COMPOSITE MATERIALS IN DEPLOYABLE SPACE STRUCTURES

[Thomas W. Murphey]* and Jeffry S. Welsh*
*Air Force Research Laboratory

Keywords: *deployable structures, truss, hinge, large elastic strain*

1 Introduction

There is a persistent cost driven endeavor to assemble greater mission capabilities (sensors, communications, power, etc.) onto smaller and lighter weight spacecraft. The U.S. Operationally Responsive Space program advocates this trend for micro-satellites. At the same time, the laws of physics drive apertures to be of greater area. For example, solar radiation has a fixed energy flux that dictates the size of solar power arrays and radio frequency electromagnetic energy diffracts at a specific rate, dictating required aperture sizes. In both cases, deployable structures that fit more deployed area into smaller launch vehicles are more amenable to meeting mission requirements.

The requirements for deployable structures are moving in the direction of lighter weight and more compact packaging. Structures with linear compaction ratios (ratio of deployed length to packaged length) of 44:1 were state of the art in 1998. Motivated by large antenna programs and solar sail programs, structures have recently been built with compaction ratios of 100:1. Similarly, structures fabricated from S2 glass fiber composites or aluminum were previously state of the art. Recent material advances have led to the fabrication of structures with 5 times greater structural mass efficiency. While these advances are significant, they do not represent the limit for deployable structures in either requirements or feasibility. Structures with 250:1 linear compaction ratios and 10 times greater structural mass efficiency have been investigated.

For both, increased compaction ratio and increased mass efficiency, the recently developed architectures have relied on material deformations to allow packaging. The architectures employ thin plates or rods that are deformed, i.e. bent, through elastic or inelastic (though reversible) mechanisms. Local bending is engineered and distributed to accommodate flattening, rolling and origami-like folding of the global structure. Several approaches have been investigated to achieve increased material strains for more compact packaging. Historically, moderate to low modulus materials that are capable of very high tensile and compressive stresses have been used so that large strains are possible. Examples are S2 glass and IM7 fiber based composites. More recently, fiber reinforced material systems with heat softenable resins (called rigidizable) have also been developed. In both approaches, materials sacrifice stiffness for larger strains. As a result, structures with both compact packaging and good deployed structural mass efficiency have not been achieved.

The current work investigates this limitation. It is shown that the limitation exists because current materials do not have a sufficient combination of strain capacity and structural performance (stiffness per mass). Second, it is shown that these materials are traditionally distributed inefficiently and that a concentrated strain approach more effectively distributes materials while maintaining compact packaging. Subsequently, the paper will focus on new materials. Deployable structures have unique material stiffness and strain requirements. While few materials have the required stiffness and strength, it may be possible to exploit the unique requirements of deployable structures to develop composite materials capable of the high strains. In the remainder of this abstract, select results and figures from the full paper are presented.

2 Large Strain Composite Materials

A measure of the bending stiffness and strength mass performance of a truss is given by,

$$\mu = \frac{\left((EI)_{req} M_{req}^2 \right)^{1/5}}{w} = \frac{\pi^{4/5}}{2^{3/5}} (\mu_t \mu_n)(\mu_l \mu_m) \qquad (1)$$

The significant parameter for the purposes of the current work is the material performance index,

$$\mu_m = \frac{E^{3/5}}{\rho} \qquad (2)$$

This index is shown in Fig. 1 for a range of engineering materials. Rigidizable composite materials, while highly flexible, require challenging thermal management systems and can result in trusses 8 times heavier than those made from ultrahigh modulus composite materials

Deformation based deployable structures typically use highly flexible, less structurally efficient materials exclusively throughout the truss. This practice is an architectural limitation and can be avoided by employing recently developed concentrated strain approaches. In this approach, less flexible but more efficient materials are used throughout the majority of the structure and flexible materials are used only in smaller hinge locations. Two concentrated strain deployable structures are shown in Fig. 2.

Material stiffness and strain requirements for concentrated strain hinges have been analyzed and they are extreme. Due to the reduced cross sectional area and reduced material stiffness of hinges, the truss stiffness is also reduced. Figure 3 shows the effective truss stiffness as a function of strain for three hinge materials. IM7 performs best, but requires unrealistically large strains. S2 glass and NiTi result in unacceptable truss performance. Materials with reasonable stiffness and large (2-5%) strains are needed.

Concentrated strain hinges have unique material requirements: the material only needs to be stiff once the structure is fully deployed. In paper, it is shown that this reduction in requirements combined with the mechanics of micro-buckled fibers, leads to a theoretical potential for composite materials ideally suited to concentrated strain hinges.

Selected References

[1] Freeland R., Helms R. and Mikulas M., "The Applicability of Past Innovative Concepts to the Technology for New Extremely Large Space Antenna/Telescope Structures". *SAE International Conference On Environmental Systems*, Norfolk, VA, 06ICES-224, 2006.

[2] Freeland R., Helms R., Willis B., Mikulas M., Stuckey W., Steckel G., Watson, J., "Inflatable Space Structures Technology Development for Large Radar Antennas". *Proceedings of the 55th Congress of the International Astronautical Federation*, Vancouver, Canada, IAF Paper IAC-04-IAF-I.1.10, 2004.

[3] Jenkins C. "*Recent Advances in Gossamer Spacecraft*". 1st Ed., American Institute of Aeronautics and Astronautics, Inc. 2006.

[4] Pellegrino S., "*Deployable Structures*". 1st Edition, Springer Wien New York, 2001.

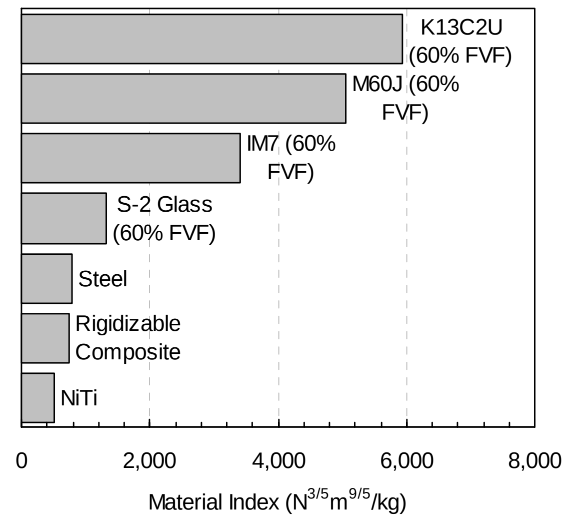

Fig. 1. Material performance indices.

Fig. 2. Partially deployed concentrated strain structures.

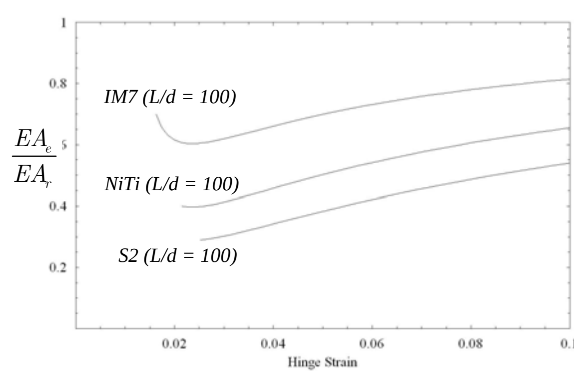

Fig. 3. Effective truss performance.