A LIGHTWEIGHT DEBRIS SHIELD USING HIGH STRENGTH FIBERS

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ABSTRACT

The purpose of this study was to develop a new lightweight shield using high strength fibers against hypervelocity impacts from space debris (in particular, 1 to 10cm in diameter). We developed the new lightweight shield using Vectran fibers. The experimental results showed that the developed shield could stop the polycarbonate projectile with 14mm in diameter, 1 gram in weight, 3.14km/s and 6.59km/s in velocity. The areal density of the developed shield was as half as that of Japanese Experiment Module (JEM). Adoption of the high strength fibers in the bumper may reinforce the protection capability and reduce the weight drastically. In addition, we compared the results of hypervelocity impact tests with the numerical analysis using SPH method.

1. INTRODUCTION

The International Space Station (ISS) will have high possibility of impacts from meteoroids and space debris because the ISS is one of the largest space structure and has a lifetime longer than 10 years. The countermeasure against hypervelocity impacts of debris is divided into 3 levels by debris size. Debris larger than 10 cm in diameter can be tracked by ground-based radio frequency radars and optical observations. These obtained debris data are available to avoid hypervelocity impacts of debris. On debris smaller than 1cm in diameter, it is possible to protect hypervelocity impacts using the present bumper shield of the ISS. The countermeasure against impacts of debris with 1 to 10 cm in diameter is not enough. It is necessary to strengthen the protection capability of the bumper shield, because these danger size debris can give fatal damage to space structures including the ISS. The purpose of this study is to develop a new light-weight bumper shield without reduction of protection capability. The main material of a new bumper is high strength fibers, Vectran.

2. LIGHTWEIGHT DEBRIS SHIELDS

The Vectran is a liquid crystal polymer fiber developed by Hoechst-Celanese. Only Kuraray Company in Japan has the technique for manufacturing the fabric. With yarn tenacity comparable to Kevlar, degree of moisture absorption is substantially zero percent. The product HT4533 is wove using 3 fibers with 1500 de. The unit de (denier) indicates a weight per unit length. One de is equivalent to 1 gram/ 9000 m. To develop the lightweight shield for spacecraft, it is indispensable that the main material of the bumper is lightweight. In this respect, a fiber is one of potential materials, and available to transport to Low Earth Orbit. Especially, Vectran is expected to be used as the bumper materials of the debris shield. This high strength fiber has been used as airbags with the Mars Path Finder.

As shown in Fig. 1, two kinds of shields were prepared for hypervelocity impact tests. To investigate the basic protection capability of one Vectran sheet, the Type I shield in Fig. 1 was tested. The Type I shield is composed of only one sheet of Vectran cloth (HT4533) with 3/3 mat stitch.

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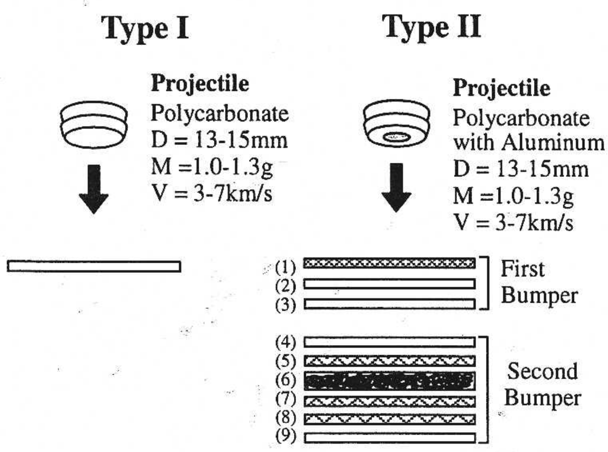


Fig. 1. Bumper Shields

Table 1. Characteristics of shielding materials [1,2]

Shield Type			Material of Bumper	Areal Density (kg/m^2)	Total Areal Density (kg/m^2)
Type I			Vectran (HT4533)	1.30	1.3
Type II	1st	(1)	Stainless Mesh	1.96	9.6
		(2)	Vectran (HT4533)	1.30	
		(3)	Vectran (HT4533)	1.30	
	2nd	(4)	Vectran (HT4533)	1.30	
		(5)	Knitted Vectran	0.41	
		(6)	Vectran Threads	1.00	
		(7)	Knitted Vectran	0.41	
		(8)	AL Mesh (AL2017) with Vectran Threads	0.60	
		(9)	Vectran (HT4533)	1.30	
Mesh Stuffed Whipple Bumper Shield including Pressure Wall (JEM)			---	---	17.0 - 26.8

The Type II shields were developed from consideration of a double-bumper multi-layers system. The first bumper is composed of a stainless mesh and two Vectran sheets, and has a role for breaking up space debris into a debris cloud at the beginning of impact. Two Vectran sheets of the first bumper cling with crossing stitch directions. The second bumper is composed of two Vectran sheets, a Vectran cloth, a lump of Vectran threads, and an aluminum mesh. This shield features a knitted Vectran cloth with crochet stitch and a sewn aluminum mesh using Vectran threads. Knitted Vectran in the Type II shield are adopted as inflatable materials, and have an important role for spreading shock waves caused by a hypervelocity impact. This protection concept is derived from a multi-shock, multi-layers shield. Table 1 provides the data sheet on areal density compared with the weight of the shield of JEM.

3. RAILGUN

The hypervelocity impact tests were carried out by using the railgun accelerator of the Institute of Space and Astronautical Science. This hypervelocity impact facility consists of a railgun and a vacuum chamber, a velocity measurement system. The inside of the chamber and the railgun bore is evacuated to the order of 130 Pa by a roughing pump. Before a test, an aluminum fuse is placed behind a projectile in the railgun bore. At the beginning of discharge an arc is initiated by the vaporization of the aluminum fuse at the starting position. The Lorentz force generated by the interaction between the magnetic field and an armature current accelerates the projectile. The accelerated projectile reaches a velocity of 7 km/sec. The projectile is made of cylindrical polycarbonate blocks with aluminum thin disks as shown in Fig.1.

4. RESULTS OF HYPERVELOCITY IMPACT TESTS

As shown in Table 2, four tests were conducted, two tests for the Type I shield and two tests for the Type II shield. In hypervelocity impact tests, bumper materials are fixed to two steel plates with 80 mm of holes by 8 bolts.

Two bumpers of Type II with 80 to 90 mm spacing are installed on the steel frame. An aluminum block with 30 mm in thickness is located behind the target.

Table 2. Conditions of Hypervelocity Impact Tests, and Results

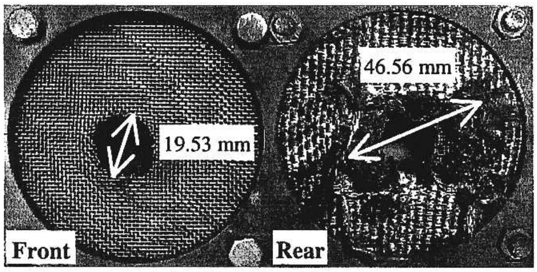
Test No.		1	2	3	4
Projectile	Material	PC	PC	PC and Al	PC and Al
	Diameter (mm)	13.86	13.86	14.26	13.56
	Thickness (mm)	6.5	6.0	6.5	6.3
	Mass (g)	1.09	1.02	1.25	1.09
	Velocity (km/s)	4.74	6.78	3.14	6.59
Shield Type		I	I	II	II
Result	Depth (mm)	---	---	32	35
	Perforation	O	O	X	X

PC=Polycarbonate; Al= Aluminum

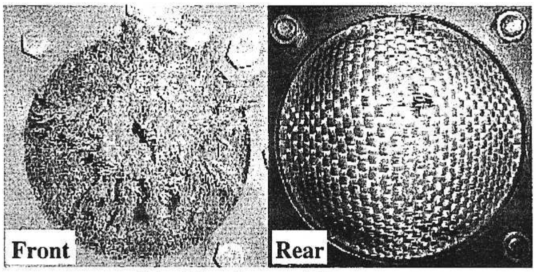
In Test No.1 and No.2, a projectile penetrated the Vectran sheet. The projectile of No.1 was 13.86 mm in diameter, 1.09 gram, and 4.74 km/s. The projectile of No.2 was 13.86 mm in diameter, 1.02 gram, and 6.78 km/s. The experimental results on the Type I shield showed that Vectran had the capability of breaking up the projectile made of polycarbonate.

In Test No.3 and No.4, the Type II shields stopped projectiles between the knitted Vectran and the lump of Vectran threads in the second bumper, perfectly.

On the damage of the second bumper of the Test No.3, a hole with expanded the Vectran threads were found on the first Vectran sheet as shown in Fig.2(b). In addition, as the result of the observation of the intermediate layers, a projectile was stopped at the point of the lump of Vectran threads. The recovered projectile was a bit of polycarbonate with approximately 6.5 mm in length.



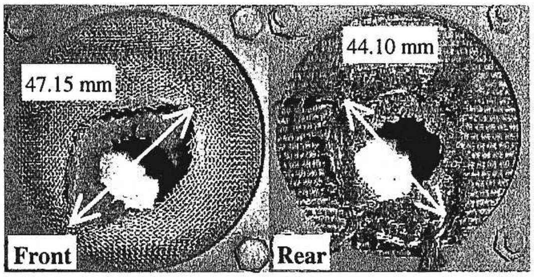
(a) The First Bumper



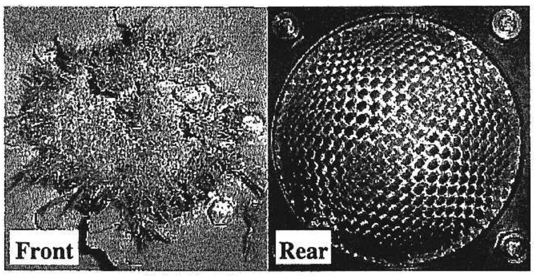
(b) The Second Bumper

Fig.2 Results of Test No.3 (V=3.14km/s)

The projectile of No.4 was 13.56 mm in diameter, 1.09 gram, and 6.59 km/s. On the damage of the second bumper of the Test No.4, the first Vectran sheet was destroyed completely by the expansion of shock waves as shown in Fig.3(b). In particular, the projectile did not perforate the layer of Vectran threads although a hole with the diameter of 20 mm was found on the first knitted Vectran sheet.



(a) The First Bumper



(b) The Second Bumper

Fig.3. Results of Test No.4 (V=6.59km/s)

5. NUMERICAL ANALYSIS

We compared the results of hypervelocity impact tests with the numerical analysis using Smoothed Particle Hydrodynamics (SPH) method[3]. However, parameters on Vectran for hypervelocity impact analysis dose not exist. In this analysis, we used parameters of Kevlar, because the characteristics of Vectran is similar to Kevlar. Table 3 represents the analysis conditions. We analyzed on the nearly same conditions as experimental conditions.

Table 3. Analysis Conditions

Test No.		1	2
Projectile	Material	Polycarbonate	Polycarbonate
	Diameter[mm]	13.86	13.86
	Thickness[mm]	6.5	6.0
	Mass[g]	1.18	1.09
	Velocity [km/s]	4.74	6.78
Target	Material	Kevlar	Kevlar
	Thickness[mm]	2.5	2.5
	Areal Density[kg/m^2]	1.29	1.29

The following is the comparison between analysis results and experimental results. Fig. 4 shows the case that projectile velocity is 4.74km/sec (Test No.1) and Fig. 5 shows the case that projectile velocity is 6.78km/sec (Test No.2).

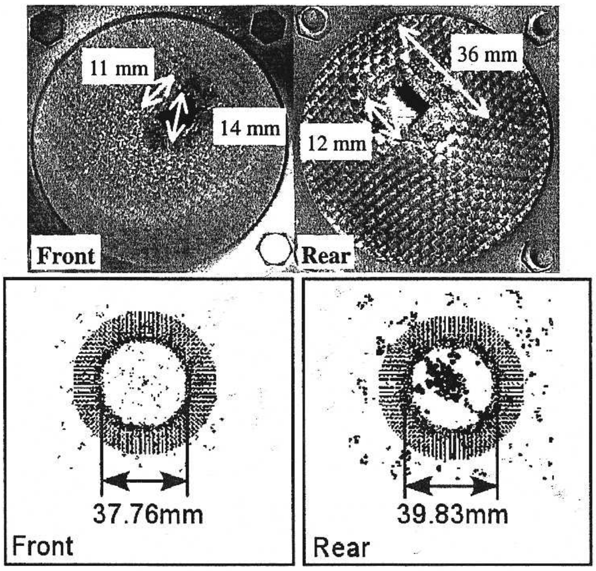


Fig. 4. Comparison of Penetrate Diameter
(Test No.1, V=4.74km/s)

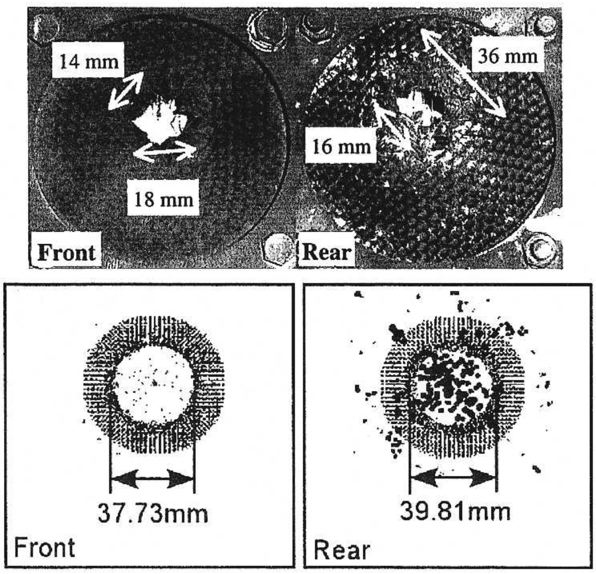


Fig. 5. Comparison of Penetrate Diameter
(Test No.2, V=6.78km/s)

The extended areas of destruction are 36mm in diameter on experimental result, and 39mm in diameter on analysis result. The analysis result is nearly equal to the experimental result. This shows that Vectran is very similar to Kevlar. In the experiment, the shape of holes was square. However, in this analysis, the shape of holes was circle. This result shows it is impossible to analyze damage of fibers with SPH method. It is necessary to define the connection between particles to represent fibers.

6. CONCLUSIONS

We developed Type Ⅱ shield without reduction of protection capability. This shield stopped the projectile, which was made of polycarbonate and Aluminum with 14 mm, 1 gram, and 3.14km/s and 6.59 km/s, perfectly. The main reason for the high protection capability may be that the mixed bumper materials consisted of the knitted Vectran and the lump of Vectran threads expands energy of shock waves caused by hypervelocity impacts. The experimental result showed the JEM shield stopped an aluminum spherical projectile with 0.9 cm, 1 gram, and 6 km/s.[2] As compared with the JEM shield, the new developed shield has the same protection capability, although the areal density is half (10 kg/m^2).

As the results of the numerical analysis, characteristics of Vectran was very similar to that of Kevlar. To analyze fibers including Vectran, Kevlar, and Nextel, it is necessary to improve SPH code.

7. REFERENCES

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[3] L. D. Libersky, A. G. Petschek, T. C. Carney, J. R. Hipp and F. A. Allahdadi. High Strain Lagrangian Hydrodynamics, *Journal of Computational Physics*, Vol.109, ,67-75, 1993.