

AN INFLATABLE RIGIDIZABLE TRUSS STRUCTURE WITH COMPLEX JOINTS

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ABSTRACT

Inflatable/rigidizable structures have shown promise for use in space, due to their inherent light weight and low packaged volume. Under this program, complex joints of inflatable/rigidizable tube members were developed. Two 150cm-long modular trusses have been designed, built and tested. Each truss consists of separate inflatable/rigidizable legs, joined together at the intersection points with cast aluminum manifolds. A thin plastic layer comprises the pressure barrier inside each tubular leg. The main tubular leg composite consists of a fabric impregnated with a water-soluble resin, which rigidizes when dehydrated by evaporation of the water, thus giving the composite its strength. One advantage of using solvent-based systems is their reversibility, i.e., the rigidized composite can be softened and re-rigidized repeatedly by controlling its water content. Outside of the composite layer is an outer enclosure which meters the evaporation of the water solvent during rigidization and also prevents blocking of the composite during packaging. The testing program consisted of packaging, thermal cycling, vibration, deployment and rigidization in ambient and vacuum conditions, bending/compression tests, and determination of natural frequency. The effects of wall thickness, diameter and lateral length of the modular cylinder and composite stiffness on the strength of the truss were determined by a finite element analysis model (FEM).

1.0 INTRODUCTION

L'Garde has made significant advances in developing inflatable rigidizable materials and the capability to deploy and then rigidize them for space applications. The use of inflatable and then rigidizable construction significantly increases the strength, stiffness and durability in hazardous space environments, (i.e.,

under the effects of meteoroids) comparable to conventional inflatable systems. Furthermore, this type of structure has considerable advantages over alternate types of space structures in terms of weight and packaging volume reduction. Development of inflatable/rigidizable structures with complex joints will also be very useful for various space applications, particularly for large space structures. 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.

The capability of fabricating inflatable/rigidizable basic tubular members and simple joints (e.g., a tee, an elbow and a three-dimensional corner joint), where up to three tubes are joined, was developed and perfected in previous work (Inflatable Rigidizable Space structures, IRSS Phase I Program). All rigidization experiments in Phase I were carried out under atmospheric conditions and, furthermore, all joints were simple and not integrated with other joints.

The technical objectives in this phase (IRSS II)² have been far more ambitious and are as follows:

- To develop the capability to fabricate actual inflatable/rigidizable structural truss members and frames that are larger, more complex than those made previously, and comprised of several different types of joints, as well as other design aspects of a complete structure. The proposed structure for this phase is shown in Figure 1.0-1.
- To examine and demonstrate vacuum deployability, packagability and strength of actual inflatable/rigidizable structural elements (i.e., frames and/or trusses) that can be utilized for prefabrication of space systems.

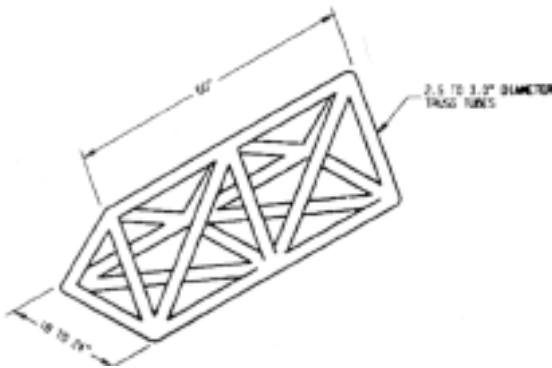


Figure 1. O-I. Structure for Fabrication and Deployment in IRSS Phase II

In addition to the above main objectives, other critical areas such as life issues (space hazards), environmental testing (vibration and thermal), contamination and outgassing, have been addressed under *this* program.

2.0 OPTIMIZATION OF DESIGN AND FABRICATION DETAILS

Figure 2.0-1 shows the cross section of a typical inflatable rigidizable membrane. The make up and details of these types of composites were worked out in previous studies^{1,2,4,5}.

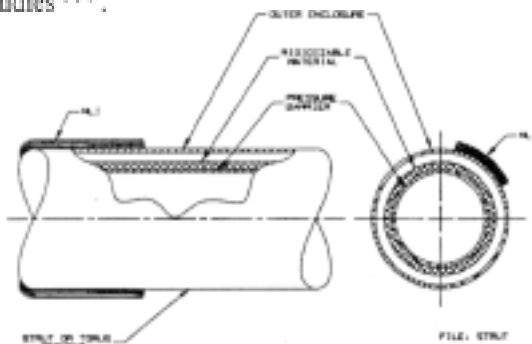


Figure 2.0-1. Cross-Section of a Typical Inflatable Rigidizable Membrane

The rigidized composite material consists of a fabric and a water-soluble resin solution that is rigidized by dehydration. The outer enclosure (see Figure 2.0-1) provides a means of obtaining and keeping a high humidity environment surrounding the rigidizable material, thereby maintaining it in a non-rigidized (softened) state until deployment and inflation have occurred and the system is ready to be rigidized. The outer enclosure also serves to prevent the adhesion (blocking) of adjacent layers of the wet rigidizable

material to one another during stowed periods. Further, this layer controls the rigidization rate (or water evaporation) during and after deployment by allowing proper venting.

The rigidizable parts will be formed into their desired shape by inflation prior to being rigidized. Since the rigidizable composite material is not a good pressure barrier, this will be provided by a thin impermeable membrane which is located adjacent to the inner surface of the rigidizable composite, as is shown in Figure 2.0-1.

Although these aspects of the technology had been addressed in detail in the past, more effort was made to optimize the composite laminate to meet the specific objective of the program.

2.1 SCREENING TESTS OF REINFORCEMENT FIBERS

The objective of this work was to identify the best possible fiber to make composites of high flexural and compression modulus. An outside mill that specialized in weaving industrial fabrics was contracted to provide fabrics of similar weave construction for our composite development experiments. To screen these fabrics, an 8-ply laminate of gel composites of each one of 10 different fabrics was made. Flexure specimens were cut and tested per ASTM D790.

Table 2.1-1 shows data obtained from the flexure test of these laminate composites. As expected, composites made out of graphite, Kevlar and glass fibers were the best performers in terms of stiffness. These fibers were selected and used in the second level tests to fabricate thin-walled, one-ply hollow cylinders (≈ 2 " diameter and ≈ 15 " long) for compression strength testing.

Table 2.1-2 shows the mechanical strengths of the rigidized tubes made of selected fibers, in compression and bending modes. The specific strength numbers in Table 2.1-2 represent strengths of the rigidized tubes divided by the weight of the 12"-long tubes. The compression data in Table 2.1-2 are the averages of the three readings; each obtained by an independent strain gauge attached to the wall surface of the tube.

Based on information given in Table 2.1-2, graphite-based composite tubes are shown to be stiffer than other composites. Graphite-based composites were particularly superior to others when specific stiffness and specific modulus values were compared to each other. Based on the data given above, graphite cloth (style 4163) was selected as the reinforcement cloth for the remaining part of this work.

TABLE 2.1- 1. COMPARISON OF REINFORCEMENT FABRICS FOR THE COMPOSITE DEVELOPMENT

Fabric Type	Density Pound/F ²	Flexural Properties @ RT		Specific	
		Modulus, PSI x 10 ³	Strength, PSI	Modulus X 10 ³ (1)	Strength X 10 ² (1)
Glass	0.8	1060	22025	1260	261
Carbon	1.0	2503	17117	2610	178
Nylon	0.7	191	8155	280	122
Vectran	0.9	88	6000	100	68
Kevlar	0.6	967	25021	1550	400
Nomex	0.7	219	7885	320	116
Polyester	0.9	98	3475	110	37
Cotton	1.1	245	5990	220	54
Cotton	0.6	96	5990	170	108

TABLE 2.1-2. PROPERTIES OF DIFFERENT GEL-BASED COMPOSITE TUBES

Fabric	Kevlar 281	Glass 7520	Graphite 4163	Graphite FDI 824	IRD II Cotton
Ultimate Compression Strength					
Load Pounds	83	72	111	41	
Strength PSI	1037	851	1445	828	
Specific Strength(1)	294	1805	3807	1867	
Compression Modulus(2)					
Modulus KPSI	910	1010	1070	1970	193
Specific Modulus x 10 ⁵ (1)	323	252	366	909	37
Stiffness					
IE, Kl b. In ² (Bending)	20	21	32	22	14
Specific Stiffness x 10 ³ (1)	709	525	1094	1005	259
Bending Modulus(3)					
Modulus KPSI	547	539	889	950	173
Specific Modulus x 10 ⁵ (1)	194	135	305	438	33
Shrinkage%	0.00	0.00	0.20	0.20	-1.50

2.2 STORABILITY

One of the most important requirements of this type of composite is that the composite should be deployable and rigidizable after prolonged storage.

The techniques for the effective and extended storage of inflatable/rigidizable materials have been developed under other programs⁶. The methods are dry storage, frozen storage and wet storage. The dry and frozen storage techniques are designed to provide storage during long periods (years) between fabrication and launch. However, the wet composite must also remain stable for shorter periods (e.g., to allow placement of the systems in the launch vehicle, before deployment and rigidization in space). Two types of storage tests were conducted, namely short-term (stored wet for two weeks) and long term storage (freezing storage for eight months).

The rigidized cylinders were softened (by rehumidification), accordion folded and stored. The folded tubes were subsequently re-rigidized again and tested for their mechanical properties. Figure 2.2-1 shows typical accordion folded/stored cylinders in their white outer enclosure. Tables 2.2-1 and 2.2-2 show the results and the effect of folding/storage in diminishing the strength for short and long term storage, respectively.

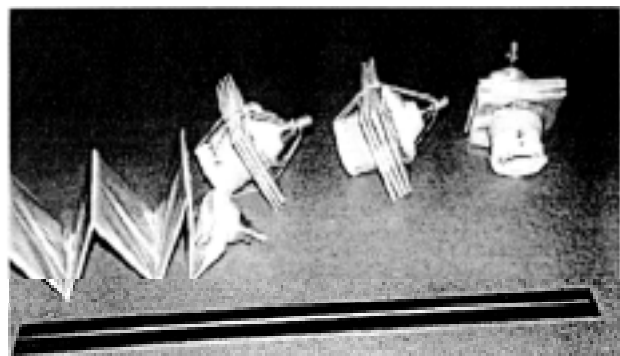


Figure 2.2-1. Folded Tube

⁽¹⁾ Note: Specific Properties are calculated by dividing the property value either by the weight (Lbs) of 1 F² of laminate (Table 2.1- 1) or the 12-in-long tube (Table 2.1- 2).

TABLE 2.2- 1. EFFECT OF SHORT-TERM STORAGE/PACKAGING ON MECHANICAL STRENGTH OF RIGIDIZED INFLATABLE RIGIDIZABLE CYLINDERS

Fabric (2116 Tubes)	Bending Stiffness LBF.IN ²		Modulus		% Change in Properties
	Before IE	After IE	Before KPSI	After KPSI	
Kevlar 281	19976	14387	550	390	-28.0
Glass 7520	21006	17101	540	440	-18.6
Graphite 4163	31958	28992	890	810	-9.3
Graphite FDI 82	21778	14715	950	640	-32.4
IRD II Cotton	13500		170	140	-16.0

TABLE 2.2-2. COMPARISON OF PROPERTIES BEFORE AND AFTER 8 MONTHS STORAGE MEASURED ON GRAPHITE-BASED COMPOSITES

	Moment @ Buckling	Elastic Modulus E from Bending Kpsi	Buckling Load lbs
Before Storage	70.9	1,313	75
After Storage	49.8	833	49
% Reduction	29.8	36.6	35

The storage test results indicated that the strength of these inflatable-rigidizable-composite cylinders were adversely affected by this process. For example, the buckling load decreases 29.8%, and the modulus decreases 36.6% of their pre-storage values in the long storage. However, the average modulus is still 833,000 psi, which is considerably higher than that of other gel-based composites previously used.

The decreases mentioned above could be due to either folding, freezing, or long term storage. There was insufficient information to determine the cause. However, we believe breakage of the warp fibers at the folds and cross folds is the main cause of weakening of the composite.

2.3 PRESERVATION OF WET COMPOSITE FROM MICRO ORGANISMS

The chemical structure of the selected water-soluble resin is similar to that of proteins found in edible foods. In a humid environment (such as a wet composite) at room temperature, these organic materials are susceptible to attack by bacteria, molds and yeast.

The objective of this work was to show that by applying a typical radiation level (dose), customary in the food industry (e.g., 0.1-1 Mrads) to the wet composite, all the harmful microorganisms are killed without affecting the basic property of the rigidized composite.

Wet flexure coupons made out of a cotton-based composite were irradiated by a Cesium 137 source to radiation levels equivalent to an absorbed dose of 1.5, 1.9 and 3.3 Mrads. Bioanalysis on all irradiated specimens showed that in all three radiation levels no microorganisms survived and no further growth could be observed.

The flexure coupons were tested before and after radiation to determine the effect of gamma radiation on their stiffness (flexure modulus).

Table 2.3-1 shows the summary of the flexure test data before and after irradiation. This indicates that at 1.5 Mrad irradiation levels, there is no significant damage to the composite. Note that a typical medium level gamma radiation in the food industry is 0.1 to 1 Mrad, which is considerably smaller than the lowest level radiation (1.5 Mrad) in this study. High levels of gamma radiation, however, had an adverse effect on the composite and the stiffness deteriorated.

TABLE 2.3-1. EFFECT OF CESIUM 137 IRRADIATION ON THE COTTON-BASED COMPOSITE

Radiation level (absorbed dose), mega Rads	0	3.4	1.9	1.5
Flexure modulus (SD)	KPSI (17)	134 (12)	60 (19)	89 (50)

3.0 TRUSS DESIGN

This section describes the design of the two trusses built for this program. Following a detailed trade study, both units were designed using modular legs and joints, rather than permanently joined legs. The trusses were built in sequence rather than in parallel, so that lessons learned and design improvements from the first truss could be incorporated into the second truss.

3.1 MODULAR DESIGN

The prototype truss consists of 21 legs and 9 joints. Six of the joints are made to connect four legs, while three of the joints (at the middle of the truss) connect six legs. Figure 1.0-1 shows the original proposed concept sketch of the truss. Fabricating the six-member joint with the traditional designs (proposed in IRSS I) would create a cluttered zone where the legs intersect, resulting in considerable difficulty during fabrication.

A new joint that is far more simple and less expensive was designed. The new design is a modular joint where all members are essentially the same except for length and are connected to a joint manifold as is shown in Figure 3.1-1. There were, however, some

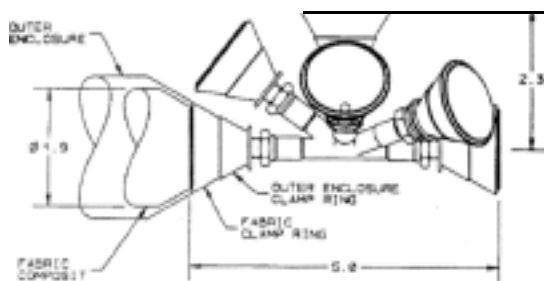


Figure 3.1-1. Six-Leg Joint

important technical questions (such as weight and packaging volume) which had to be resolved before such a change could be implemented.

To answer these issues two development joints were fabricated, one of the new design and one of the old design. The results showed that the new design would increase the truss weight by 6% and increase the packaged volume by 83%. In spite of these disadvantages, the new modular design was preferred, because it offered considerable other advantages, such as accuracy, ease of assembly, reusability and repairability. The design of the the four-legged joint with frustum-ended legs is shown in Figure 3.1-2.

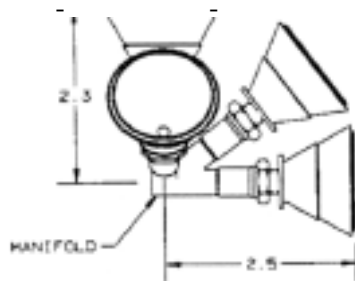


Figure 3.1-2. Four-Leg Joint

3.2 DEVELOPMENT TESTS OF THE MODULAR DESIGN

Before fabrication of Prototype #1, two "test legs" were constructed to examine the manufacturability, strength, and stiffness of the new frustum-ended design. Figure 3.2-1 shows a typical single modular leg. The 24" long legs had the new frustum design on one end, and a simple cylindrical fitting on the other. The test leg was tested in bending at both ends.

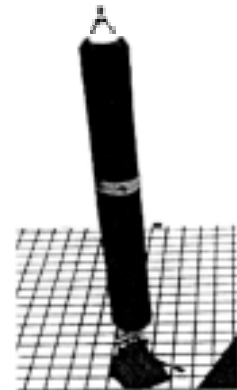


Figure 3.2-1. Modular Leg

The frustum section was designed and built out of three layers of the fabric and was expected to be nearly as stiff as the one-ply cylindrical section of the leg. This, however, was not realized and it was found that the frustum end of the leg had a stiffness that was only 42% of the cylinder-end stiffness. No further effort was made to increase the frustum stiffness and the truss units were built using the frustum design as is.

4.0 TRUSS FABRICATION AND TESTING

4.1 GENERAL

Once the development tests were complete, the trusses were built and tested in sequence. Truss #1 is shown in Figure 4.1-1. Table 4.1-1 shows the list of tests performed on each unit. Note that most of the tests performed on Prototype #1 were repeated on Prototype #2 to quantify the improvement achieved as a result of the design changes. While the details of the testing are not described in this paper, Figures 4.1-2, 4.1-3, 4.1-4, and 4.1-5 show pictorial highlights of the testing.

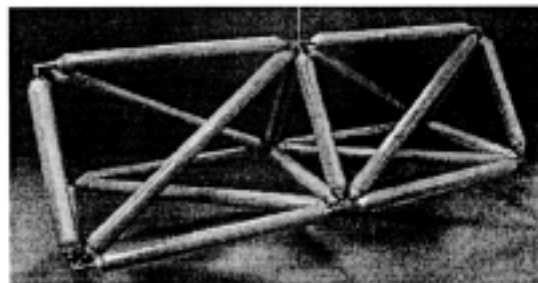


Figure 4.1-1. Prototype #1 Truss

TABLE 4.1-1. TEST SUMMARY FOR PROTOTYPES #1 AND #2

TEST	PROTO-TYPE	
	#1	#2
Assembly & adjustment of truss	x	x
Natural frequency before packaging		X
Humidification	X	X
Truss measurement after humidification	X	
Packaging	x	x
Random Vibration	X	
Thermal Cycling	X	
Deployment in ambient conditions	x	x
Rigidization	X	X
Truss measurement after deployment	X	
Natural frequency	x	x
Bending stiffness	X	X
Compression stiffness	x	x
Bending strength	x	x
Humidification		X
Packaging		X
Vacuum deployment		X
Vacuum and ambient rigidization		X
Modal testing		X



Figure 4.1-3. Packaging of Truss

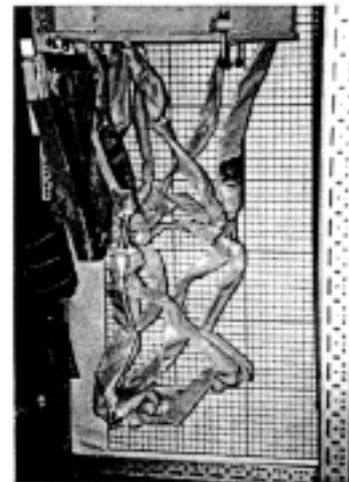


Figure 4.1-4. Deployment Test- Halfway Deployed

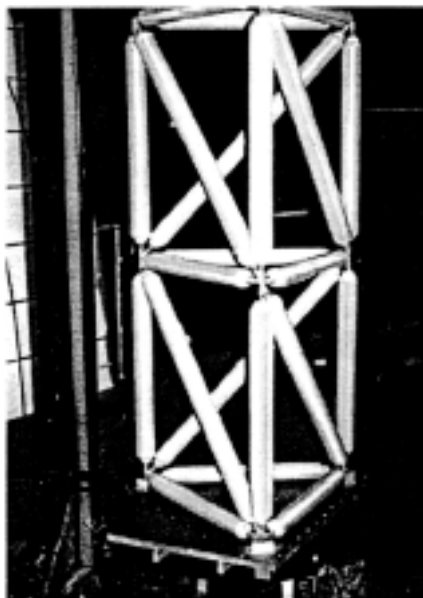


Figure 4.1-2. Height Gage Setup



Figure 4.1-5 Deployment Test- Fully Deployed

The most notable difference between the testing of the first and second units was the inclusion of the vacuum deployment and modal tests for Unit #2. These tests are described in more detail in the following sections.

4.2 VACUUM DEPLOYMENT TEST

The major test for Prototype #2 was the vacuum deployment test. This was performed in L'Garde's 3-foot-diameter by 3-foot-long vacuum chamber. A photo of the chamber and test equipment is shown in Figure 4.2-1.



Figure 4.2-1. Vacuum Deployment Test Setup

The instrumentation and controls, both pneumatic and electrical, were quite involved. The truss was initially packaged in a sealed box which was kept pressurized at one atmosphere (absolute). This was necessary to prevent the truss from rigidizing prematurely while in the folded state during pumpdown. The box was designed so that it could be vented prior to the door being opened. This was necessary to reduce the load on the latches, and to keep the box from "exploding" open.

A video camera was placed underneath the chamber to view the truss deployment. Figures 4.2-3 through 4.2-6 show the truss during deployment. These views were taken looking upward.



Figure 4.2-2. Vacuum Deployment (Door still closed)



Figure 4.2-3. Vacuum Deployment (Door open, truss still packaged)



Figure 4.2-4. Vacuum Deployment (Truss during inflation)



Figure 4.2-5. Vacuum Deployment (Truss deployed, but not at full pressure)



Figure 4.2-6. Vacuum Deployment (Truss fully deployed)

Shown in Figure 4.2-7 is the pressure profile during the test. Both the chamber pressure and truss pressure were measured. The truss was maintained at 3.0 psi (differential) after deployment.

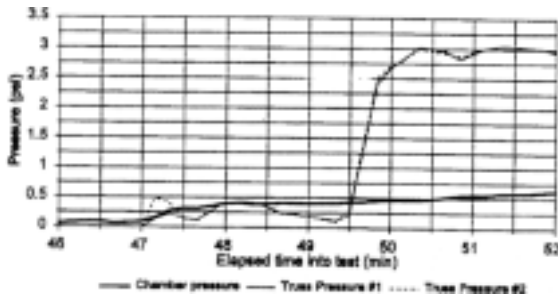


Figure 4.2-7. Deployment Pressures vs. Time

Figure 4.2-8 shows the temperature of the truss, box, and chamber during deployment. Note that the truss temperatures started to drop when the box was vented. When the truss was inflated, however, the chamber pressure rose to a level above the vapor pressure of water, reducing evaporation and, therefore, the cooling of the truss. For the remainder of the test, the temperature stayed at 65-70°F.

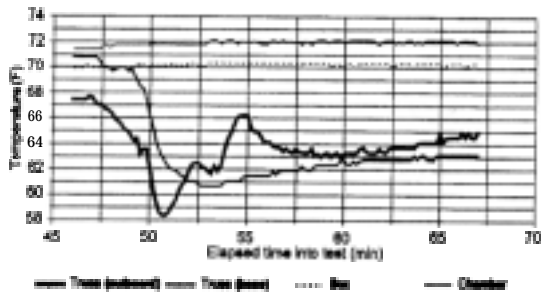


Figure 4.2-8. Deployment Temperatures

4.3 MODAL TEST OF PROTOTYPE #2

Following the vacuum deployment test, the truss was subjected to a modal test at NASA Goddard Space Flight Center (GSFC). The truss was mounted in the deployed state on GSFC's shaker table in the vertical position. Three triaxial accelerometers were mounted on the three joints at the top of the truss, while three single axis accelerometers were mounted at the middle joints. The test consisted of sine sweep and random vibration excitations.

The first two lateral modes of the truss were observed at 33.8 and 38.2 Hz. The 33.8 Hz mode was associated with the x-axis test, and the 38.2 Hz mode was associated with the y-axis test (see Figure 4.3-1). These two modes had damping coefficients of 15.5% and 6.2%, respectively. More details on the Modal test will be presented in a paper being prepared by NASA-JPL.

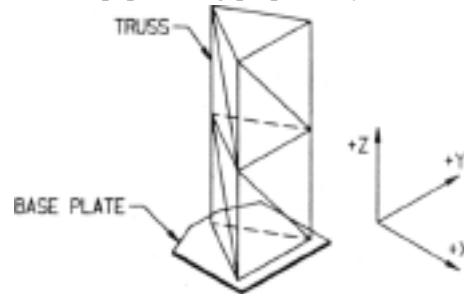


Figure 4.3-1. Coordinate Definition for Modal Test

4.4 SUMMARY OF TEST RESULTS

A brief summary of test results is shown in Table 4.4-1. These results show that the strength and stiffness of the truss improved when Truss #2 was compared with #1. In the case of compression strength, the improvement was 108%.

TABLE 4.4-1. SPECIFICATIONS OF TRUSS

PROPERTY	VALUE - PROTOTYPE	
	#1	#2
Mass	1917 g	2028g
Package Volume	1953 in ³ *	1953 in ³ *
Deployed Length	60.10 in.	60.10 in.
Natural Frequency Before Packaging (cantilever mounted)	[Not measured]	42.3 Hz
Natural Frequency After Ambient Deployment (cantilever mounted)	26.8 Hz	38.5 Hz
Bending Stiffness	5560 in-lbs/inch	17,200 in-lbs/inch
Compression Stiffness	0.280 lbs/microstrain	0.652 lbs/microstrain
Compression Strength	138.8 lbs	288.5 lbs
Bending Moment at Buckling	484 in-lbs	2360 in-lbs

*We did not make a strong attempt to minimize the packaged volume.

5.0 SUPPORTING ANALYSIS — PARAMETRIC STUDY

A thorough analysis was performed on the truss unit, using both Finite Element Analysis (FEA), and hand calculations. The primary purpose of this supporting analysis was to investigate the effects of the following tube parameters -thickness, diameter, length, and elastic modulus – on the strength of the truss.

The results of the study were:

1. The existing truss legs have a much higher long column buckling strength than local buckling strength, under both compressive and bending loads; i.e., the primary failure mode is local buckling. Optimal design can be achieved by adjusting the parameters until both strengths are about the same.
2. The critical loads occur at the three longitudinal members, close to the fixed end. This finding is confirmed by actual test results.
3. Increasing the thickness increases the strength dramatically, under both compressive and bending loads; e.g., 36% increase in thickness will increase both the compressive and bending strengths by 100%. This increases the strength/weight ratio.
4. Decreasing the diameter increases the local buckling critical load, but decreases the long column buckling critical load, under both compressive and bending loads; e.g., 32% decrease in diameter will increase the compressive strength by 13% and the bending strength by 9%. This increases the strength/weight ratio.
5. Increasing the length of the shortest tubes (i.e., increasing the triangular base of the truss) increases the strengths, under both compressive and bending loads; e.g., 20% increase in tube length will increase the compressive strength by 12% and the bending strength by 19%. This does not increase the strength/weight ratio.
6. Increasing the elastic modulus increases the strengths linearly, under both compressive and bending loads; e.g., 33% increase in the

modulus will increase both strengths by 33%. This increases the strength/weight ratio.

7. The material thickness of the actual truss legs is uneven. The thickness in some areas is smaller than the average. This is the main reason for the truss not being able to achieve the theoretical strength (289 vs. 484 lbs under compression, and 39 vs. 116.5 lbs under bending). Combined with the Finding 3. above, it is beneficial to increase the thickness, and the uniformity of the thickness.
8. Optimal design can be achieved by increasing the thickness and decreasing the diameter at the same time, until the local and long column buckling critical loads are about the same.

Under compressive load, the optimal design is found to be a truss leg diameter of 1.33” and a thickness of 0.0157”. This increases the strength by 146%. Under bending load, the optimal design is found to be a diameter of 1.384” and a thickness of 0.0151”. This increases the strength by 117%. Since the thickness is increased, and the diameter decreased, the weight and volume are unaffected.

6.0 CONCLUSIONS & SUMMARY

The main objectives for this program were; 1) To develop methods of joining elements of an inflatable/rigidizable structure with complex joints, and to demonstrate these methods. 2) To demonstrate vacuum deployability, packagability and strengths of an inflatable/rigidizable truss unit. Both these objectives were accomplished.

During the design and development of the truss, a modular joint design was chosen over the flexible joints. This change was implemented after performing a detailed trade study and a series of comparison tests. The results showed that while the modular design would result in a higher system mass and packaged volume, its advantages showed it to be superior.

Two prototype truss units were built and tested in sequence, rather than in parallel, to allow improvements to be made to the product namely; the change to seamless tubing and several minor design changes to the modular joint. These changes resulted in a truss strength increase of 108% (based on the truss compression test).

The highlights of the Prototype #2 test effort were the vacuum deployment and modal tests. The vacuum test demonstrated that the truss could survive the dynamics of deployment, and that the venting of the entrapped gases was adequate. The modal test (conducted at NASA-Goddard) showed that the truss possesses a very high stiffness and excellent damping properties.

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