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An Inflatable Rigidizable Truss Structure Based on New Sub-Tg Polyurethane Composites

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ABSTRACT

New aromatic-rich polyurethane resins have been developed by L'Garde and used to make 3-ply composite laminates for fabrication of sub Tg rigidizable structures. These composite are used to fabricate ultra-lightweight deployable rigidizable structures for space applications. Versatile polyurethane chemistry was chosen because it allows formulation of the desired glass transition (Tg) for any specific application over a wide range of temperatures. New composites made from these urethanes show considerable resistance to ionizing radiation, and was demonstrated in simulated ground-based tests.

Under the SSP program (Space Solar Power Truss), a 24 foot long inflatable / rigidizable truss (Figure 1) was designed and manufactured from the new laminate at L'Garde and then compression tested at NASA / LaRC. The truss withstood a compression load of 556 pounds, 10% above its designed compression strength. The truss weighed only 9 pounds and consisted of separate inflatable / rigidizable legs (longerons and diagonals) bonded together at manifold intersections made out Delrin plastic. The rigidization method is based on a sub-Tg method in which the laminate rigidizes when exposed to the low temperatures of space. Comparisons of the SSP truss with other mechanically deployed structures showed that the inflatable truss has the potential to reduce the mass by a factor of 3-4.

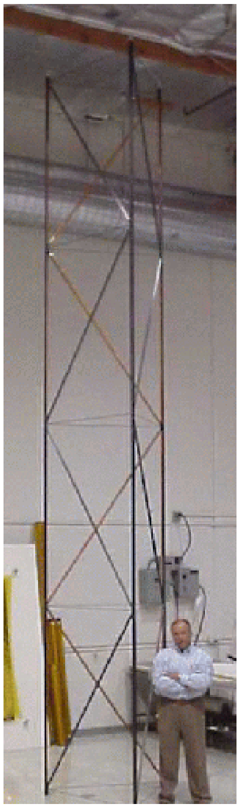

Figure 1. Sub Tg Rigidizable Truss

INTRODUCTION

L'Garde has been investigating and manufacturing space rigidizable hardware for over 15 years. Based on L'Garde studies [Ref. 1] there are five different space rigidization methods which the potential for future utilization. These are:

- Pressure rigidized aluminum foil
- Sub Tg rigidizable thermoplastic and thermoelastomeric composites
- Hydrogel rigidization
- Thermoset rigidization
- UV rigidization

Rigidizable structures are significantly more resistant to the hazardous space environment than constantly inflated structures. With mission duration leaks can develop in the structure mainly due to micrometeoroids. Rigidizable structures do not require internal pressure after deployment and are not as susceptible to these space hazards and do not require any makeup inflatant.

Furthermore, this type of structure has considerable advantages over alternate types of

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space structures in terms of weight and packaged volume reduction. This will result in considerable savings in hardware and launch costs. The technology will be very valuable and can be utilized in areas such as inflatable / rigidizable solar arrays and concentrators, communication satellites (antennas) and many other structural components on commercial spacecraft.

Figure 2 is a picture of a 4M diameter Optical Calibration Sphere (OCS) which was launched into space in 2000. The OCS flight unit was deployed, inflated and successfully rigidized in low earth orbit (LEO) on January 26, 2000 from Vandenberg, California. The rigidizable composite used to make the OCS walls was based on a 5-layer laminate of pressure rigidized aluminum foil which was only 1.2 mils thick.

Figure 2. OCS Space Rigidizable Sphere

SUB TG RIGIDIZATION

We have studied and compared major rigidization methods for space use and concluded that sub-Tg rigidization is preferable to other methods in terms of overall performance [Ref 1]. One of the most important qualities of the sub-Tg rigidization is its ability to be ground tested. Further, contrary to thermoset and UV based systems, the sub Tg rigidizable resin is in its final cure stage and stable before launch. Therefore these composites have unlimited shelf life. The following summarizes the main attributes of sub-Tg rigidizable composites:

Sub-Tg Rigidizable Advantages

- Reversible and ground testable
- Long shelf life
- Ability to turn into nearly void-less composites
- Unlimited deployment lifetime
- Stable matrix
- Simple passive rigidization (pending thermal environment)
- No maximum thickness limitations
- Tailorable Tg (glass transition temperature)
- No need for auxiliary equipment and hardware
- Ability to form faultless end joints

We further have shown that none of the existing space rigidization methods are perfect and meet all requirements of an ideal method. As a result, this method of rigidization has its own shortcomings, which are mainly the need for minimal thermal environment and low power heaters. The latter may be needed to soften the packaged composite prior to deployment.

SPACE SOLAR POWER (SSP) TRUSS

The SSP mission calls for very large structures, possibly kilometers in length. To bind the problem it was agreed a truss 60m long capable of withstanding 500 lbs. of longitudinal compression would be useful and representative of this class of structure. Though some bending capacity will also be required currently no requirements exist and the bending capacity was not addressed. Low mass is also very desirable as is a low packaged volume. As resources precluded construction of a complete 60m long structure, a full scale 8m section, comprising of 4 bays was fabricated to validate the performance, see Figure 3. The main elements of the truss are as follows:

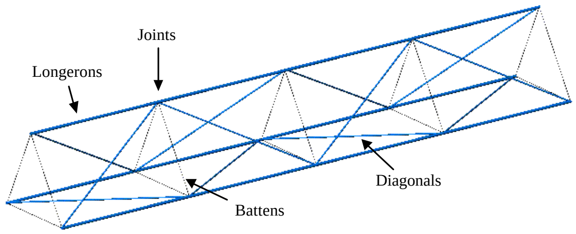


Figure 3. SSP Truss Segment

Longerons

The Longerons are the main structural elements of the truss and together are required to withstand the 500 lbs in compression. They were constructed of a Sub Tg rigidizable laminate developed and optimized for this purpose. The laminate is 13.7mils thick and has a tested modulus of 9.54 mpsi.

The compressive loading on the Longerons manifests itself in two distinct failure modes. The first is short column or local buckling, which is dictated mainly by the material modulus and to a certain extent the tube diameter. The second is Euler or long column buckling which is very sensitive to tube length and geometric straightness.

Diagonals

The diagonals in an axially loaded truss experience very low loads and are mainly for stabilizing the longerons. There are some loads on the diagonals due to geometric imperfections in the truss but they are very small when compared to the loads in the longerons and are difficult to predict. In bending however the loads in these elements can rise substantially but are not directly addressed in this effort. The truss was designed to absorb longitudinal compression only.

The diagonals were constructed of the same 13.7mil thick sub Tg rigidizable material, stowed, and inflatably deployed like the longerons. As the loading in the diagonals is very small, the main parameter sizing the structure is that of manufacturability. Ideally, a very small diameter, very straight tube would be capable of stabilizing the structure, however, experience shows that a tube length / diameter ratio of about 110 is the practical limit for fabrication of geometrically straight tubes. For our analysis, this length / diameter ratio of 110 dictates the geometries of the diagonal members. In structures where the bending capacity requirements are high, these members may become larger.

Joints

To keep the joint design as simple as possible it was decided to pursue a rigid design and not an all-inflatable design. An all-inflatable joint is complex to design and fabricate, and as the structure is so large, the stowed volume savings afforded by an inflatable design is very small in comparison to the overall structure. It was decided to baseline a rigid joint design.

A key parameter to the joint design is that all loads should pass through a single point on each joint. It is possible to design a lower mass joint with the diagonal element attach points closer together near the middle of the joint; however, these loads would act through a moment arm and create bending moments within the truss structure. While these loads are considered small it was decided to eliminate these moments by bringing all compressive loads in the joint to a single point (see Figure 4). The longeron loads are carried through the joint by a central cylinder. The diagonals are bonded to endcaps, which are bonded to shoulders in the joint design. The batten is bonded to the joint though a reinforced boss.

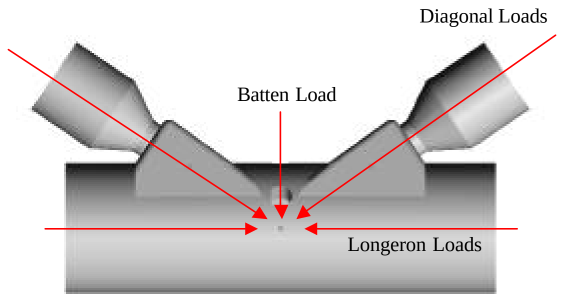


Figure 4. Joint Design

Battens

As the footprint of the truss is relatively small, rigid battens may be utilized without adversely affecting the packaging flexibility and volume. Additionally the rigid battens complement the rigid joint design. Similar to the diagonal members, the loads in the battens are quite small. Thin rigid carbon fiber rods were selected for these members. These rods have a very high modulus of around 30mpsi. The rigid batten and joint assembly is shown below in Figure 5. This assembly represents all rigid components in the truss design; all other components are inflatable and constructed of Sub Tg rigidizable materials. The battens are hollow tubes and serve as a gas flow path to aid in the inflation / deployment.

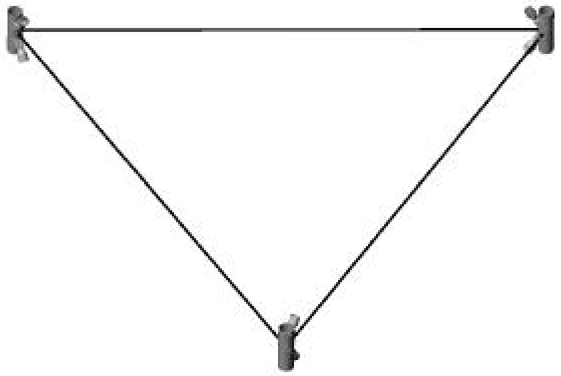


Figure 5. Battens and Joints

RADIATION-RESISTANT RESINS

One of the major space hazards in Geosynchronous orbits (GEO), where the SSP truss will operate, is ionizing radiation (electrons & protons). Therefore, any inflatable / rigidizable composite used in such an environment must be resistant to this type of radiation. Further, since these composites are folded for packaging, they must regain their original configuration similar to that of elastic materials. One major disadvantage of elastomers is that these materials are not resistant to particle radiation. Among elastomers, polyurethanes are known to exhibit good resistance to ionizing radiation [Ref 2]. As a result, urethane elastomers were selected for further development and improvement for this application. The UV hazard was not specifically addressed since the truss elements will be protected by an MLI envelope for thermal control.

Formulation & Synthesis Of Polyurethanes

The formulation of radiation-resistant polyurethanes was based on well known basics relating to "structure vs properties" of polymers [Ref 3]:

a- Aromatic groups impart significant radiation resistance to polymer molecules.
b- Some chemical bonds and groups are particularly sensitive to radiation. These include COOH, C-X (where X = halogen), SO_2, NH_2 and C=
c- Composites are generally more resistant to ionizing radiation than their respective pure matrixes.

Based on the literature search, the following structural units were selected for formulation of ionizing radiation resistance polyurethanes:

- Aromatic isocyanates
- Aromatic polyester polyols
- Cyclic polycarbonate polyols
- Aromatic chain extenders

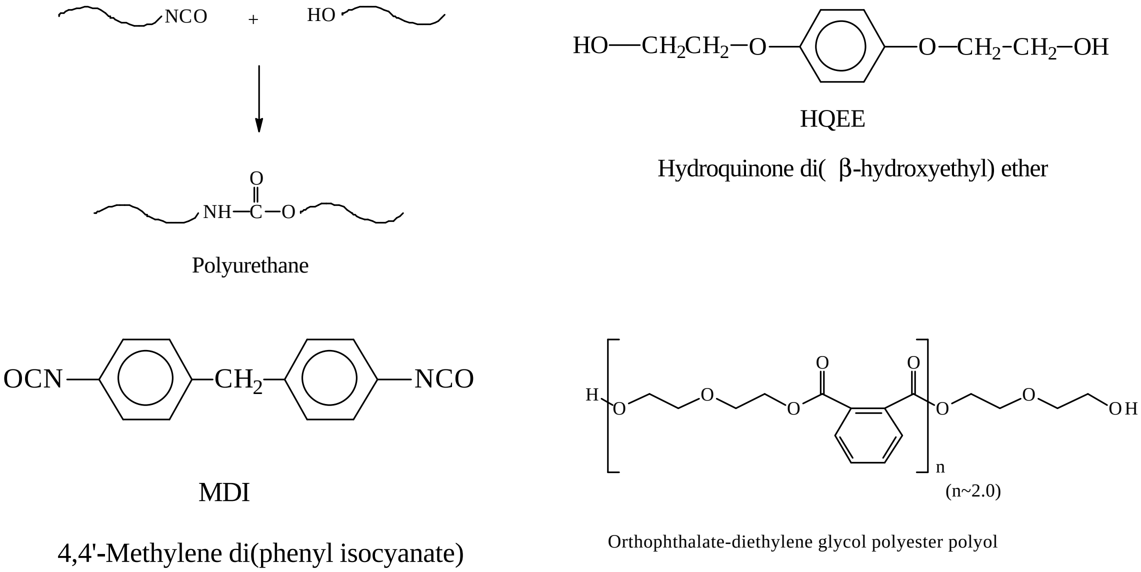


Figure 6. Molecular Formulations

The exact formulation of developed urethanes can not be published since at the time of writing this paper, we are considering obtaining patent rights pertinent to these materials. Figure 6 shows some of the typical precursor materials that were used in formulating these urethanes:

In addition to aromatic-rich urethanes, polyurethane based on poly (oxytetramethylene) glycols and aliphatic polycarbonate polyols were also prepared as references. All formulations were prepared utilizing the one-shot method at the same NCO / OH equivalent weight ratios. A total of 24 elastomers were prepared for initial screening. This resulted in selection of 5 potential candidates as are shown in Table 1.

Table 1. Properties of Selected Urethanes

Material	Tg °C	CTE ppm / °C	E KSI	Armaticity %
L-8	44-54	103	110	13
L-15	38-47	48	246	13
L-10	30-36	73	215	28-37
L-5	43-53	76	584	36-42
L-16	27-31	73	447	36-42

These polyurethanes were selected based on the following two criteria:

a. Chemical composition which is expected to have good ionizing radiation resistance (e.g. calculated % aromaticity), and
b. Glass transition temperature close to the preferable temperature range of 30-40? C.

Compounds L5 &L16 were selected for radiation testing solely based on their initial properties (i.e. Tg & % aromaticity) given in table 1

RADIATION TESTS

Calculation of radiation doses and the actual exposure to ionizing radiation were conducted at Aerospace Corporation facilities in El Segundo California [Ref 4]. AE8MAX models were used to determine the predicted simulation dose profiles and orbital dose profile for GEO orbit over a 15-year mission. The specimens were made out of two selected pure polyurethane resin (L5 & L16) and resin L5 / graphite composite. Figure 7 shows the radiation effect on the flexural modulus over 12 simulated years in GEO. As is seen the modulus of both resins and their composites are not affected by the radiation.

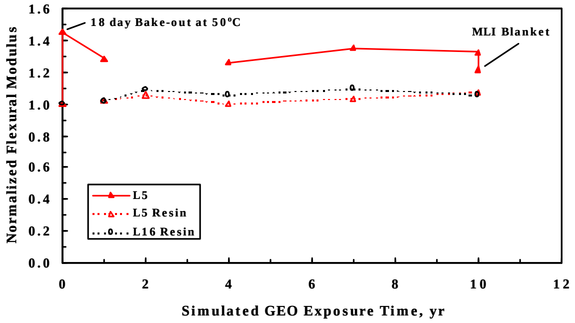


Figure 7- Effect of Ionizing Radiation

LAMINATE DESIGN AND FABRICATION

The laminate for this work was designed by using CADEC Code– *computer-aided design environment for composites*. [Refs 5&6]. The code was used to predict the properties of different possible laminate configurations. These configurations were initially and intuitively designed based on some number of criteria as follow:

- To have majority of the fibers along the longitudinal axis of the tubes where the compression loads are acting.
- Sufficient strength along the transverse direction to stand inflation pressure during deployment
- Thin packagable / foldable laminates

CADAC was selected because it is user-friendlier than other similar codes and has an excellent *GUI* (graphical user interface). The results of the CADEC was compared with those obtained from similar codes such as *VISILAM* (written by Mikulas). The two codes gave identical results. Table 2 gives the input into the CADEC code. The pre-preg composite was selected from many candidates and made out of 3 ply graphite cloth and L5 resin with 0-0 / 90-0 lay up.

Table 2- Input to CADEC Code

Fiber modulus (T300 graphite):	33.36 Million psi
Fiber Poisson's Ratio:	0.27
Fiber CTE:	-0.6 ppm / C°
Fiber volume fraction:	0.45
Resin modulus:	435,000 psi (@-50C)
Resin Poisson's Ratio:	0.30
Resin CTE:	30 ppm / C°

In-plane modulus (Ex) numbers predicted by CADEC and experimental values measured on single cylindrical tubes, coupons were 12.9, 9.54 and 11.0 Mpsi respectively. These indicate reasonable agreement between the experimental and CADEC numbers. The lower modulus numbers obtained during testing of the cylindrical tubes is believed to be due to endcap slippage of the test specimens.

Laminate Fabrication

Large scale laminate production was performed using a solution of L5 resin in NMP solvent (1-methyl-2-pyrrolidone). The resin solution was used to impregnate the graphite fabric using conventional rollers. NMP was found to be the least toxic and most effective solvent to dissolve L5 resin.

Effect Of Temperature On Modulus

The flexural modulus as a function of temperature was measured over the +23°C to -150°C range at Aerospace Corporation. Figure 8 graphically shows the modulus as a function of temperature. Basically, the modulus was constant from room temperature to -150°C, but decreased significantly at 75 and 125°C. As expected, the sudden drop in modulus took place around the glass transition temperature of the material (i.e., at 50 - 60°C).

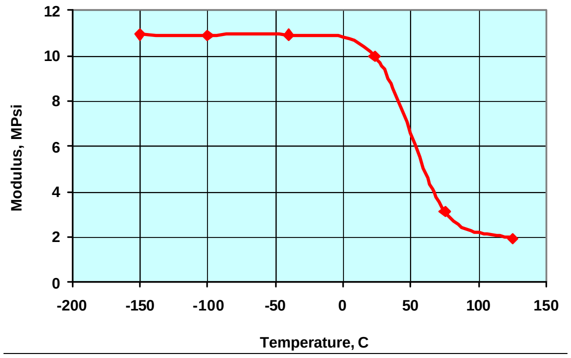


Figure 8 In Plane Modulus vs. Temperature

TRUSS DESIGN

An analytic technique developed by Dr. Martin Mikulas was utilized at L'Garde [Ref 9]. The technique predicts the loads in the truss members given the geometries, estimated imperfections, and loading conditions. L'Garde incorporated the technique into a spreadsheet and conducted trade studies to optimize the design. The optimization technique solves for key parameters of the truss design given the material properties, expected geometries, and compression loading conditions. The technique solves for the loads within the truss and calculates tube diameters to withstand the expected loads with the desired safety factors.

An example input case is shown in Table 3. As mentioned the required compressive load is 500lbs and the total truss length is 2362.2" (60m). Two safety factors were applied, an overall truss Euler safety factor of 1.5, and an individual longeron element Euler safety factor of 1.15. The Bay Length / Width Ratio specifies the aspect ratio of an individual bay and is generally iterated to find the ideal value. Material densities, modulus, and thickness are dictated by the sub Tg laminate used in fabrication. It should be noted that these predictions were run before the final laminate was available, hence the predicted thickness of 12 mils instead of the measured laminate thickness of 13.7mils. The longeron Length / Diameter ratio of 110 represents the longest thinnest tube that can be reasonably fabricated geometrically straight. Finally the Truss Imperfection/Length ratio represents the maximum expected bow in the fabricated truss. In this case a fabricated truss bow deflection of 2.36" from straight can be tolerated without compromising the structure and accelerating Euler buckling.

Table 3. Design Tool Input Values

Inputs	Value	Units
Compression Load	500.000	lbs.
Total Truss Length	2362.205	in.
Truss Euler S.F.	1.500	
Longeron Euler S.F.	1.150	
Bay Length/Width Ratio	1.49	
Material Density	0.060	lb/in3
Material Modulus	7500000.000	psi
Longeron Thickness	0.012	in.
Lengeron Length/Diameter	110.000	
Joint Factor	3.000	
Diagonal Thickness	0.012	in.
Batten Thickness	0.012	in.
Truss Imperfection/Length	0.001	

The calculated parameters given the above input case are shown in Table 4. The geometric outputs are self-explanatory and represent the calculated values required to meet the above input case. The output weights are theoretical based on expected component densities and volumes. The weights are theoretical estimates and should be used for comparisons only.

Table 4. Design Tool Output Values

Inputs	Value	Units
Batten Length	46.569	in.
Diagonal Length	83.567	in.
Radius of Truss	26.887	in.
Longeron Area	0.052	in^2
Radius of Longeron	0.692	in.
Radius of Diagonal	0.380	in.
Radius of Batten	0.212	in.
Weight of Joints	4.094	lbs.
Weigt of Longerons	22.170	lbs.
Weight of Diagonals	14.666	lbs.
Weight of Battens	4.554	lbs.
Pfailure	0.7914	
Total Weight	45.484	lbs.
Number of Bays	34	

Using the described design tool and safety factors an optimization process was embarked on to determine the geometry for the lowest mass truss. The Bay Length / Width ratio was varied and the component geometries and masses were calculated. The Truss Mass as a function of number of bays is shown below in Figure 9. In the region of 30-60 bays the overall truss mass varies very little and is quite flat. While the number of bays near the optimum configuration has little affect on overall system mass, other considerations would favor a truss with fewer bays. As the joints are rigid and take up a specific volume, the greater the number of bays the larger the packaged volume will be. Additionally, deployment of the truss, not directly addressed under this effort, is complicated by a larger number of bays. For these reasons a compromise of 34 bays was selected to minimize the number of bays while keeping the masses relatively low.

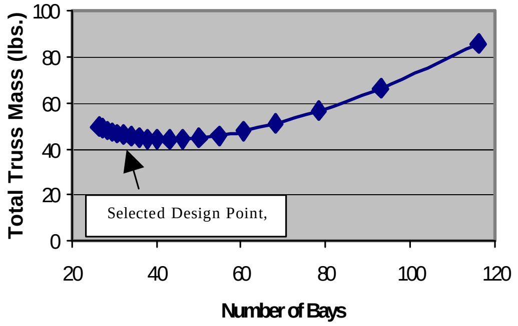


Figure 9. Truss Mass vs. Number of Bays

The longeron diameters corresponding to the same design points as shown above again show an insensitve region (Figure 10). In this case the larger number of bays requires a slightly larger diameter longeron but with almost no mass penalty.

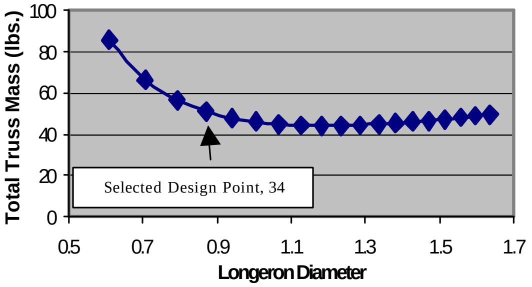
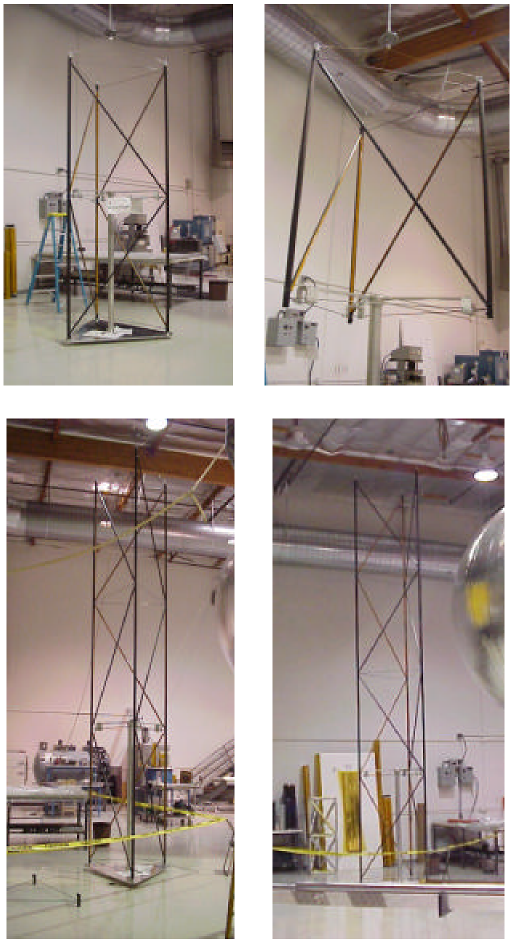


Figure 10. Truss Mass vs. Longeron Diameter

TRUSS ASSEMBLY AND FABRICATION

The truss mainly consists of four different elements as is graphically shown in Figure 3. An assembly fixture was designed and used to put different parts of the truss together, one bay at the time, in an accurate and precise manner. Figure 11 shows the truss during different stages of assembly. Table 5 gives the weight of different parts of the finished truss.



Figures 11 SSP truss at different assembly stages

TABLE 5. DETAILS OF SSP TRUSS WEIGHT

Truss Elements	Weight, Grams
Longerons*	136.59
Diagonals*	107.95
Spars	30.94
Manifolds	46.64
Total weight for one bay	966.36
Calculated weight of the truss** (W/O adhesives)	3865.45
Total Truss Weight	4084.60
Adhesive weight (calculated)	219.15

* Longerons and Diagonals weights include the 2 mils thick Kapton bladder

COMPRESSION TEST

To simulate a structure deployed in space truss was packaged and deployed before compression testing. Given the LaRC test lab requirement of room temperature testability, a Sub Tg resin was selected with a high Tg temperature to leave the structure rigid at room temperature. A resin with a lower Tg more representative of an actual space system would require low temperatures for testing and severely complicate the test setup. Consequently, to render the structure flexible for packaging, its temperature must be raised above 100°C. Since the structure must packaged by hand it was not possible to provide a survivable working environment to accomplish this procedure. Instead, the structure was disassembled and the individual elements heated locally and packaged in a representative manner, Figure 12. After each element was packaged and deployed, the truss structure was reassembled. Please note that for a space system, a resin with a lower Tg temperature would be utilized, and the truss could be packaged normally at room temperature. The requirement to conduct structural tests at room temperature required these packaging procedure modifications.

Figure 12. Packaged Truss Element

The SSP truss was shipped to NASA/LaRC for compression testing. Figure 13 shows the test setup. The truss withstood 556 pounds (approx. 10% over its designed strength) of compression before it buckled [Ref 7]. The failure initiated at the seam of one of the longerons, starting at about 350 pounds. Figure 14 shows various aspects of the truss failure. Figure 15 is load deflection plot of the compression test.

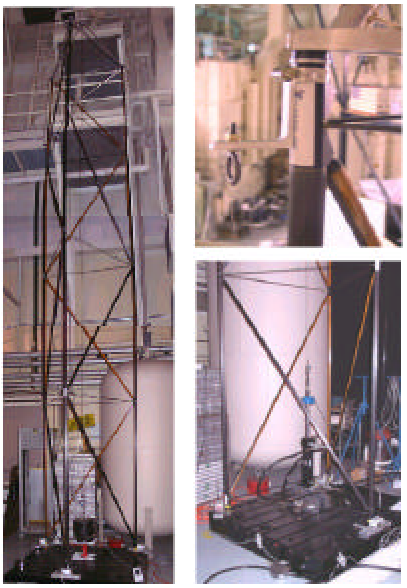


Figure 13. Compression Test Setup

Figure 14. Joint failure at the seam

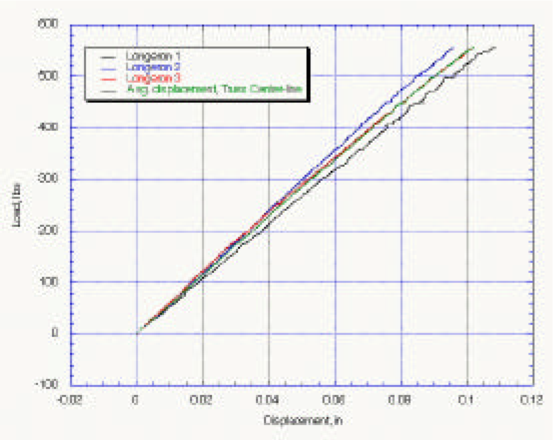


Figure 15- Compression load vs deflection

COMPARISON WITH EXISTING SYSTEMS

Martin Mikulas [Ref. 7] showed that a good way to compare the structural performance of trusses with each other is to plot their compressive failure load (P_{cr}) vs. their normalized weight and length parameter. He showed that the later is best represented by: ($c^{1/3}$ W / $L^{5/3}$) where

C = loading condition (1 for compression)
W = weight, in pounds
L = length, in inches

Thus by comparing the plots of $C^{1/3}$ W / $L^{5/3}$ vs. P_{cr} of each truss system, the very basic important property (i.e., strength and stiffness per unit mass) could be compared in an unbiased normalized fashion. Currently available mechanically deployable trusses include the Coilable longeron and ADAM (ABLE Deployable Articulated Mast).

Figure 16 compares the SSP truss with current commercially available trusses. As is seen the inflatable truss concept has the potential to reduce the mass by a factor of 3-4 compared to mechanical deployables.

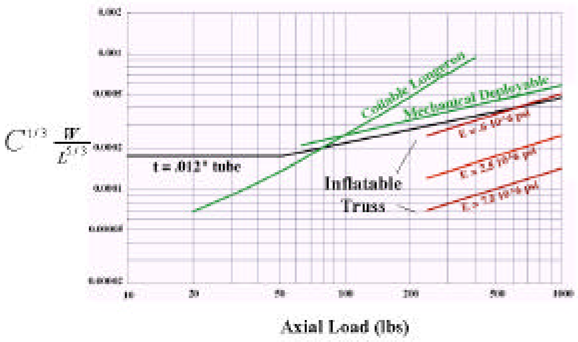


Figure 16. Comparisons

CONCLUSIONS

The aromatic rich urethanes developed specifically for sub Tg rigidization use in space exhibited excellent resistance to ionizing radiation present in GEO environment. One important advantage of urethanes is that their glass transition can be tailored by modifying their chemistry and therefore can be customized for specific environmental (thermal) condition. The final 4-bay truss weighed a total of 9.01 lbs. If extrapolated to the full 34-bay truss, the predicted fabricated mass should be around 76.5 lbs which is considerably more than the analytically predicted 45.5 lbs. Though the trends in the predictions are still valid, more work needs to be done to "close the loop" and refine the design tool to better predict the final fabricated structure masses. In terms of truss performance, the truss withstood 556 pounds (approx. 10% over its designed strength) of compression before it buckled. Further the inflatable truss concept has the potential to reduce the mass by a factor of 3-4 compared to mechanical deployables

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REFERENCES

1- K. Guidanean, “Large Radar Antenna, Comparison of Space Rigidization Techniques”, L’Garde Technical Report LTR-00-KG-012, September2000

2- P. Beynell Et al, “Compilation of Radiation Damage Test Data for Materials Used Around High Energy Accelerators”, CERN 82-10, European Organization for Nuclear Research, Geneva, Nov 4, 1982

3- J. Mark, “Physical Properties of Polymers Handbook”, AIP Press, 1996

4- W. Stuckey, M. Meshishnek & G. Steckel, “Aerospace Briefing Report on Inflatable Materials”, TOR-2000 (3327)-1, May 2000

5- E.J. Barbero, “Introduction to Composite Materials Design”, Taylor and Francis, Inc., 1999.

6- R. Luciano, and E.J. Barbero, “Formulas for the stiffness of composites with periodic microstructure”, I.J. Solids Structures, 31, 2933-2944 (1994).

7- Private Communication with Judith Watson of NASA / LaRC, 7 / 30 / 01.

8- Martin Mikulas, “Merit Function and Weight Comparisons for Deployable Beam / Column Concepts,” February 1999.

9- Martin Mikulas, “Truss Design Tool”, April 1999