D1

Kevlar・Beta Cloth の微小デブリ貫通限界重量と厚さ

Ballistic Limit Weight and Thickness of Kevlar and Beta Cloth for Sub-millimeter Debris Impact

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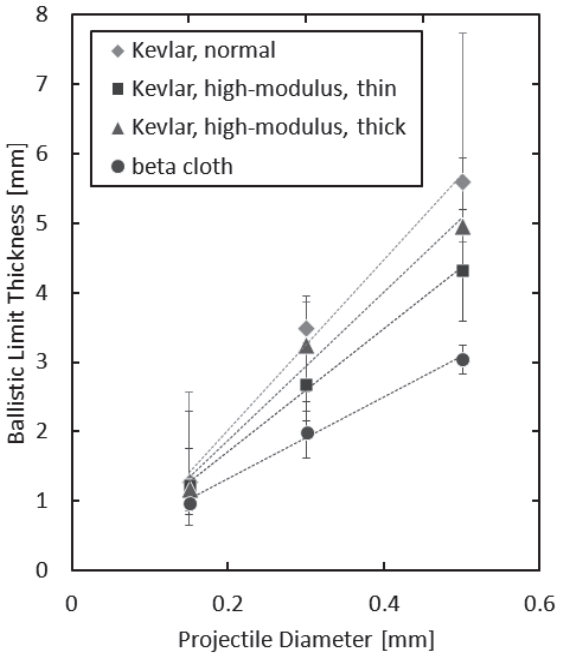
デブリ衝突頻度の高いコンポーネントには防護性能の高い材料を採用することが望ましい. しかし, 進展部やハーネス等の柔軟な構造は防護性能の高い材料を適用することが困難で, 衝突に対して脆弱である. これらを防護するために, 形状に柔軟性のあるバンパ材料が必要とされている. 本研究では高強度繊維織布に着目をした. 高強度繊維のうち, アラミド繊維は超高速衝突に対しても優れた防御性能を持つことが知られており, 国際宇宙ステーションに搭載されているデブリバンパ材料として使用されている. デブリ環境モデルによると, 低高度軌道の人工衛星は1mm以下のデブリ衝突頻度が高い. 従って, 本研究では高強度繊維織布に 1mm 以下の微小デブリが衝突した時の貫通限界について調べた. Kevlar 織布と Beta Cloth の貫通限界について報告する.

To protect a satellite from space debris impact threat, a satellite designer should employ structure material which has enough protection capability against debris impact. However, for some flexible components, it is impossible to use such strong materials, for example, expandable structures and wire harnesses. To protect these flexible components, a flexible debris bumper is needed. High strength fiber fabric is one of flexible debris bumper material. Since the alamido fiber has high tensile and shear strength, the alamido fiber fabric is known to be also useful for high velocity impact protection. The alamido fiber fabric was used as a part of the Staffed Whipple Bumper installed on the International Space Station. A satellite on the low earth orbit needs to pay attention to impacts on debris smaller than 1 mm, because debris environment models show such small debris will impact on the satellite during its operation lifetime. Therefore, to employ the alamido fiber fabric as a debris bumper, it is necessary to know their sub-millimeter debris impact damage. The purpose of this study is to investigate sub-millimeter debris impact damage of the fiber fabric.



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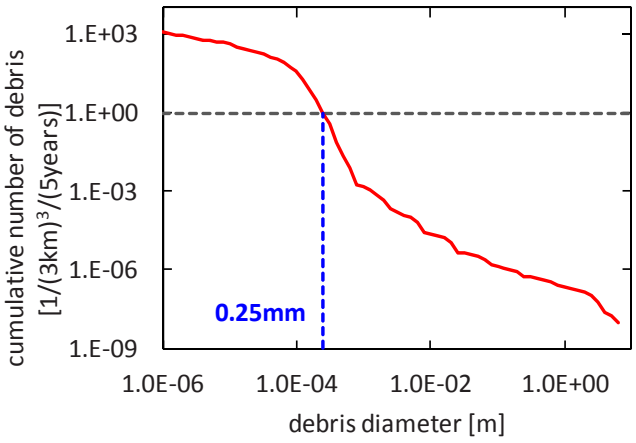
Background

Sub-millimeter debris impact is threat of mission failure for LEO satellites.

Important components, their failure means critical damage for the satellite, should be installed inside of satellite structure.

However, it is impossible for some components. (expandable structure, harnesses, etc.)



debris flux in LEO calculated by MASTER2009

Purpose

To protect components installed on the outside of the satellite structure, flexible debris bumper is needed.

→ **Fabric bumper shield** made of high strength fiber

Investigate ballistic limit weight and thickness of fabric bumper shield

- Alamido fiber fabric (Kevlar cloth)
- Glass fiber fabric coated with aluminum (Beta cloth)

Procedure

1. Perform HVI experiments on a stack of high strength fiber fabrics
2. Count perforated layers in the impacted stack
3. Calculate perforated thickness from the perforated layers
   → **Ballistic limit thickness**
4. From the ballistic limit thickness, calculate areal density of the perforated layers
   → **Ballistic limit weight**

Kevlar Fiber

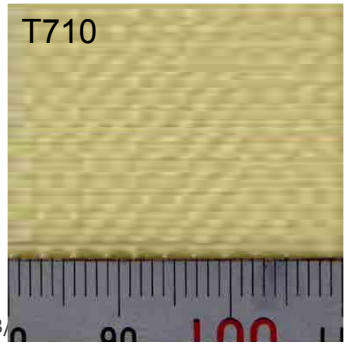
Kevlar: Alamido fiber

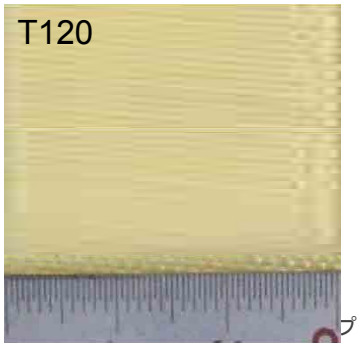
特性	単位	KEVLAR®29	KEVLAR®49
原糸			
繊度（フィラメント数）	dtex（本）	1,670（1,000）	1,270（ 768）
密度	g/cm³	1.44	1.45
平衡水分率＊1	%	4.5	3.5
＊1 一度絶乾にした後24℃、55%RHで保持			
機械的性質（原糸）		ASTM D885-85（参考）JIS L1017	
引張強力	N	338.0	264.0
引張強度	cN/tex（g/d）	203（23.0）	208（23.6）
tensile strength	MPa	2,920	3,000
引張弾性率	cN/tex（g/d）	4,900（555）	7,810（885）
tensile modulus	GPa	70.5	112.4
破断時伸度	%	3.6	2.4
fracture elongation			

Ref. DuPont

Kevlar Cloth

	T710	T120	T328
Fiber	K29（normal）	K49（high-modulus）	K49（high-modulus）
Weave	Plain		
Fabric Density [bundle/inch]	24x24	34x34	17x17
Areal Density	319g/m^2	58g/m^2	217g/m^2
Thickness	0.43mm	0.08mm	0.33mm

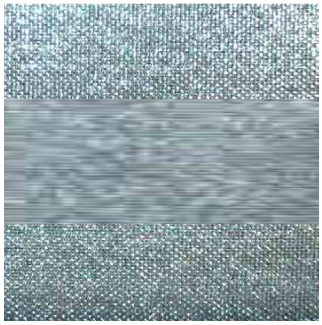




Beta Cloth

Beta Cloth: Glass fiber fabric coated with aluminum

Parameter (independent of film)	Specified Value	
Cloth type	Beta Cloth	1060
Intermittent temperature range	-151° C to 315° C (-240° F to 600° F)	-185° C to 260° C (-300° F to 500° F)
Continuous temperature range	-151° C to 260° C (-240° F to 500° F)	-185° C to 200° C (-300° F to 400° F)
Fabric side solar absorptance (α)	≤0.45	≤0.85
Fabric side hemispherical emittance (ε)	≥0.80	≥0.80
Aluminum side absorptance (α)	≤0.22	
Aluminum side hemispherical emittance (ε_H)	≤0.30	
Weight (g/m^2)	274 Typical	≤170
Thickness	0.009±0.001 in.	
Tensile strength (lb./in. of width)	≥90 Warp ≥80 Fill	≥40 Warp ≥39 Fill
Tear strength (lb.)	≥4.0 Warp ≥4.0 Fill	
Width (in.)	51 (1.30 m)	36 (0.91 m)
Item number	146626	146585
Old part number	G423800	G414500

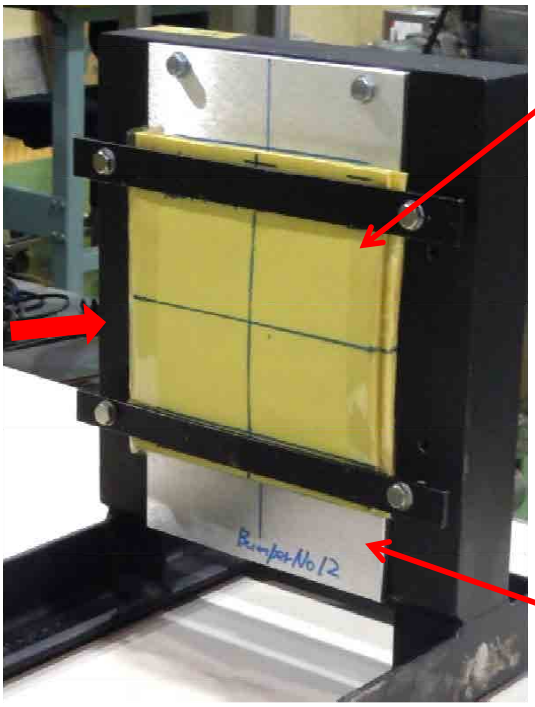


Ref. Sheldahl

Glass Fiber Fabric in Beta Cloth

Fiber	ECD450 - Tensile Strength 3200MPa - Tensile Modulus 78GPa
Weave	Plain
Fabric Density	60x46 bundle/inch
Areal Density	47g/m^2
Thickness	0.055mm

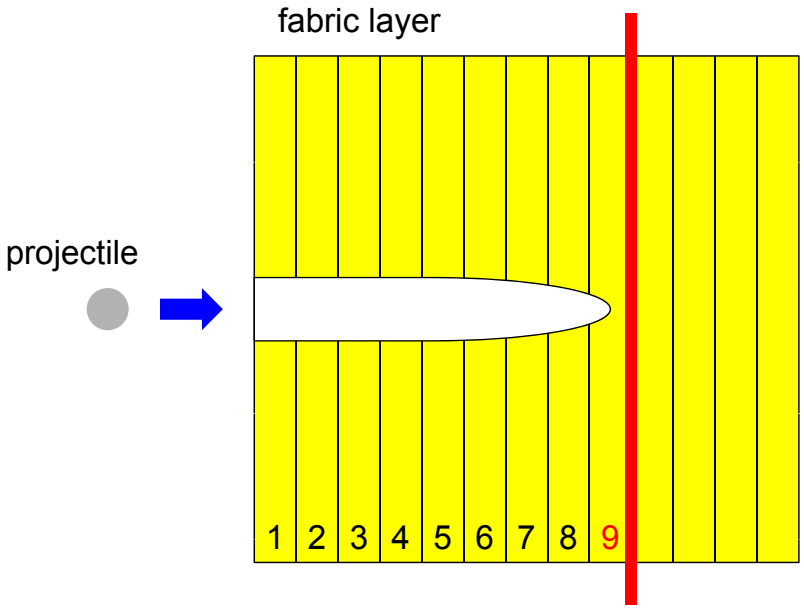
Impact Experiment Condition



Impact velocity
6 km/sec

Projectiles
SUS304, sphere
ϕ0.15, 0.3, 0.5mm

Definition of “Perforation”



“Perforated layer + 1 layer” is defined as ballistic limit.

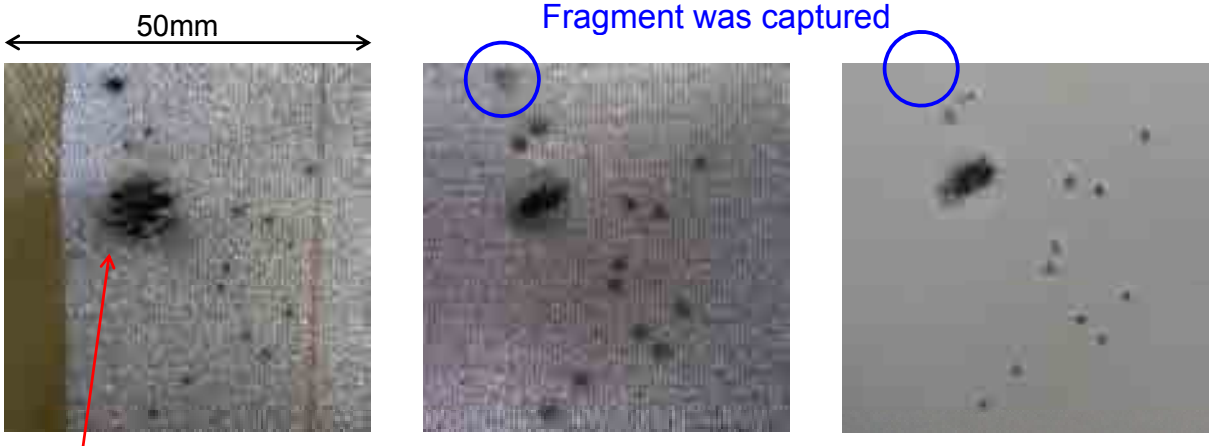
Kevlar T710 (ϕ0.3mm projectiles)

Front layer
Impact surface

9th layer
Front surface

9th layer
Back surface

Beta cloth (ϕ0.3mm projectiles)



Front layer
Impact surface

7th layer
Front surface

7th layer
Back surface

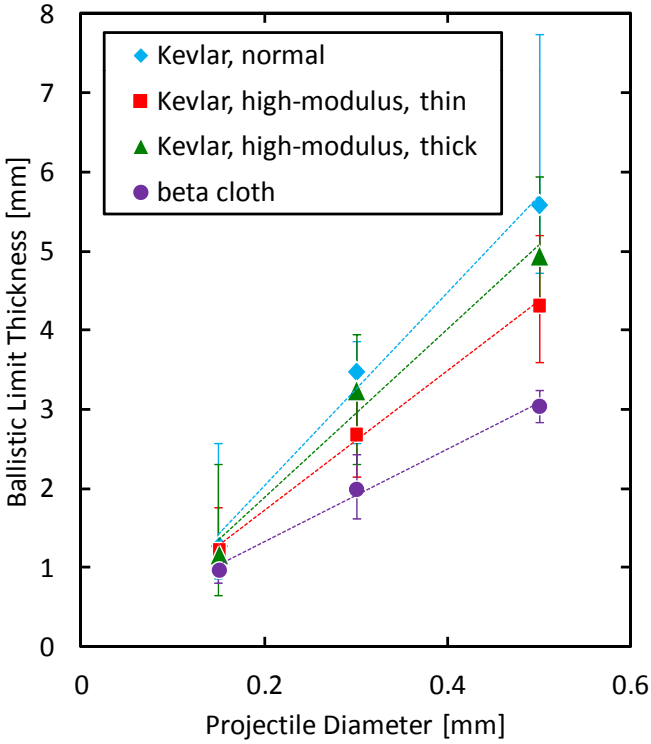
Sabot fragment impact

Experiment Results

Impact velocity: 5.61～6.30 km/sec

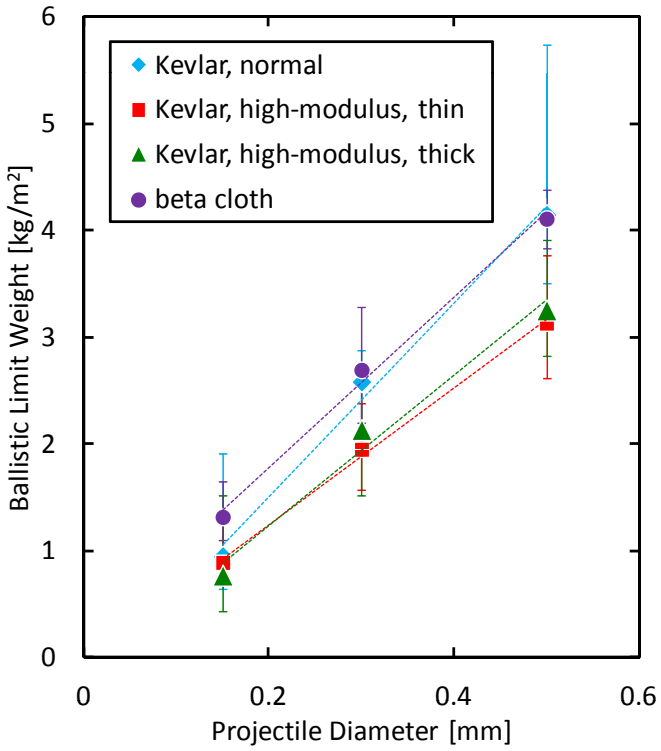
projectile dia.		Kevlar, normal	Kevlar, high-modulus, thin	Kevlar, high-modulus, thick	Beta Cloth
0.15mm	data	**51**	**53**	**131**	**42**
	BL	**2-6ply**	**12-22ply**	**2-7ply**	**4-6ply**
0.3mm	data	**10**	**22**	**31**	**12**
	BL	**6-9ply**	**27-41ply**	**7-12ply**	**8-12ply**
0.5mm	data	**9**	**11**	**14**	**3**
	BL	**11-18ply**	**45-65ply**	**13-18ply**	**14-16ply**

Ballistic Limit Thickness



- Beta Cloth was the thinnest bumper.
- Kevlar cloth made of high modulus fiber showed better protection capability than normal fiber.
- To stack thinner clothes was effective to decrease the ballistic limit thickness.

Ballistic Limit Weight



- High modulus Kevlar cloth was the lightest weight bumper.
- Beta Cloth was the heaviest bumper.
  → To increase areal density contributes to decrease the ballistic limit thickness.
- Kevlar cloth made of high modulus fiber showed better protection capability than normal fiber.

Comparison with Aluminum Bumper

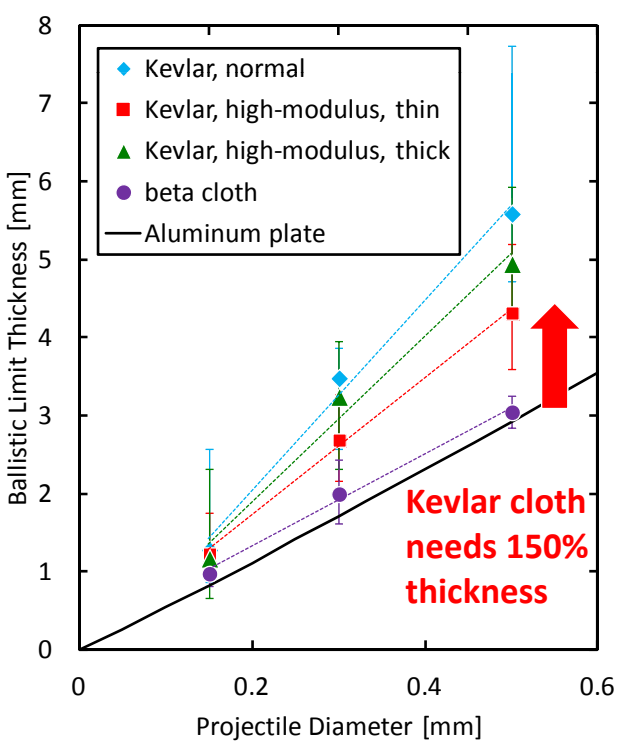
E.Christiansen, Meteoroid/debris shielding, *NASA TP 2003-210788*, 2003.

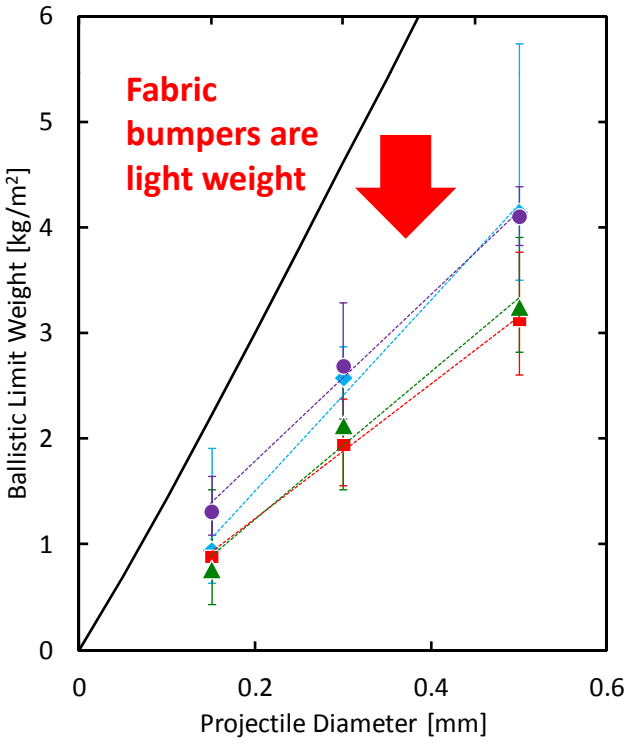
$$\text{when } \frac{\rho_p}{\rho_t} < 1.5 \quad t_w = 1.8 \times 5.24\, d^{19/18} H^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{V_n}{C}\right)^{2/3}$$

$$\text{when } \frac{\rho_p}{\rho_t} \geq 1.5 \quad t_w = 1.8 \times 5.24\, d^{19/18} H^{-0.25} \left(\frac{\rho_p}{\rho_t}\right)^{2/3} \left(\frac{V_n}{C}\right)^{2/3}$$

ρ_p: Projectile Density (g/cm^3)
ρ_t: Target Density (g/cm^3)
t_w: Target Perforation Thickness (cm)
d: Projectile Diameter (cm)
H: Brinell Hardness of Target
C: Speed of Sound in Target (km/s)
V_n: Normal Component of Impact Velocity (km/s)

Results





Summary

- 3種類のKevlar織布とBeta Clothに超高速衝突試験を実施し，貫通限界を求めた
- 薄いバンパが必要な場合はBeta Cloth，
  軽いバンパが必要な場合は高弾性のKevlar織布が有効
- 弾性率が高いKevlar原糸で作られた織布の方が
  デブリバンパとしての性能が高い

Handbook

材料名	Kevlar T710	Kevlar T120	・・・	
材料構成	Kevlar（アラミド繊維）織布 原糸：K29（通常タイプ） 織り方：平織り 密度：24×24本/inch	Kevlar（アラミド繊維）織布 原糸：K49（高弾性タイプ） 織り方：平織り 密度：34×34本/inch	・・・	セラミック繊維織布とガラス繊維織布について同様の評価を実施予定
1層の厚さ	0.43mm	0.08mm		
1層の重さ	319g/m^2	58g/m^2		
貫通限界式	n=28d-0.97	n=110d-0.46		
入手性	数日	数週間		
作業性	- 切断面から繊維がほつれる	- 切断面から繊維がほつれる - 張力をかけると織目が崩れる		
コメント	- 紫外線に弱い	- 紫外線に弱い		