Deployable foam structures with potential application in space industry

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Student research project, 2019

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1 Introduction

Deployable structure is a structure which can change shape so to significantly reduce its size when it is not used. Umbrellas, bi-stable structures, scissor-like structures and origami shapes are deployable structure which are widely used in daily life.

Deployable structures in everyday life

Deployable structures play very important role in space industry because satellites and other machines are transported into space by rockets or spaceships. The cost of transportation depends on the volume and mass of these objects during transportation. The volume-dependent cost can be reduced by using deployable structures for large components outside the body of that machine, for example antennas, booms holding instruments, solar sails, or solar panels.

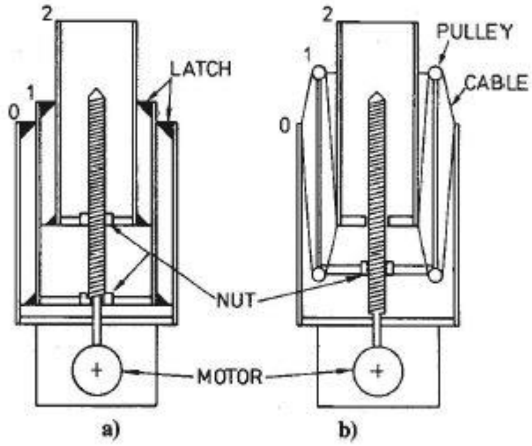
View of the deployed Sentinel-1 spacecraft with large deployable solar panels (image credit: ESA, TAS-I)

In my work I review the most popular types of deployable structures in Section 2. Then I propose a new concept of deployable structure and make experiments in Section 3. Section 4 is devoted to the result of my experiment. Also I develop measures of performance in Section 5. With Section 6, I conclude my work.

2 Current deployable structures

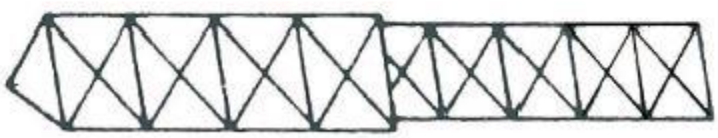
In this section I summarize the state of the art of deployable structures using Chapter 2 of the book [1] and [2] . In some cases, I also present available data about the strength, stiffness, volume, and mass of that structure. The figures of items 1-17 are copied from [1] whereas the remaining figures of this section are from [2].

1. Telescopic booms



a) Sequential and b) synchronous deployment of telescopic mast

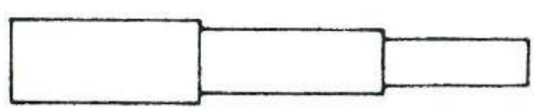
Telescopic triangular or square truss



Telescopic triangular truss

Telescopic trusses are built using concentric truss sections supported on rollers to allow movement. Steel truss structures are used for larger applications such as masts or antennas

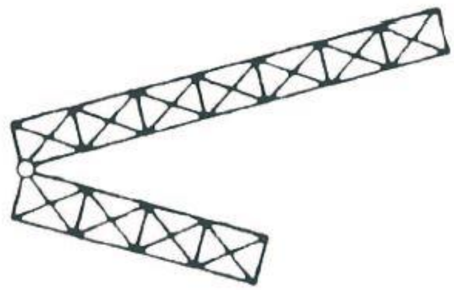
2. Telescopic cylinders



Telescopic cylinder

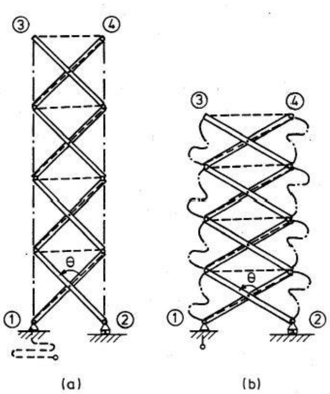
These structures are often used for smaller antenna sizes and deployable booms on satellites and are constructed using concentric tubular sections. For space application, materials are typically aluminium alloys and CFRP. For earth application, steel.

3. Folding beam



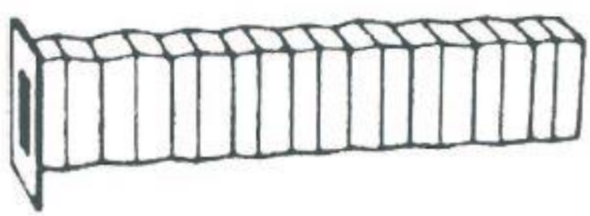
Folding beam

4. Active/passive cable systems



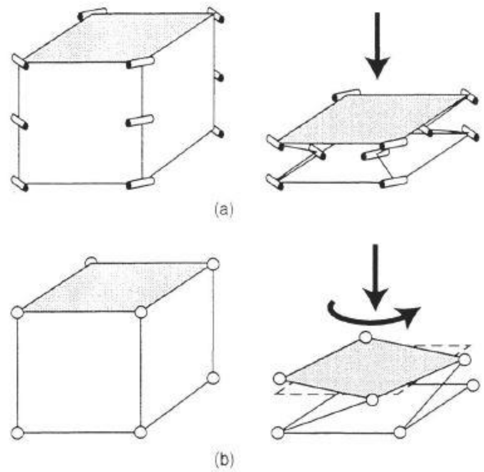
Simple two-dimensional deployable structure showing the use of active and passive cable elements

5. Box bellows



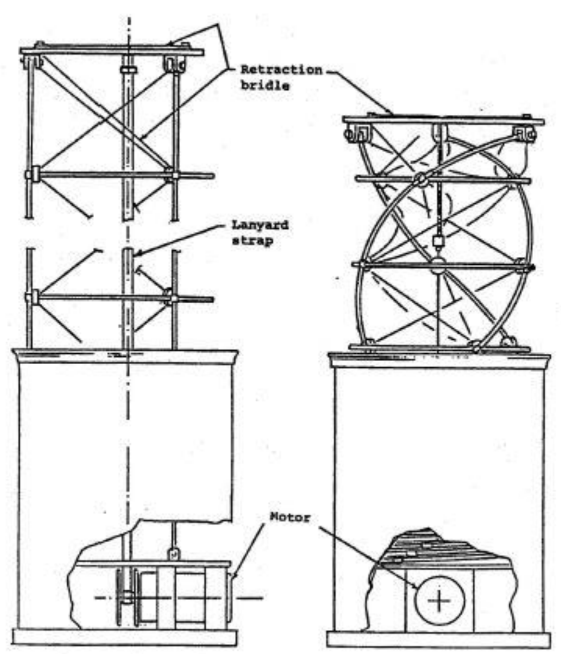
Box bellows

6. Folding articulated truss

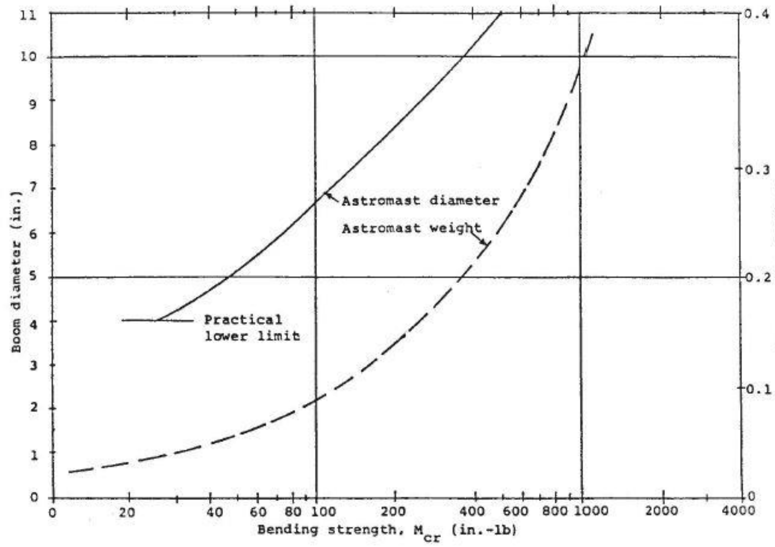


Folding principles for folding articulated trusses

7. Coilable truss

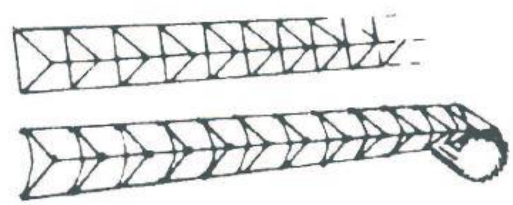


Deployment of ‘Astromast’ coilable truss using a lanyard



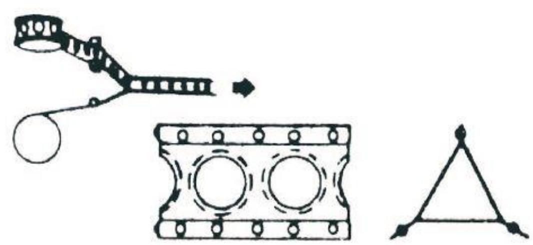
Design chart of Astromast from Astro Research Corporation

8. Triangular wire boom

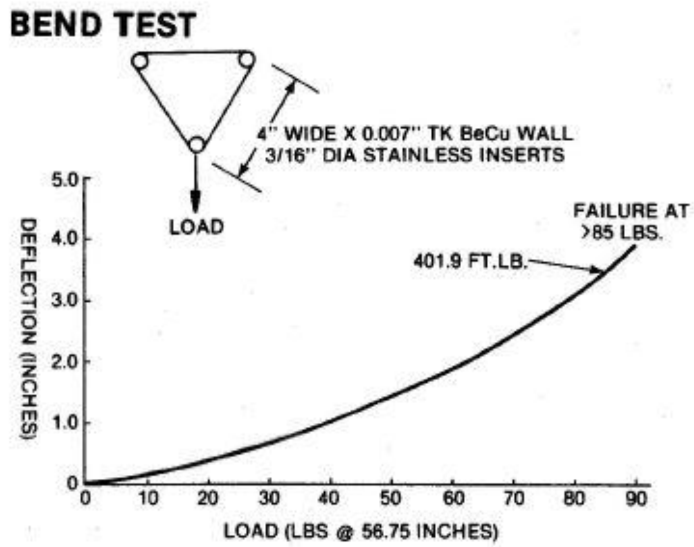


Triangular wire boom

9. Tri-beam

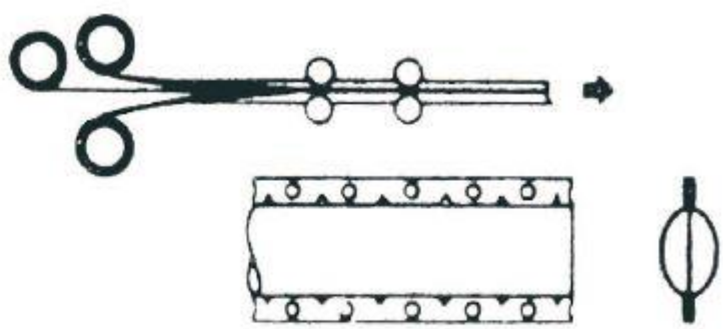


Tri-beam



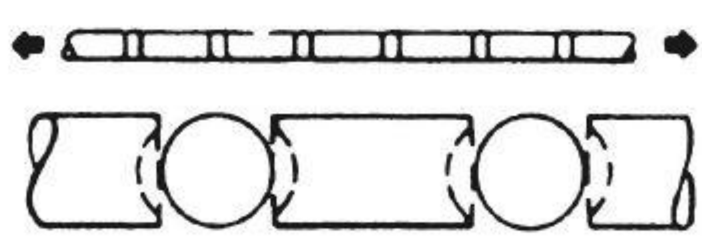
Result of bending test on Tri-Beam

10. Instarect



Instarect

11. Flexible tether

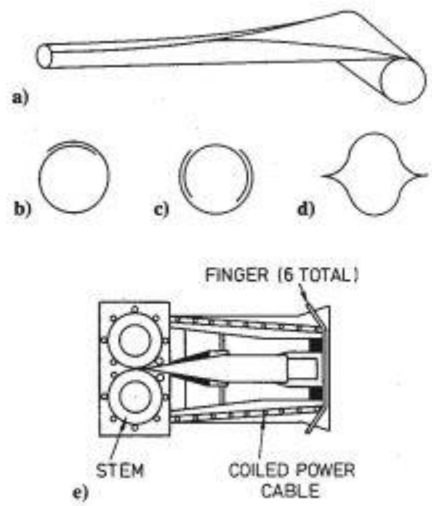


Flexible tether

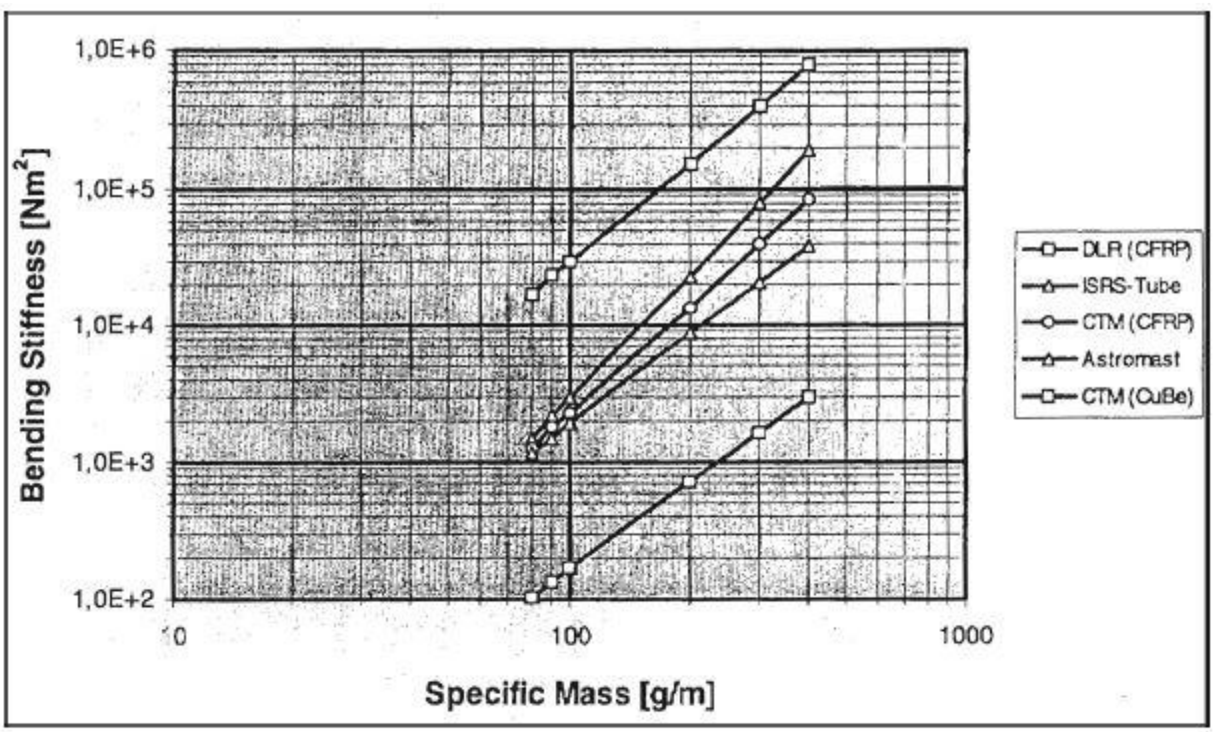
12. Thin-walled tubular boom

These structures increase ability of thin-walled shells to deform elastically. Number of configurations have been made due to its common use. It was mostly built from Beryllium copper, stainless steel, and CFRP.

13. Overlapping or singular boom (STEM)



(a) Tubular boom, (b-d)different cross sections, and (e) deployment cassette for bi-STEM



Overview of bending stiffness for various flexible shell systems.

14. Bi-STEM

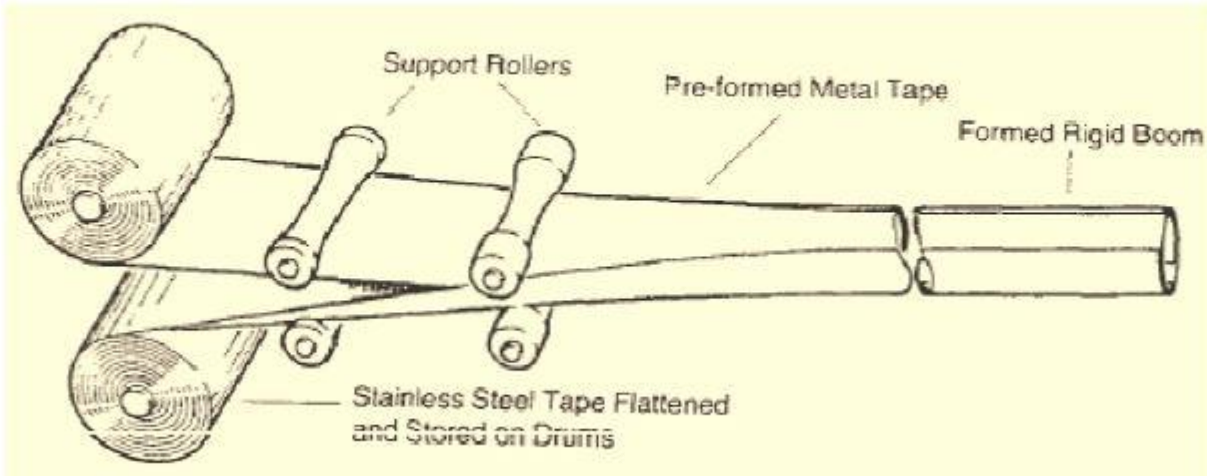
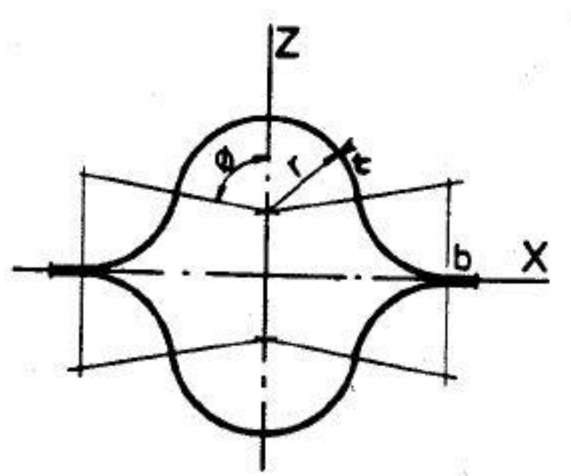


Illustration of the Bi-STEM

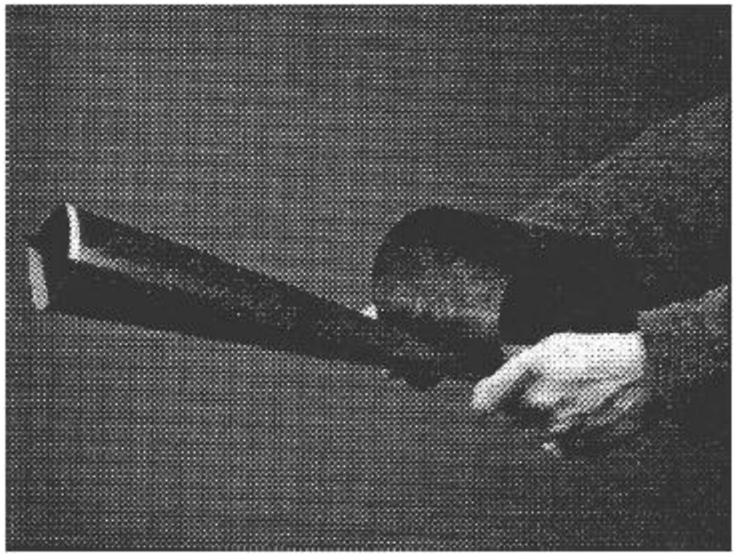
15. Interlocking and tablock Bi-STEM

Bi-STEM configuration can be improved in the future by interlocking the two deployed strips while they're deployed. Done by tapping inner strips in the edges and guiding them into outer strip. It improves the torsional stiffness. These structures were used in space industry in early procedure, but due to its complexity and its reliable problems, are no longer used.

16. Collapsible Tube Mast



Cross-section of collapsible tube



Collapsible tube

17. Bi-stable tubes

These materials are stable in two shapes; as a straight tube and compact coil. Booms produced by these composites have the advantage of more dense stowage, thus the container can be made smaller and lighter.

18. Stacer

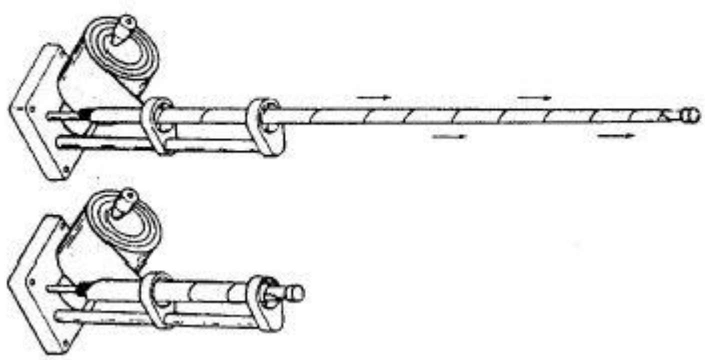
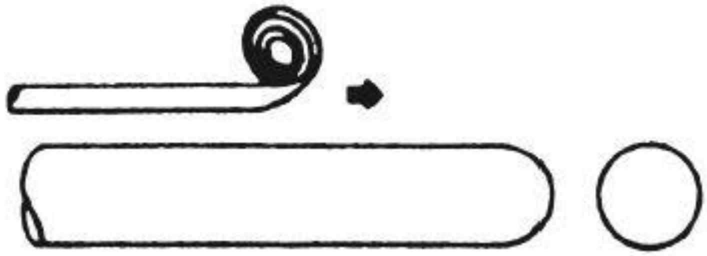


Figure 2.43: Back-wound spring helix

19. Inflatables



Inflatable tube rolled on reel

20. Jackscrew Deployed Boom

Jackscrew Deployed Boom Under Test

SNC Space Systems Jackscrew Deployed Boom is high strength and high stiffness truss. It deploys vertically without need of a special tool. The jackscrew boom provides multiple payload or cabling possibilities along the length of the boom. The jackscrew drive systems provide volume efficiency over canister-deployed booms.

Advantages are:

- Full structural integrity throughout deployment
- Allow mid-deployment spacecraft maneuvering or other loading without risk of collapsing
- Can be re-stowed after deployment

The main component consists of deployable boom assembly and deployer assembly.

Features	
• Purely linear/axial deployment	• High-force deployment/retraction
• Highly tailorable for thermal stability, strength, and stiffness	• Highly scalable and mass optimized
• Simple, high-reliability, high-tension deployment	• Full stiffness and strength during deployment
• Exposed payload interfaces throughout deployment and during pre-flight integration	

Applications	
• Solar array and solar-sail deployment and retraction	• Instrument deployment and retraction
• Antenna deployment/retraction	• Gravity gradient mass deployment and retraction
• Synthetic Aperture Radar (SAR) deployment and retraction	• Spacecraft separation

Product Specifications for a 10-Bay Jackscrew Boom		
• Dimensions: 190-in long x 15.5-in diameter	• 1st Bending Mode: 6.9 Hz	• Tip Torsion Stiffness: 13,594 in-lb/rad
• Mass: 11.7 lb	• 1st Torsion Mode: 16.4 Hz	• Tip Shear Stiffness: 25 lb/in

10-Bay Jackscrew Deployed Boom (stowed) *Deployed Boom Cantilevered with 11-lb Tip Mass (no offloading)*

21. K-truss boom

K-truss Boom with Quadrifilar Helical Antenna Under Test

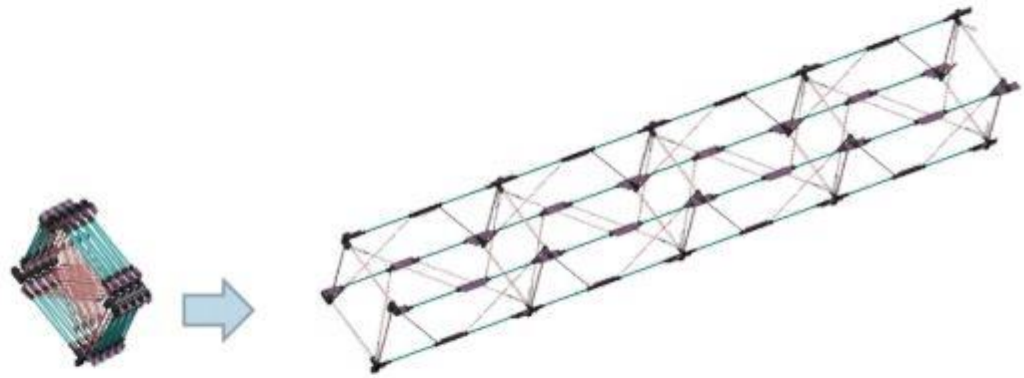
Sierra Nevada Corporation's (SNC) Space Systems K-truss Boom is an elastical boom which utilizes stowed energy for deploying. The K-truss boom deploys vertically. Therefore the K-truss boom provides cabling attachment points to allow the deployment of objects along the length of the boom at any cycle of deployment. It provides non-rotating deployment with thermal stability, precision, and repeatability, in addition to high stiffness and high strength. This type of boom simplifies deployable structures on small satellites by eliminating the need for a drive motor and electronics. This type of deployed structure is also applicable to many spacecraft that have been traditionally limited to fiberglass coilable type booms. This structure increase satellite application capabilities, improve reliability, and reduce costs.

Features	
• Exposed payload interfaces throughout deployment and during pre-flight integration	• Nonconductive/magnetically "clean" materials available for integrated antennae or magnetometers
• Highly tailorable for thermal stability, strength, and stiffness	• Highly scalable and mass optimized
• Predictable deployment behavior	• Zero deadband monolithic structure
• Elastically deployed "tape" joints eliminate motorized actuation mass	• Precision deployment and pointing accuracy of the payload

Applications		
• Solar array/solar-sail deployment	• Attitude control thrusters	• Gravity gradient mass deployment
• Antenna deployment	• Instrument deployment	• Magnetometer deployment

Product Specifications*	
• Dimensions: 101.5-inch long x 9.5-inch diameter	• 1st Bending Mode: 3.5 Hz
• System Mass: <15 lb	• Bending Stiffness: 1.14 lb/in

The stowed and deployed K-truss boom is shown below.



Stowed K-truss Boom Deployed K-truss Boom Section

3 Experiment

3.1 Basic concept

Most of the existing solutions use folding, bending or rolling of the solid components of the structure. A notable exception is inflatable structures where the gas pressure gives the integrity of the structures. This makes inflatable structures very efficient since gas has low mass, it can be stored in a small volume, and the shape of its container can be fit to available spaces. At the same time inflatable structures are somewhat unsafe. Leaking gas may cause failure of the structure, and it can also destabilize a satellite when it acts like a small rocket.

In my work I investigate a similar solution: a structure filled with solid foam instead of a gas. This structural concept has the same advantages as inflatable structures, but we avoid the risk of leaking. I chose to create deployable structures by filling plastic bags with polyurethane foam used in building industry, since these components are all cheap and easily available.

3.2 Properties of the material:

“Polyurethane is a polymer composed of organic units. Otto Bayer and his coworkers at IG Farben in Leverkusen, Germany, first made polyurethanes in 1937. Polymers are traditionally formed by reacting di- or triisocyanate with a polyol. Polyurethanes are used in the manufacture of high-resilience foam seating, rigid foam insulation panels, microcellular foam seals and gaskets, durable elastomeric wheels and tires automotive suspension bushings, electrical potting compounds, high-performance adhesives, surface coatings and surface sealants, synthetic fibers, carpet underlay, hard-plastic parts, and hoses.

One of the most desirable attributes of polyurethanes is their ability to be turned into foam. Making a foam requires the formation of a gas at the same time as the urethane polymerization (gellation) is occurring. The gas can be carbon dioxide, either generated by reacting isocyanate with water or added as a gas; it can also be produced by boiling volatile liquids. In the latter case heat generated by the polymerization causes the liquids to vaporize. The liquids can be HFC-245fa HFC-134a , and hydrocarbons such as n-pentane.”

Quoted from https://en.wikipedia.org/wiki/Polyurethane

“Advantages of the material:

Filling the Gap Between Rubber and Plastic

Polyurethanes are outstandingly able to withstand more loads than rubber because they are harder than rubber and yet more flexible than plastics. Their flexibility is accountable for their strength and remarkable ability to resist impact.

Abrasion Resistance

Polyurethanes are the perfect choice for applications against severe wear regardless of low temperature. For some decades now, they have been the most used materials for environments that are highly abrasive owing to their super ability to resist abrasion. No other form of elastomers, metals, and plastics has a better abrasion resistance than polyurethanes. Their abrasion resistance ability is rated to be 10 times better than what other materials can provide.

Oil and Chemical Resistance

Like their abrasion resistance ability, the properties of polyurethane materials are highly capable of resisting oil and chemicals. This enables them to maintain stability (with minimal swelling) in water or oil etc. If you are looking for elastomer materials to use in subsea, then polyurethanes should be your ideal choice.

Affordable manufacturing process

Productions such as prototypes as well as one time products or one-off parts are often manufactured using polyurethanes.

Polyurethane Resilience

Resilience is generally a product of hardness. Polyurethanes are the perfect choice for elastomer applications that can absorb shock. They have a high vibration frequency or outstanding ability for quick recovery. Their remarkable resilience ensures polyurethanes are very tough materials."

Quoted from: https://plantech.com/benefits-advantages-polyurethane/

"Advantages of Spray Polyurethane Foam (SPF)

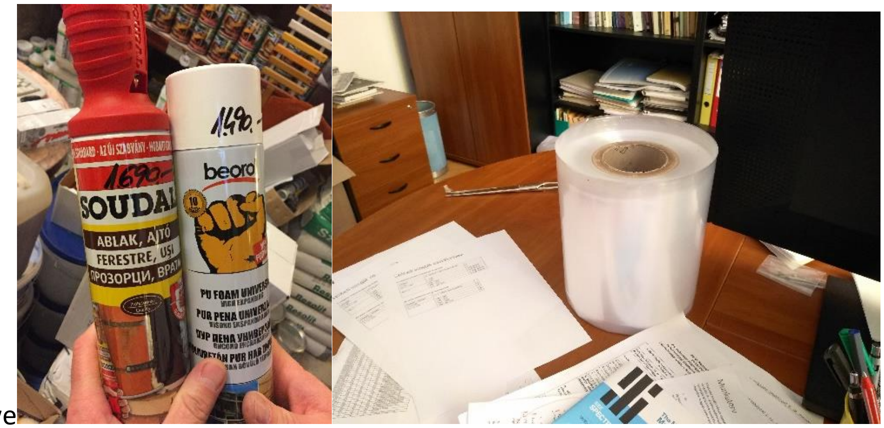
- SPF retards air transfer, minimizing air infiltration and the noise, pollutants and pollen that often infiltrate buildings
- It can be applied to difficult to reach or architecturally complicated structure features, such as cathedral ceilings, thereby helping to increase building design creativity
- Some SPFs help control moisture and condensation and reduce the growth of mold and mildew
- Some SPFs add structural strength and can help a building withstand high winds and hurricanes"

Quoted from: https://polyurethane.americanchemistry.com/Polyurethane-Products-and-Benefits/

3.3 Method of the experiment

I filled up 6 plastic tubes (commonly used in pet stores) with diameter of 13.5 centimeters with different types of polyurethane foam mostly consist of 0.7 l. Some water has been added, which is necessary for foam formation. The bag was left open at one end for one day while the foam expanded to 3-4 times its fresh size, and hardened. A 0.7 l bottle of polyurethane foam forms about 1 meter long 13.5cm beam.

we



Photos of foam beams under construction

After forming the beams, we performed 3-point bending tests with spans of 60 cm or 1m, depending on the length of the beam. We used the Zwick Roell testing machine in the Czako Adolf Laboratory of the Department of Mechanics, Materials, and Structures. The experiment was displacement controlled: the displacement of the midpoint was increased at a rate of 10 cm/minute up to a point where the midpoint of the beam touched the base of the machine. The force-deflection curves were recorded. Some of the beams were loaded and unloaded several times to see differences between loading and unloading and the effect of degradation.

Photos of the experimental setup

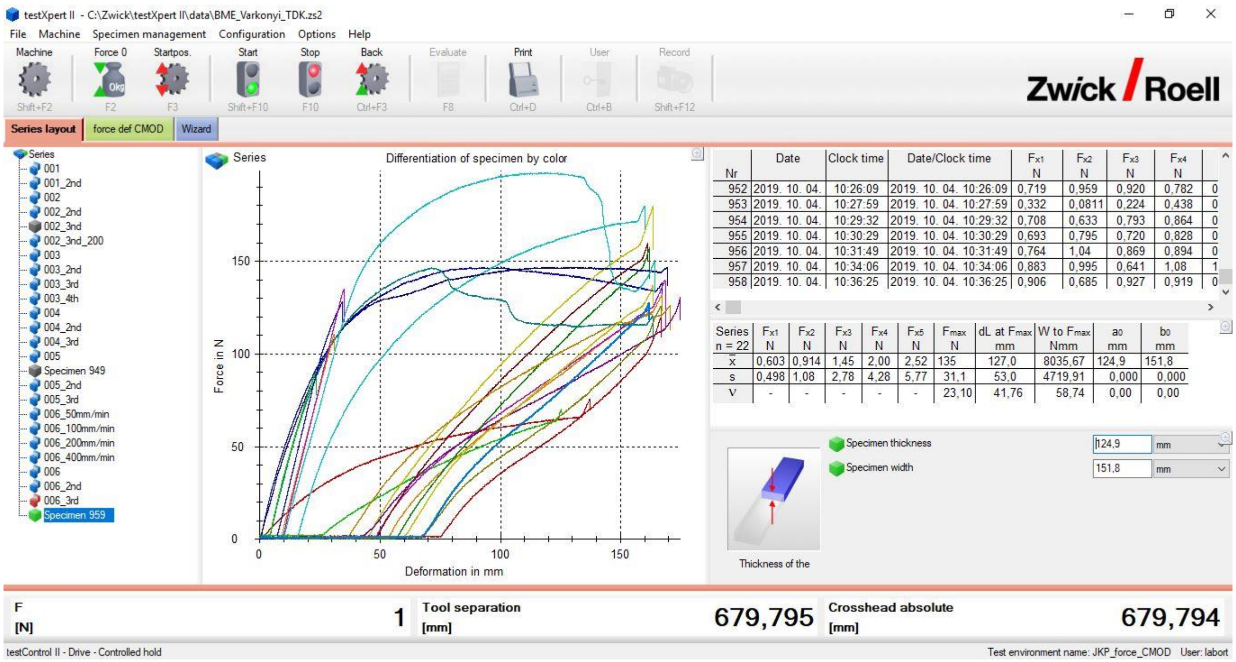
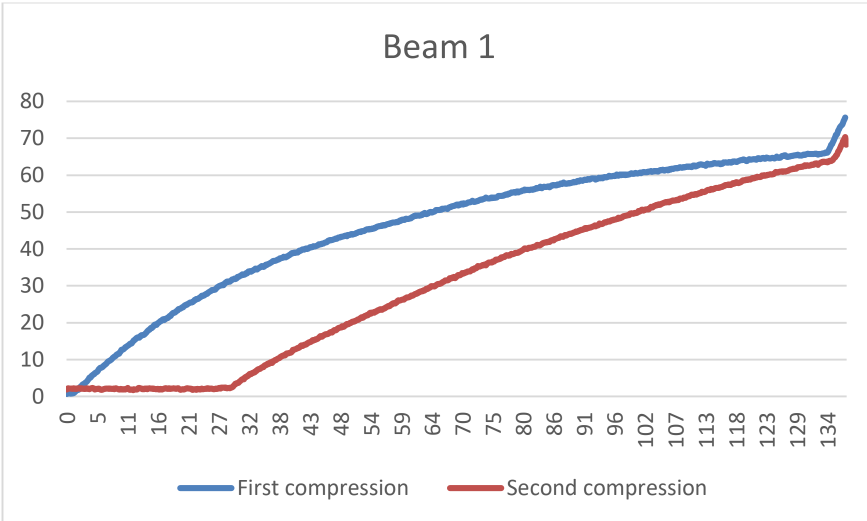
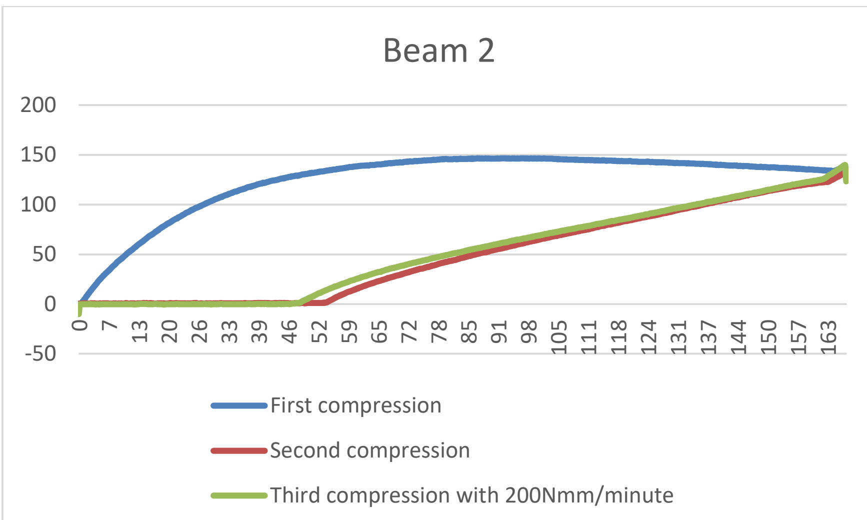


Illustration of the experimental results

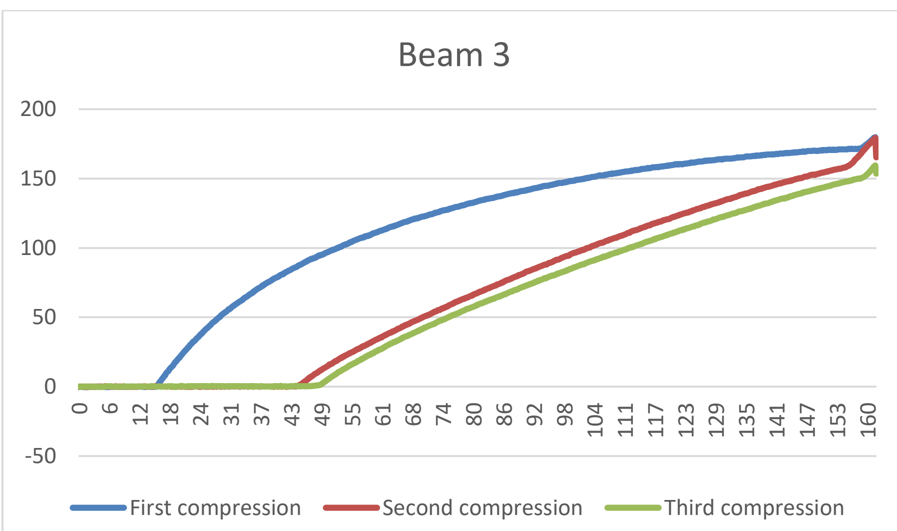
Failure of one of the beams at its midpoint



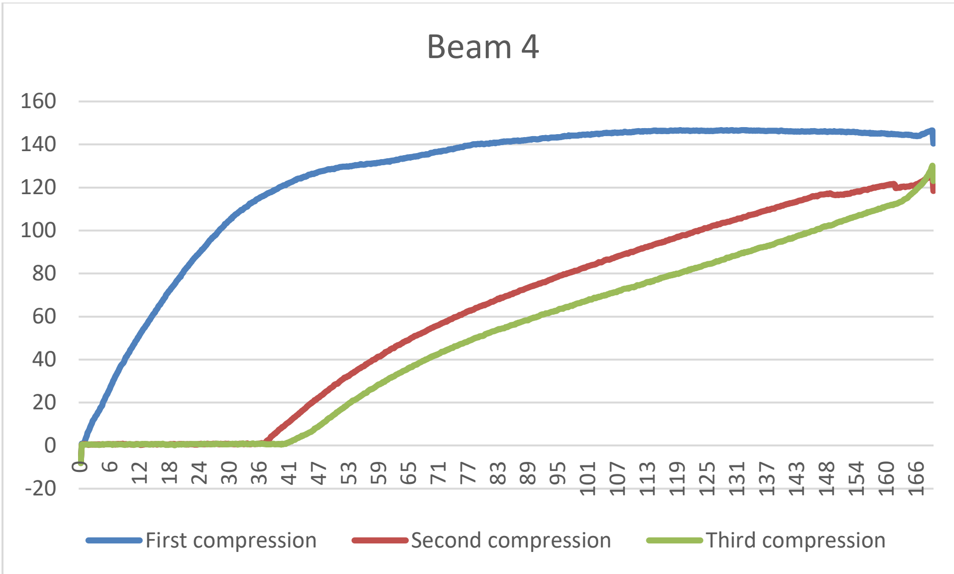
Beam 1
80
70
60
50
40
30
20
10
0
0 5 11 16 21 27 32 38 43 48 54 59 64 70 75 80 86 91 96 102 107 113 118 123 129 134
First compression
Second compression

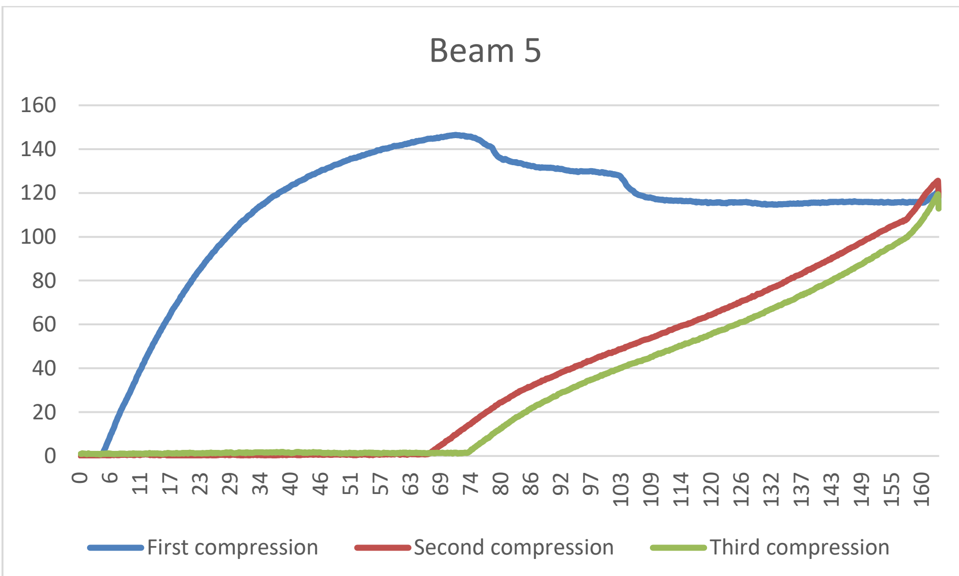


Beam 2
200
150
100
50
0
-50
0 7 13 20 26 33 39 46 52 59 65 72 78 85 91 98 105 111 118 124 131 137 144 150 157 163
First compression
Second compression
Third compression with 200Nmm/minute



Beam 3
200
150
100
50
0
-50
0 6 12 18 24 31 37 43 49 55 61 68 74 80 86 92 98 104 111 117 123 129 135 141 147 153 160
First compression
Second compression
Third compression





Force (vertical axis, in units of N) versus displacement (horizontal axis, in units of mm) curves of the beams

4 Estimation of beam properties

4.1 Estimation of mass and stowed volume

First I estimated the mass and stowed volume necessary for each beam. Each beam was longer than the span used in the bending test. To take this into account, I cut off the unused parts of each beam and measured the masses of the useful (m_{us}) and unused (m_{unus}) parts. The first one (m_{us}) was used as estimate of the mass of the structure. At this point I did not take into account the additional mass of the container so this is a rough estimate only. The stowed volume of the structure was estimated by $V_{us}=Vm_{us}/(m_{us}+m_{unus})$ where V is the volume of the PUR bottle. This estimation does not take into account the volume necessary for stowing the plastic bag and the volume of the opening mechanism of the container. The results are summarized in the following table

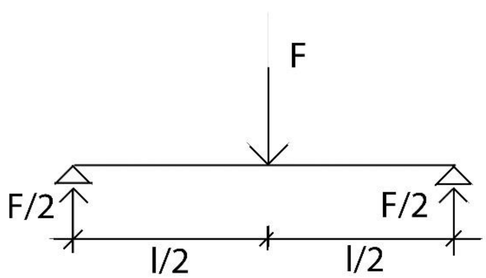
	Total mass	Mass of useful part	Mass of useless part	length of beam	Volume of container	Estimated stowed volume of structure
	(x0.1kg)	(x0.1kg)	(x0.1kg)	(m)	(liter)	(liter)
Beam 1	5	3.5	1.5	1	0.8	0.56
Beam 2	5.5	2	3.5	0.6	0.8	0.29
Beam 3	8.7	2.3	6.4	0.6	1.6	0.42
Beam 4	4.5	2	2.5	0.6	0.7	0.31
Beam 5	4.1	3	1.1	0.6	0.5	0.36

4.2 Estimation of bending moment capacity

The bending moment capacity can be calculated from the expression

$M_{max}=Fl/4$

which is true for simple supported beams with length l loaded by force F in the middle.



So the bending moment capacity can be calculated from the maximum value of the force when a beam is loaded for the first time. I could do this only for beams 2,4,5,6. Beams 1,3 did not reach the maximum value of the force.

4.3 Estimation of bending stiffness

The deflection of a linear elastic beam in a 3-point bending test is

$D=Fl^3/(48k)$

where D is deflection and k is the bending stiffness.

From this expression, I can estimate k as

$k= (F/D)\ l^3/48$

F/D is the steepness of the force-displacement curve. In my experiments, these diagrams are curved. An average steepness was estimated as:

Steepness $=F^*/D^*$

where F* is 1/3 of the maximum value of the force, D* is the deflection measured under F* minus the initial deflection. The curves of the first-time loading were used for this. For beams 1 and 3, I used the largest value reached during the experiment as maximum value.

4.4 Effect of repeated loading

For all beams, the loading was repeated several times. These results confirm, that the structure is more or less elastic when the force is not too large, its behavior is similar to elastic-plastic, when the force is large. For beam 1 and 3, Fmax was not reached before the beam touched the underplate.

quantity	F_{max}	D at F_{max}
unit	N	mm
Beam 1	75.85849	137.1751
Beam 1 2nd	70.34658	125.3442
Beam 2	146.7945	101.4509
Beam 2 2nd	132.0689	167.2776
Beam 2 3rd	139.909	168.4017
Beam 3	179.9791	159.9676
Beam 3 2nd	179.5833	163.5175
Beam 3 3rd	159.7308	161.3476
Beam 3 4th	157.4975	162.0142
Beam 4	146.8377	132.3076
Beam 4 2nd	126.0685	170.5842
Beam 4 3rd	130.5643	174.8412
Beam 5	146.5273	71.41756
Beam 5 2nd	125.76	166.7109
Beam 5 3rd	119.5572	166.7123

Maximum force and corresponding deflection of beams

quantity	F_{max}	deflection at F_{max}	1/3 F_{max}	deflection at 1/3 F_{max}	Steepness	M_{max}	bending stiffness
unit	N	mm	N	mm	N/mm	Nm	Nmm^2
Beam 1		133.64	22.07	16.08	1.20		25000000
Beam 2	146.54	92.68	48.85	10.41	4.87	21.981	21915000
Beam 3		157.23	57.36	15.22	1.87		8415000
Beam 4	146.43	135.52	48.81	11	4.43	21.9645	19935000
Beam 5	146.45	71.46	48.82	9.3	3.66	21.9675	16470000

5 Quantities measuring the performance of the structure

A beam is considered good if it has high moment capacity and high stiffness. The cost of the beam depends on its mass and stowed volume. I need indicators of performance that do not depend on the length and the size of cross-section of a structure, but they depend on the type of that structure. So I chose the following 4 quantities where all values are given in units of kg, N, and m.

	$(Mmax)^2 l^3/m_{us}^3$	$(Mmax)^2 l^3/V_{us}^3$	$k*l^2/m_{us}^2$	$k*l^2/V_{us}^2$
	1000*N2m5/kg3	109N2/m4	10^{-6}*Nm^4/kg^2	10^3*N/m^2
	moment capacity relative to mass	moment capacity relative to volume	stiffness relative to mass	stiffness relative to volume
beam 1			48828125	39062500
beam 2	13.04543775	203.8349648	9245390.625	12327187.5
beam 3			443759.7656	1183359.375
beam 4	13.02586003	303.8101464	12553819.24	14646122.45
beam 5	3.86056845	833.8827852	28460160	23716800

6 Conclusions and future plans

In my work I created PUR foam beams. I determined their moment capacity and bending stiffness using lab experiments. I developed quantities that measure their performance when they are used as deployable structure.

As next stage of my work I will calculate the performance values of existing deployable structures, and compare them with the performance of foam beams. I will need to do a careful literature search for this, since very little data is available about products of space industry.

Later I also have to examine many other issues of practical application. For example, PUR cannot be used in space because it has low tolerance of UV light It probably does not tolerate space radiation (see: https://www.nasa.gov/analogs/nsrl/why-space-radiation-matters). Also creating a foam on earth is not the same as creating a foam in vacuum. So many further examinations are necessary and new materials may also be considered.

7 Acknowledgement

Many thanks to Péter László Várkonyi for his guidance and help through this paper and Károly Péter Juhász for his help in the lab experiments.

8 References

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