal fiber cloth. To stack many thin clothes is effective to decrease the total bumper thickness. From the numerical simulation results, the crater depth equation of normal Kevlar cloth was obtained. If the ballistic limit was assumed to the same as crater depth, the ballistic limit curve showed in good agreement when the impact velocity was over 5 km/s.

Acknowledgment

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