INFLATABLE STRUCTURES FOR DEPLOYABLE AERODYNAMIC DECELERATORS*

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ABSTRACT

Deployable aerodynamic decelerators have a widely recognized potential for aeroassist and planetary landing applications. Deployable devices are needed whenever the dimensions of the required aerodynamic surface exceed the limitations imposed by the launch fairing. Examples of missions operations that may benefit from deployable aerodynamic decelerators include planetary aerocapture, earth-return aerocapture, planetary atmosphere entry, and supersonic deceleration for planetary landing. Designs that rely on mechanical expansion of the aerodynamic surface may be capable of approximately two-times the stowed area. Inflatable concepts are enabling when a large expansion of aerodynamic surface area, ten-times or more, is required.

The implications of large area expansion include reduced spacecraft heating, increased stability margin and center-of-gravity range, and dilution of trim and control authority. Considering an inflated torus as a typical structural element, the strength, stiffness and inflation pressure requirements are derived as functions of peak operating conditions. The use of fiber reinforcement to achieve a given strength, burst pressure and bending stiffness is discussed. The interaction of an open fiber network with the gas-barrier film and implications for a minimum mass design are analyzed.

INTRODUCTION

Inflatable cylinders and tori, cylinders curved upon themselves into toroidal shapes, are the basic building blocks of most of the inflatable aerocapture decelerator (IAD) concepts now being studied. The basic requirements of inflatable structures used for IADs include strength and stiffness sufficient to support and maintain the shape of the decelerator, and the ability to operate at temperatures near the useful limit of available materials.

The basic materials of IADs are films and fibers. This paper explores the properties of available films and fibers and analyzes how they may be combined in a, minimum mass design that has adequate burst strength at the necessary inflation pressure.

The examples presented are based on the IAD concepts advanced by McRonald[8], Hall[7], and others in which a large inflatable decelerator (low ballistic coefficient) flies a trajectory through the low-density edge of a planetary atmosphere, such that surface temperatures on the inflatable do not exceed 500C. We further assume that the effective duration of exposure to peak temperature is 120 seconds.

At 500C the specific strength of available fibers is approximately 100 times that of films. This results in a substantial advantage in structural mass-efficiency in favor of fiber reinforcement of inflatable structures. Film is still necessary in order to contain the inflation gas, but this paper will suggest that an efficient design will use the thinnest film practicable and reinforce it with high strength-to-weight fiber.

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RESULTS AND DISCUSSION

FIBER REINFORCEMENT OF FILMS

High strength AirBeams™ are an example in which the surface of the inflatable structure is covered entirely by the reinforcing fiber, and both are shown in Figure 1. These beams are characterized by hoop stress of greater than 1,000 lb/in at working pressure, which necessitates such high-strength reinforcement.


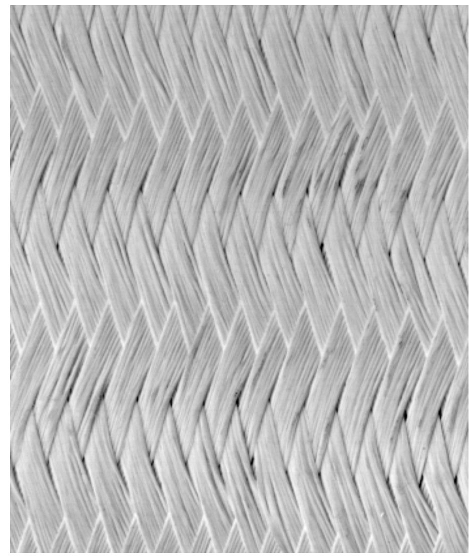

Figure 1. High Strength AirBeam and Reinforcing Fiber

Aerocapture ballutes, however, are characterized by hoop stress of less than 50 lb/in. A minimum-weight fiber-reinforced film may comprise widely spaced reinforcing fibers bonded to the surface of the film, as shown in Figure 2.

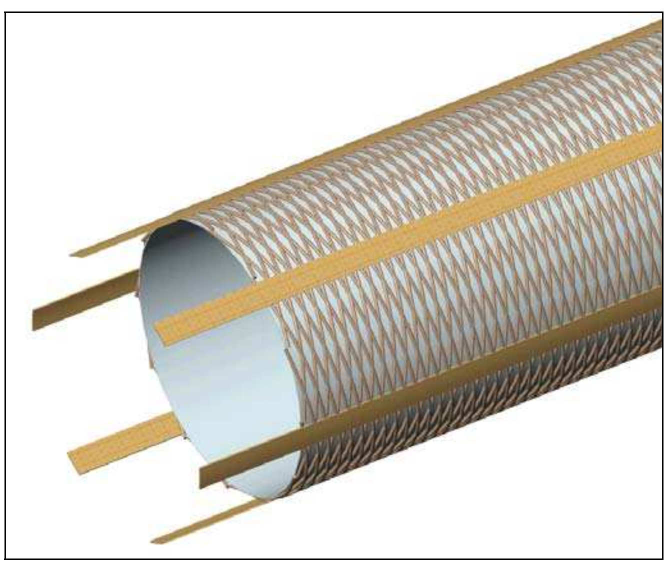

Figure 2. Reinforcing Fibers

The reason for fiber reinforcement of an inflatable cylinder is evident by considering the hoop (circumferential) stress in reinforced and un-reinforced cylinders of the same diameter inflated to the same pressure. The hoop stress in the un-reinforced cylinder is related to pressure, P, film thickness, t, and section diameter, D, by the equation,

$$\sigma_{hoop} = \frac{PD}{2t}.$$

A section of a reinforced cylinder, however, is characterized by evenly spaced high modulus fibers with the film bulging outward in the spaces between the fibers. The hoop stress in the film is related to inflation pressure and the radius of curvature of the bulge, *R*, by the equation,

$$\sigma_{hoop} = \frac{PR}{t}.$$

Because the radius of curvature of the film bulge is much smaller than the radius of the cylinder, the stress in the film is much less. Thus, fiber reinforcement can allow the use of thinner film and a lower total mass. The objective of this paper is to quantify such mass savings using specific examples.

FIBER REFERENCE PROPERTIES

The most useful tensile property of a reinforcing fiber for the purposes of mass estimation is specific strength. Specific strength is conveniently expressed in units of length.

$$SS = \frac{T_{brk}}{W/L}$$

By using weight, *W*, instead of mass, and breaking tension, T_{brk}, in the same units, a value in length units is obtained. One must remember, when converting to mass, that Earth gravity is included via $W = Mg$. Specific strength can be visualized as the maximum length of a particular fiber that can support itself, hanging in Earth gravity, without breaking.

The weight of a tensile element can be calculated from its design strength, T_{des}, length, L, and specific strength by

$$W = \frac{T_{des}L}{SS}.$$

Data on the physical properties of materials at 500 C is not generally available. At such high temperatures, strength and elongation vary with time, making the estimation of properties even more difficult. For the purposes of this study, we have estimated allowable specific strength that includes reductions for temperature, flex fatigue, aging, and adhesives and coating. (Adhesives and coatings reduce specific strength by adding weight rather than by reducing strength.)

The properties necessary for estimating the weight of an inflatable structure are the specific strength of the film and the fiber, and the elongation of the film at the reference specific stress. The values used are shown in the Table 1.

Table 1 Film Reference Properties

Reference Property	Material	Cold - Ultimate	Hot - Allowable
Fiber Specific Strength	PBO (ZylonTM)	370,718 m	60,000 m
Film Specific Strength	Polyimid (KaptonTM)	12,689 m	500 m
Film Elongation	Polyimid (KaptonTM)	70%	20%

MASS OF AN UNREINFORCED FILM TORUS

The minimum film thickness of an unreinforced inflatable torus is

$$t_{\min} = \frac{(1+\varepsilon_{design})P_{design}d}{2\sigma_{design}}$$

ε_{design} and σ_{design} are the design elongation and stress respectively. These quantities are associated with each other and chosen to be at or below ultimate values at design pressure and, thus, have adequate margins at working pressure.

Actual thickness will be the next available thickness above the calculated minimum. As an example, available thicknesses in Kapton are 7.6, 12.7, 25.4, 50.8, 76.2 and 127 μm.

The mass of a film torus with thickness, *t*, section diameter, *d*, and generating diameter, *D*, is

$$M_{un\_film} = \pi^2 Ddt \cdot sg \cdot sa$$

Where sg is the specific gravity of the film, gm/cm^3, and *sa* is a seam allowance factor. For example, a seam overlap of 5% of the total area would mean

sa=1.05.

We will use the 20m torus described in Table 2 below as an example to be used for comparison with other structural elements.

Table 2. Torus Example

Tore axis diameter	D=	20	m
Tore section diameter	d=	1	m
Slenderness ratio	πD/d=	63	
Design Pressure	P_{design}=	1	psi
		6895	N/m^2
		6.895	KPa
Area	A=	197	m^2

The yellow cells are input values. The other cells are derived values. Slenderness is calculated to verify that the torus has an adequate section diameter. As a rule of thumb, slenderness greater than about 100 would not be a stable structure in compression. Reference 5 derives the section properties necessary for the stability of a slender inflated torus in compression.

Table 3 below summarizes the calculation of film mass for the example torus.

Table 3 Calculation for Film Mass of the Example Torus

circumferencial (hoop)	t=	344	N/
		20	pli
allowable working	allow=	500	psi
		3.5	kg/m 2
		3.45E+	N/ 2
working	=	20%	
calculate			
minimum	tmin=	100.	m
		3.94E-	in
actual	t=	127.	m
calculate film			
areal		189.	gm/m
film	Mfilm=	37.3	kg

STRESS IN REINFORCED FILM

Now consider the same film cylinder, reinforced by an open pattern of fibers applied in a bias orientation (± β) and forming a pattern of open diamonds between the fibers, as shown in Figure 3.

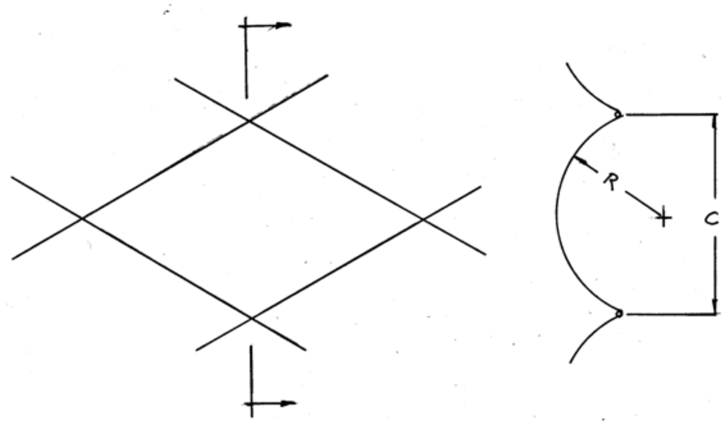

Figure 3. Open Pattern of Fibers

The strain in the film is a function of both the diamond geometry and the radius of curvature taken by the pressurized film between nodes of the reinforcing fiber diamond structure. This is a 3-D problem that requires FEA to solve any specific problem. However, we can understand the general problem, and calculate an upper-bound stress, by solving the 2-D problem of the film bridging the gap, *c*, between reinforcing fibers.

A bulge between fibers will have radius, *R*, which is related to strain in the film, ε, by the equation:

$$\sin^{-1}\left(\frac{c}{2R}\right) = (1+\varepsilon)\frac{c}{2R}$$

Solving for the bulge radius, *R*, using the first terms in the polynomial expansion of the arcsine gives a close approximation:

$$R \cong \frac{c}{2\sqrt{6\varepsilon}}$$

The stress equation is:

$$\sigma_t = \frac{PR}{t}$$

By substituting for *R*, a convenient equation for maximum fiber spacing, c, is obtained in terms of stress, σ_t,, elongation ε_t, and pressure, *P*:

$$c_{\max} \cong t\frac{\sigma_t 2\sqrt{6\varepsilon_t}}{P}$$

As an example, consider Upilex film having a burst stress of 5,800 psi at a temperature of 500º C. Maximum elongation is a function of temperature, increasing at high temperatures, 60% being a typical value at 300º C (500º C data is not available). Figure 4 below shows, for example, that the maximum spacing between reinforcing fibers for a 1-mil film, 60% elongation, with 1-psi differential pressure is approximately 8 cm.

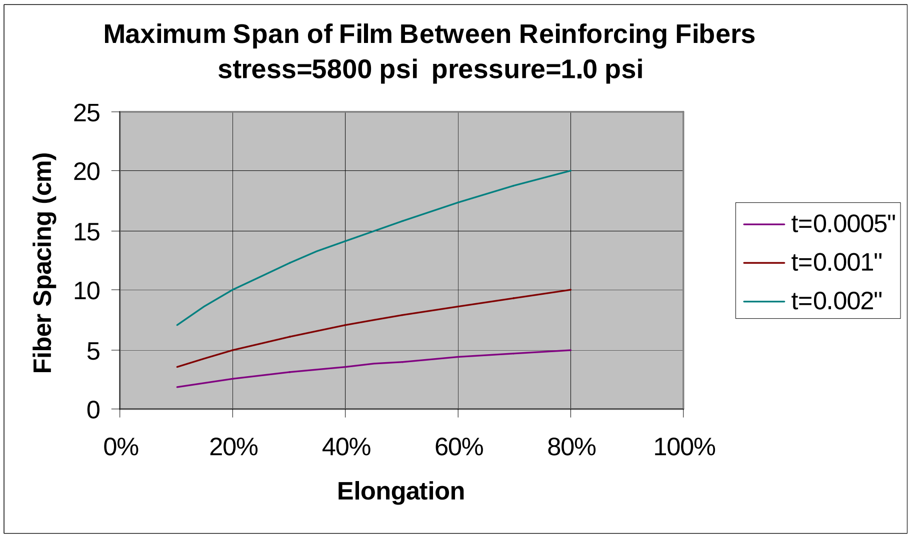

Figure 4. Maximum Span of Film Between Reinforcing Fibers

Given reinforcement of the proper strength at this spacing, an inflatable cylinder, or torus, of *arbitrarily large* section diameter can support this inflation pressure. Without the reinforcement, the film alone would support this pressure at a maximum diameter of only 14.7 cm.

CALCULATING THE GAP

The gap that must be spanned by film is a function of the number of carriers on the braiding machine, *C*, the section diameter, *d*, the bias angle, β, and the width of the band of fibers formed by each carrier, *w*.

The gap in the hoop direction is given by

$$h = \frac{2\pi d}{C} - \frac{w}{\cos\beta}.$$

The gap in the axial (longitudinal) direction is given by

$$a = \frac{2\pi d}{C\tan\beta} - \frac{w}{\sin\beta}.$$

The width of the fiber band is a function of the number of yarn ends, *E*, in the band and the weight of yarn used, *den*, in denier. For typical high tenacity yarn types, bandwidth can be estimated by

$$w = 0.0005E\sqrt{den} \text{ inches.}$$

See Figure 5.

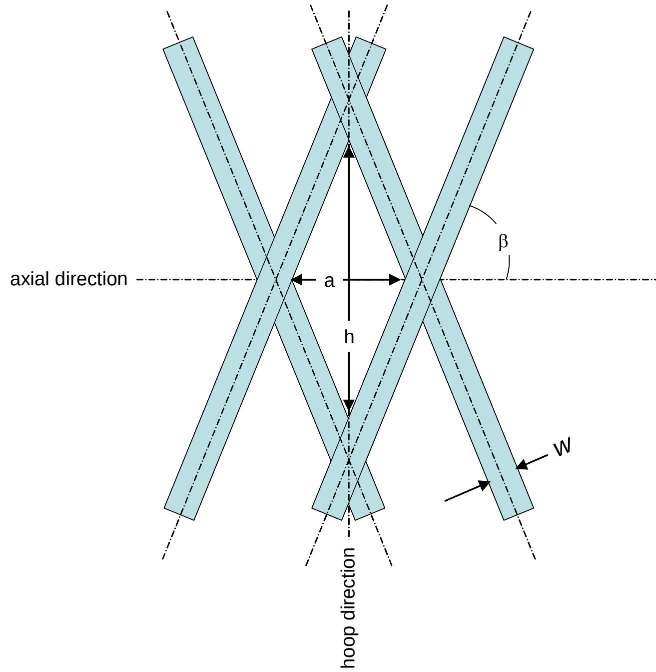

Figure 5 Calculating the Gap

ESTIMATING MASS OF BIAS FIBERS

The mass of the fibers needed to reinforce a toroidal inflatable structure of section diameter, *d*, major diameter, *D*, and bias angle, β, can be found by starting with the burst equation:

$$P_{burst} = \frac{2}{\pi}\frac{\sum[total\_strength\_of\_fibers]}{d^2\left(1+\frac{1}{\tan^2\beta}\right)\cos\beta}$$

The total mass of reinforcing fibers is found from the strength of those fibers and the specific strength of the fiber material by the equation:

$$M_{fiber} = \frac{\sum[total\_strength\_of\_fibers]\bullet[fiber\_length]}{[specific\_strength]}$$

The quantities in the mass equation are found in the equations below,

$$\sum[total\_strength\_of\_fibers] = \frac{\pi}{2}P_{burst}d^2\left(1+\frac{1}{\tan^2\beta}\right)\cos\beta$$

$$[fiber\_length]_{tore} = \frac{\pi D}{\cos\beta}$$

$$[specific\_strength]_{500C\_Zylon} = SS_{allow}$$

which, after substitution, yields a convenient form of the mass equation in terms of design variables:

$$M_{fiber} = \frac{\pi^2}{2}\frac{P_{burst}d^2D}{g \cdot SS_{allow}}\left(1 + \frac{1}{\tan^2\beta}\right)$$

In this equation we have included one Earth gravity in the denominator to account for the force-mass equivalency used in the specific strength, so that the result is mass units.

Figure 6. Toroidal Inflatable Structure

The torus in Figure 6 has a six-inch section diameter and a burst pressure of over 1,000 psi.

Table 4 below calculates the mass of fiber reinforcement needed for the example 20 m torus.

Table 4. Fiber Reinforcement

Fiber Reinforcement

design specific strength	SS_{design}=	60,000	m
bias angle	β=	75	deg
total mass of fiber and adhesive	M_{fiber}=	1.5	kg
total denier	C*E**den* =	2.10E+05	denier

For the same example, we verify that minimum gauge film is adequate for the braid gap formed, as shown in Table 5.

Table 5. Film Spanning Fiber Gap

Film Spanning Fiber Gap

calculate fiber gap			
no. carriers	C=	300	
axial gap	a=	0.0051	m
		0.51	cm
calculate curvature			
working stress	σ=	4000	psi
		2.8	kg/mm^2
		2.76E+07	N/m^2
working elongation	ε=	20%	
radius of curvature	r=	0.233	cm
calculate thickness			
minimum thickness	t_{min}=	0.583	μm
		2.29E-05	in
actual thickness	t=	7.6	μm

A 300-carrier braider is needed for a 1 m diameter section, even though the resulting gap is much smaller than necessary for minimum gauge. The mass of minimum gauge (7.6 μm) film is calculated below, see Table 6.

Table 6. Minimum Gauge Film

Minimum Gauge

film thickness	t=	7.5	□m
		0.0007	cm
		0.000	in
specific gravity	sg=	1.4	gm/cm
seam allowance factor		1.0	
areal density		11.	gm/m
film mass	M_{film}=	2.2	kg
max gap for min gauge	w_{max}=	6.5	cm

One additional structural element is necessary to stiffen the bias reinforcement in bending and to provide the section stiffness, EI, necessary for the torus to be stable under compressive loading. Straps, oriented in the axial direction (parallel to the generating axis of the torus) and bonded to the bias fibers, provide the needed additional reinforcement. A minimum of three straps is required to provide the required EI in the two axes needed for stability. We typically impose the requirement that each strap be strong enough that they can take the full axial reaction to pressure when the structure is fully buckled. This tension may actually be seen on a single strap during deployment as the[L1] rate of gas inflow causes the inflatable to be filled before it is fully deployed. We calculate this strap design tension by

$$T_{strap} = \frac{\pi}{4} P_{design} d^2 .$$

The total mass of the straps is the following function of number of straps, N_{straps}, strap tension, T_{strap}, torus major diameter, D, and design allowable specific strength, SS_{allow}:

$$M_{straps} = N_{straps} \pi D \frac{T_{strap}}{SS_{allow}}$$

Table 7 below calculates strap mass for the same 20 m diameter torus example.

Table 7. Strap Mass

Axial Straps

number of straps	N_{straps}=	3	
specific strength of straps	SS_{strap}=	60000	m
buckling tension	T_{strap}=	5415	N
		553	kgf
	M_{straps}=	1.7	kg

SUMMARY: 20 m TORUS EXAMPLE

Table 8. 20 m Torus Example

Tore axis diameter	D=	20	m
Tore section diameter	d=	1	m
Slenderness ratio	πD/d=	63	
Design Pressure	P_{design}=	1	psi
		6895	N/m^2
		6.895	KPa

The mass estimate for the 20 m torus example is summarized in Table 9.

Table 9. Mass Estimate for the 20 m Torus Example

Mass of Reinforced Tore

Bias Fibers	1.5	kg
Axial Straps	1.7	kg
Film	2.2	kg
Total	5.4	kg

Mass of Un-Reinforced Film 37.4 kg

SUMMARY AND CONCLUSIONS

For the example of a 20-meter diameter torus, the 12X advantage in specific strength of fiber compared to film results in a 7X lower mass, compared to the same size torus fabricated with unreinforced film for the same burst pressure. An inflation pressure greater than the 1-psi example will increase the mass advantage of fiber reinforcement, while a lower pressure will decrease the difference.

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or benefit near and mid-term NASA space science missions by significantly reducing cost, mass and travel times.

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