LESSONS FROM STRUCTURAL DESIGN OF A HIGHLY-FLEXIBLE SPACE STRUCTURE: THE SPACE-TOW SOLAR SAIL

G. Tibert [1] and A. Lennon[2]

[1]Department of Mechanics, Royal Institute of Technology (KTH)
SE-100 44 Stockholm, Sweden

[2]ABL Engineering Ltd
Clonmel, Tipperary, Ireland

OVERVIEW

The solar-tow is a recently proposed configuration that can overcome many of the problems with other configurations proposed for solar sails. The dimensions of the space tow differ by several orders of magnitude, leading to conceptual difficulties in structural design. This paper presents a short summary of the basic structural design of an example space-tow. Of particular interest are the vastly differing scales for the structural design and the governing criteria for the design.

NOMENCLATURE

a_c	characteristic acceleration of the space-tow (including payload)
A_p	sail area of a single panel
A_s	cross-sectional area of a strand of the truss
A_t	total reflective area of sail
b_r	width of rim (cross-section)
d_p	panel diameter
E_f	Young's modulus for sail film
E_r	Young's modulus for panel rim
E_s	Young's modulus for strands in cord joining panels
F_s	Load in a strand of the truss
F_t	Load in the truss joining the panels
h_a	adhesive thickness per rim
h_r	height of rim (cross-section)
h_g	gap
H_{stow}	stowed height of the space-tow structure
l_p	distance between adjacent panels (bay length)
l_t	total length of the sail (without payload)
m_f	mass of the film in a panel
m_r	mass of a rim (including adhesive)
m_{total}	total structural mass of the space tow
m_{tr}	average mass of the truss for a bay
n_p	number of panels
n_s	number of strands per truss member
$n_{s,av}$	average number of strands in truss members
p_e	effective pressure
p_s	solar photon pressure (at 1 AU)
$q_{r,cr}$	critical buckling load for the rim
$q_{r,in}$	in-plane load on the rim
$q_{r,out}$	out-of-plane load on the rim
y_r	out of plane displacement of the rim
γ	areal density of the structure
γ_{sp}	areal density of the spacecraft (structure and payload)
Δ_c	central deflection of film in sail panel
$\varepsilon_{s,a}$	allowable strain in a strand
η	sail reflectivity
θ_r	slope of sail film at the rim
ν_f	Poisson's ratio for sail film in a panel
ν_r	Poisson's ratio for panel rim
ρ_f	density of sail film for a panel
ρ_r	density of rim material
ρ_s	density for strands in cord joining panels
σ_0	pre-stress in sail film
ϕ_s	angle of incident sunlight

1. INTRODUCTION

Solar sails have a comparatively long history as proposals for space missions but the first flight of a solar sail has not yet occurred. Mission design and dynamics are maturing[1] but solar sail technology has not advanced to the point where solar sails are available as realistic near-term options for space missions. Their large spatial dimensions create a limiting problem for design, manufacturing, testing, and deployment.

Hedgepeth[2] identified that large space structures must be *"designed to deal with phenomena as primary criteria which have been considered as only secondary in the past"*. Solar sails are particularly problematic because they combine two large spatial dimensions with a small film thickness forming the third dimension. This third dimension is many orders of magnitude less than the two large spatial dimensions defining the area. This combination pushes solar sails outside the boundaries for which intuition and engineering judgement are readily available. Design and manufacture of solar sails are difficult and testing is almost impossible prior to launch.

Greschik[3,4] has proposed a scalable solar sailing system, known as a *space-tow*. This system is a series of small sails connected together in a train. The advantage of this system is its scalability as the desired surface area can be achieved by joining a number of small sails. Design, manufacture, and testing can be performed on the small sail, regardless of the final number of sails and overall sail-area. The space-tow opens the possibility of launching a solar sail in the near term.

The dimensions of the space tow are on vastly differing scales. The length of the train is of the order of kilometres, the width of sail panels is of the order of metres, the supporting rim for the panels of the order of millimetres, and the thickness of the sail film is of the order of microns. Structural design occurs at each of these levels, which vary by six or seven orders of magnitude.

This study discusses the structural design of an example space-tow solar sail. The focus is on the structural design challenges and lessons from design of the various components for the structure rather than a presentation of a completed design.

2. SOLAR TOW SPACE SAIL

The space-tow solar sail differs from other solar sail design by dividing the sail area into a large number of small panels, arranged in a train. Each panel is a small solar sail but together the structure acts as a solar sail with the combined surface areas of the panels. FIG 1 shows a schematic representation of eight panels of a space-tow, a truss of connecting members made of strands, and a payload.

Sail panels are sufficiently small to make them easy to manufacture, test, handle, and stow for launch. The panels can be identical allowing easy prototyping and testing. The space tow has the advantage that no structural element has dimensions greater than a few metres, unlike flat solar sail designs which can have booms that are several tens of metres in length. The dimensions of the space tow come from joining the individual sub units.

3. STRUCTURAL DESIGN

3.1. Overview

The example space-tow design uses a series of circular panels supported by rims, with the panels connected by a truss of light tension members (strands). Structural design raises a number of issues relevant to the design of highly flexible structures. Examples of these issues are the configuration for the tension truss connecting the panels, the design of a supporting rim for the individual sail panels. This project identifies some of the issues likely to be encountered by other designers of highly flexible structures that meet Hedgepeth's description.

3.2. Initial Configuration Selection

Initial design begins with a series of self-imposed constraints:

1) The selected configuration must facilitate comparison with alternative solar sail configurations and designs.
2) Materials and manufacturing processes must be available now or in the near-term.
3) Stowed dimensions of the space-tow must fit in the payload bay of a commercial launcher.
4) Design and deployment of the structure must be capable of being studied with the tools that are currently available or that can be developed within a short time frame.

These constraints ensure that the initial design reflects a real structure that can be manufactured using current technology or technology that will be available in the near-term.

The chosen design is not optimised but is suitable for study because of its simple geometry and relatively straightforward design. Note that this configuration differs from the configuration used by Greschik[4,5], which has square panels supported by diagonal members.

3.3. Global Configuration

The overall configuration has 10 000 m^2 sail area, equivalent to a square sail of 100 m x 100 m. Choose a panel sail area of 1 m^2, giving 10 000 panels. We calculate the distance between panels for full illumination given the angle of inclination to the incident sunlight. TAB 1 gives the dimensions of the sail and panels.

Parameter	Value	Unit
A_t	10 000	m^2
A_p	1	m^2
n_p	10 000	—
d_p	1.128	m
l_p	1.954	m
l_t	19.544	km

TAB 1. Selected geometry for the space-tow

3.4. Panel Design

Design of the sail panels takes place on a significantly smaller scale than that of the global configuration. The global configuration has 10 000 m^2 of sail area (1 hectare) and a length of almost 20 km. Design for the individual sail panels consider a maximum dimension of 1.128 m, which is more than four orders of magnitude smaller.

The sail panel has three components: sail film, supporting rim, and connection of the film and rim. The sail film is simplified to an isotropic membrane for the design and the rim is assumed to be a relatively stiff material that supports load in compression. The connection between the film and rim is assumed to be an adhesive and its mass and thickness are included in calculations.

TAB 2 presents the properties for the membrane material chosen for the sail and TAB 3 presents the loading on the sail.

Parameter	Value	Unit
E_f	3500	MPa
ν_f	0.3	—
ρ_f	1390	kg/m^3
t_f	1.0	μm

TAB 2. Sail film properties

Parameter	Value	Unit
η	0.85	—
p_s	9.126	μPa
p_e	7.757	μPa
ϕ_s	30	deg
σ_0	0	Pa

TAB 3. Sail film loads

Note that the areal density of the film is 1.39 gm/m^2 and the mass m_f of the film for a single panel is

(1) $$m_f = 1.39 \text{ gm}$$

Having chosen the sail panel size and the material, the next step is to calculate the maximum stress in the panel and the loads on the supporting rim. We assume zero pre-stress to minimise loading on the rim. Previous design iterations showed problems with rim design if pre-stress was present in the film. We can calculate the central deflection using the solution from Fichter[5], combined with the solution from Campbell[6]. (The full method and solution is not reproduced here.) The resulting central deflection is

(2) $$\Delta_c = 0.361 \text{ mm}$$

Proportional to the diameter of the panel, this deflection is

(3) $$\frac{\Delta_c}{d_p} = 0.032\%$$

We see that the deflection due to photon pressure is several orders of magnitude less than the diameter of the panel. This result agrees with expectations as the effective solar pressure is small but non-zero.

3.5. Rim Design

The rim uses stiff material (CFRP) with the properties given in TAB 4. The rim is a ring with a rectangular cross-section of height 0.3 mm and width 1 mm. Allow an adhesive thickness of 12 μm and a gap[3] of 50 μm for imperfections.

Parameter	Value	Unit
b_r	1.0	mm
h_r	0.2	mm
h_a	12	μm
h_g	50	μm
E_r	350	GPa
ν_r	0.35	—
ρ_r	1400	kg/m^3

TAB 4. Panel rim properties

Calculate the mass of a rim by

(4) $$m_r = \pi\left(d_p + b_r\right)b_r\left(h_r + h_a\right)\rho_r = 1.05 \text{ gm}$$

The first step in checking the adequacy of the selected ring size is to calculate the loads on the rim. The slope of the film at the rim is given by

(5) $$\theta_r = 0.08 \text{ deg}$$

and the associated in-plane and out-of plane loads on the rim are

(6) $$q_{r,in} = 1.12 \text{ mN/m}$$

(7) $$q_{r,out} = 1.64 \text{ μN/m}$$

We check the rim for deflection by assuming that the supporting truss has three attachment points, equidistant around the rim (see Section 3.6). Displacement y_r is a maximum at the midpoint between the truss attachment points.

(8) $y_r\left(\max\right)=43.97\ \mu\text{m}$

The next step is to check the rim for torsional-flexural buckling. In this model we consider the rim to act as a set of three arches that are clamped at the ends. Pi and Bradford[7] provide the necessary equations for this case. Note that the in-plane loads are three orders of magnitude greater than the out-of-plane loads thus the check is for buckling under in-plane loads. The critical buckling load $q_{r,cr}$ is

(9) $q_{r,cr}=9.19\ \text{mN/m}$

This value gives a factor of safety of

(10) $\text{factor of safety}=\dfrac{q_{r,cr}}{q_{r,in}}=8.2$

3.6. Truss Design

The final structural item for design is the truss connecting the panels in the bays. We design the truss on the basis of the maximum load in the truss, which occurs for the bay nearest to the payload. Design the truss for the bay nearest the payload, which is the most highly loaded. Allow a reduction in the number of strands for other bays to reflect reduced load.

The first step is to choose the arrangement of the truss. The obvious choice is to use a truss with diagonal members, such as the one seen in FIG 1. We find that a no-diagonal truss is required to eliminate large radial in-plane forces that will buckle the rim and to avoid deployment problems. This truss is three cords passing directly from one rim to the next in straight lines along the axis of the space-tow.

Parameter	Value	Unit
E_s	450	GPa
ρ_s	2000	kg/m^3
n_s	49	—
$\varepsilon_{s,a}$	10^{-6}	—

TAB 5. Properties for cords joining panels

We choose carbon fibre strands for he cords. TAB 5 gives the properties for the cords in this design.

Assume that each truss member can take 1/2 of the nominal load on the truss rather than the nominal 1/3. From the effective pressure in TAB 3 and the incident angle we can calculate the load F_t

(11) $F_t=58.178\ \text{mN}$

The load in an individual strand is then

(12) $F_s=0.594\ \text{mN}$

The required cross-sectional area A_s for a strand to limit the strain to allowable values is

(13) $A_s=1.319\times10^{-9}\ \text{m}^2$

The maximum number of strands per truss member is 49, but is allowed to decrease towards the front end of the space tow while retaining the same cross-sectional area per strand. The average number of strands per truss member is 25. The total cross-sectional area of strand A_t at any bay is

(14) $A_t=3\times n_{s,av}\times A_s=9.89\times10^{-8}\ \text{m}^2$

The average mass of strands per bay (truss mass) is

(15) $m_{tr}=\rho_t A_t l_p=0.387\ \text{gm}$

4. MASS BUDGET AND PERFORMANCE

The total mass of the structure is of critical interest. The lower the mass of the structure the greater the mass available for the payload. The important performance metric for space-tow is the acceleration that it can provide to the payload.

The total mass of the structure is the sum of the mass of the panels film, panel rim, and the joining truss.

(16) $\sum m_f=13.90\ \text{kg}$

(17) $\sum m_r=10.53\ \text{kg}$

(18) $\sum m_{tr}=3.87\ \text{kg}$

The total structural mass is

(19) $m_{total}=\sum m_f+\sum m_r+\sum m_{tr}=28.30\ \text{kg}$

We see that the sail film contributes most of the mass (49%) of the space-tow structure, followed by the panel rims (37%). The truss connecting the panels contributes approximately 14% to the mass of the structure. The areal density (reflecting surface area) γ of the space-tow without payload is

(20) $\gamma=2.83\ \text{gm/m}^2$

Allowing a payload of 50 kg, the areal density γ_{sp} of the entire spacecraft is

(21) $\gamma_{sp}=7.83\ \text{gm/m}^2$

We calculate the characteristic acceleration (at 1AU) of the spacecraft

(22) $a_c = \dfrac{p_e \cos^2 \phi_s}{\gamma_{sp}}$ =0.74 mm/s^2

The other metric of importance is the stowed size of the structure. Assuming that the cords of the truss can be stowed inside the rims, then the stowed height of a bay is the height of the rim plus adhesive. Including 12 µm for the adhesive layer and a further allowance for a gap [3]of 50 µm, the stowed height is

(23) $H_{stow} = n_p \left(h_r + h_a + h_g \right) = 2.62 \text{ m}$

5. OPEN ISSUES AND FURTHER WORK

This study focuses on the design of the space-tow. There are additional issues to be studied such as materials selection, manufacturing, testing. Another issue is the deployment of the space-tow, which is the subject of a study by the authors. The space-tow deploys along a single axis, unlike other space-tow designs where deployment is along two axes. The space-tow is a long flexible structure and deployment must account for the time to deploy and for control during deployment.

Control and navigation are issues that are outside the scope of this study but also require attention. From TAB 1 we see that the length of the space-tow is almost 20 km, providing a challenge for control.

The design presented in this paper is an example and is not optimised. Optimisation could consider the optimal number of panels for given area, subject to constraints on stowed dimensions, the rim size, and optimising the design of the truss to account for the varying loads along the structure. Reducing the number of panels would significantly reduce the stowed height of the structure.

6. DISCUSSION AND CONCLUSIONS

The design presented in this paper is an example of a large flexible structure in space. The dimensions of the structure vary from 1 µm for the film thickness up to 20 km for the total length of the structure. This variation in scale requires structural design at different levels. Structural design occurs at four levels

1) Sail film, µm scale.
2) Panel rim, mm scale.
3) Cords connecting panels, m scale.
4) Total structure, km scale.

The advantage of the space-tow design is the ability to design the structure in terms of bays, avoiding the need to design members that stretch for the full length of the structure. This property reduces the maximum length for design from hundreds of metres (e.g. booms for single plane square sail design) to the metre scale for the truss members and rim.

We can draw a number of conclusions from this example of the space tow.

1) The design takes place over various orders of magnitude.
2) The smallest scale is that of the sail film, where the dominant load is the pre-stress (set to zero in this example).
3) The main load in the rim is the pre-stress from the sail film.
4) Buckling considerations dominate rim design.
5) Cord design dominated by pressure loading on panels.
6) Use a compliant structure without diagonal members to join panels.
7) Total stowed dimensions very small.

7. ACKNOWLEDGEMENTS

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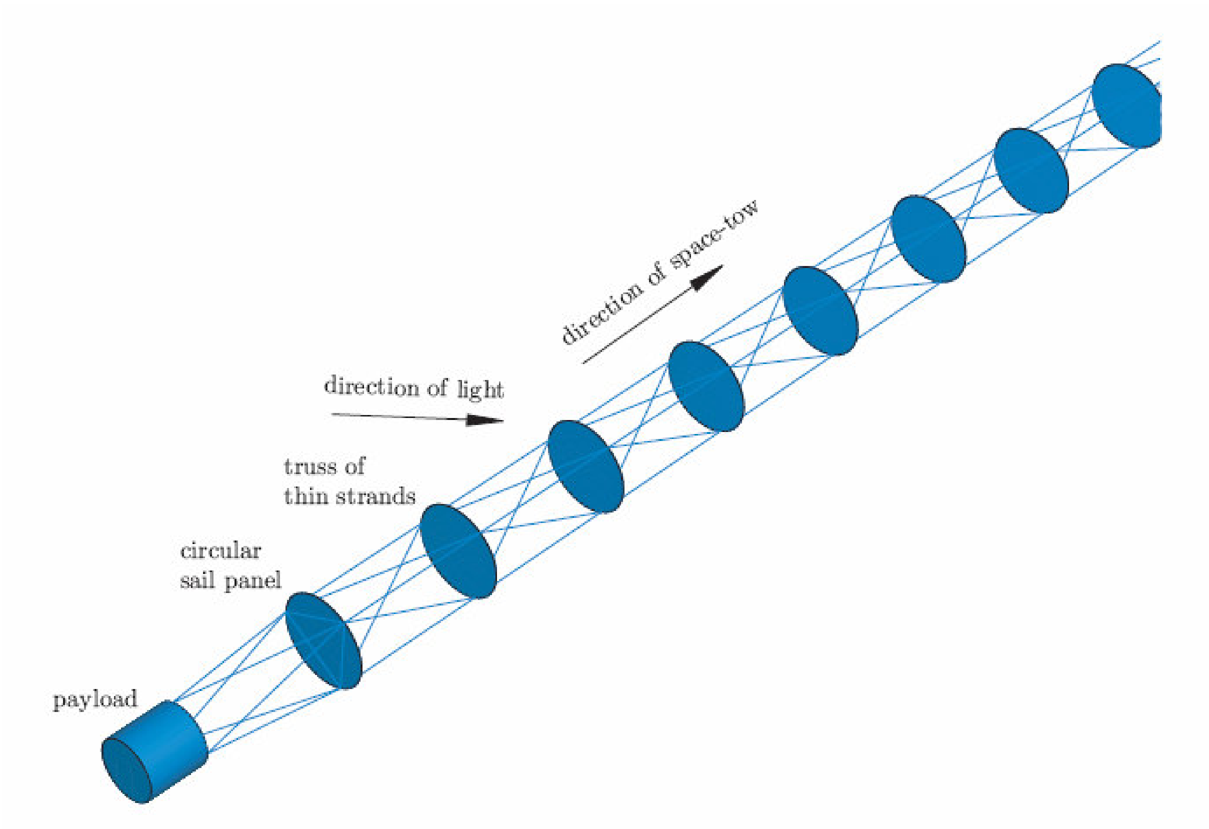

FIG 1. Space-tow with circular sail panels connected by a truss of very thin strands.