Rigidization of Gossamer Space Structures

Abstract
Gossamer technologies offer the potential for large, lightweight structures to be stored in compact form for launch and deployed to their full dimensions in space. The use of materials that enable these inflated structures to become rigid in orbit may enable the development of large space structures that would otherwise not be feasible, such as large antennas, solar sails, solar arrays, and reflectors. This report outlines advancements and opportunities in the rigidization of inflatable space structures and offers a critical assessment of their feasibility given the current states of the underlying technologies.

Introduction
The wide range of applications offered by lightweight inflatable structures make them promising candidates for future space missions. Similar to other inflatable structures, the initial deployment of inflatable rigidizable structures occurs with a pressurizing gas or foam. Unlike traditional inflatable structures, which require a continuous source of gas to keep the structure rigid as gas inevitably escapes the structure, Gossamer inflatable structures are rigidized through a mechanical, thermal, or chemical process. This makes inflatable rigidizable structures ideal for applications where the final structure is large and must maintain its structural integrity for more than a few weeks. By storing the structures in a flexible state on liftoff and rigidizing in flight, gossamer structures could enable space systems to be built that would have otherwise been infeasible.
This promise has fueled steady research into rigidization techniques and technologies since the start of the space age, but only a few expendable structures have flown in space [1]. The majority of large structures deployed in space are comprised of rigid components that then change their geometry with actuation mechanisms [2]. As with many maturing technologies, the approaches to the implementation of rigidizable gossamer structures is diverse. Rigidization technologies are typically organized in the literature by their technical requirements, the geometric form of their elements, or the process used to make the structure rigid. This paper will organize rigidization techniques into categories according to the rigidizing material and the primary rigidizing process as shown in Table 1.

Table 1. Gossamer rigidization technologies categorized by material and process.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mechanical</th>
<th>Chemical</th>
<th>Thermal</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>Stretched Metal Laminates</td>
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<tr>
<td></td>
<td>Photolyzable Structures</td>
<td></td>
<td></td>
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<tr>
<td>Polymer Resin</td>
<td>UV Setting Gas and vapor curing</td>
<td>Thermosetting Glass Transition</td>
<td>Solvent boil-off</td>
<td></td>
</tr>
<tr>
<td>Foam</td>
<td>UV Setting</td>
<td>Thermosetting</td>
<td></td>
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**Mechanical Rigidization**

**Stretched Metal Laminates**

Stretched metal laminates are the earliest and most mature form of rigid gossamer structures. These structures are created by inflating a metal structure until the metal yields, and then slowly depleting the gas. Once pressure is removed, the stressed metal maintains its shape. Some examples are the Explorer IX and Explorer XIX missions, which demonstrated the concept in the early 60’s [2]. Explorer XIX, which measured the density of Earth’s upper atmosphere, is shown in a ground test in Figure 1.
These structures are the most common rigidizable gossamer structures because they are simple to manufacture, rigidize predictably, and have little to no outgassing. However, they have limited load carrying capacity because the laminate typically has a thickness on the order of 100 μm. The overall thickness of metal present in the laminate has to be very small to prevent debonding during deployment and thermally induced stresses. Furthermore, only simple geometries such as spheres and cylinders are feasible because stresses must be anisotropic.

**Photolyzable Structures**
Photolyzable structures consist of at least two materials: a thin and flexible film and an embedded metal frame. When the structure is deployed, the photolyzable film acts as a bladder that draws the metal frame into its final shape. After a few days or weeks exposed to solar radiation, the film vaporizes and leaves behind the wire frame [4]. The only two missions known to have used this technique are the US Air Force’s PasComSat (Figure 2) and Gridsphere experiments, which acted as passive communication satellites with low aerodynamic drag [5].
Chemical Processes

UV Setting
The use of solar UV for curing space-rigidized objects frees rigidizable gossamers from many of the geometric constraints of mechanical rigidization techniques. In this method, a composite material is impregnated with a UV-setting resin and cured upon deployment. The source of UV radiation can be either the sun or internal lamps. This method has been studied in combination with foam driven insulation, internal lamps operating at various wavelengths, and with passive solar radiation [4] [6]. This method is by far the most popular in the literature, but has not yet been demonstrated in orbit [4]. Figure 3 shows a passive UV-setting radiation experiment.
There are three primary architectural choices related to rigidization in designing a UV setting gossamer structure: active or passive UV radiation source, the type of reinforcing fiber, and the resin. A solar UV radiation source is simple, but less controlled than an active UV radiation source such as lamps. Uneven curing can cause warping, so active UV radiation sources are typically chosen. The choices of reinforcing fiber, if required, are limited because UV radiation must penetrate all layers of the laminate.

Gas and Vapor Curing
Gas and vapor curing techniques are a novel set of methods for rigidizing resins. In these processes, a polymer matrix or foam is excited by a gas or vapor catalyst that starts a curing process. The catalyst can be stored with the inflation gas to initiate passive curing. Although this process is attractive for its simplicity, it causes significant outgassing and has fallen out of favor relative to UV and thermal processes.

Thermal Processes
Thermosetting
Thermally cured composites are attractive because they have a long heritage in terrestrial applications and have high structural performance [8]. Thermosetting structures, as with all thermal and chemical processes described in this paper, are formed from one or more flexible structural materials that are impregnated with a resin that cures when exposed to heat. These resins are compatible with a wide range of geometries, resins, and curing profiles. They also typically have low out-gassing, low CTE, high stiffness, and high strength [4]. Despite these benefits, thermosetting resins have only recently been considered as serious candidates for rigidizable gossamer structures because they have historically suffered from short shelf lives.
However, advancements in thermosetting resin technologies in the late 1990’s has made them a promising technology. Although active rigidization requires significantly more power and mass from resistive heating systems than lamps in UV-curing resins, they typically have better strength, CTE, and stiffness [8].

**Glass Transition**
Glass transition composite materials, also called second order transition change (SOTC) or Sub-$T_g$ materials, consist of a thermoplastic or thermoset that is heated above its glass transition temperature to soften them for deployment and then are cooled to become rigid. Prior to deployment, spacecraft radiant energy or resistive heating elements are used to maintain a high material temperature. Once the inflation gas fills the structure’s volume to create the desired shape, the structure radiantly cools and hardens. As with thermosetting resins, glass transition gossamers have experienced significant ground development but have limited flight heritage [8]. L’Garde Inc. has developed many glass transition resins in their boom designs, most notably a 20-meter solar sail demonstrator and a Kevlar glass transition boom flown on the Cibola Flight Experiment [9].

**Physical Processes**

**Solvent Boiling**
Some resins can be kept flexible with softening solvents, which then boil off after deployment. This method is considered appealing for its simplicity, but the possibility of uneven drying and large outgassing have made it impractical [4]. Gelatins, hydrogels, and polyvinyl alcohol were proposed as potential rigidizable materials in the early 1960’s [11] [12] [13], but only some
demonstration structures have been completed recently. L’Garde’s IRSS truss, which used a hydrogel, is shown in Figure 4.

![Figure 4. L'Garde's IRSS truss using rigidized hydrogels [10].](image)

**Technology Readiness**

These technologies can be compared by evaluating their potential utility and their maturity. In this analysis, utility is a qualitative assessment of how each technology fulfills current commercial and civil space mission needs. This assessment evaluates utility by two primary factors: (1) Each technology’s ability to fulfill primary structural functions as booms, antennas, reflectors, solar arrays, and any specialty structures that the technology may enable; and (2) system-level impacts such as outgassing, power budget, ratio of stored volume to expanded volume, and thermal requirements. The severity of system-level impacts is mission dependent, so an approximation is made based on the current portfolio of operating and proposed missions that have elements that could employ rigidizable gossamer structures.

Technology maturity is measured using NASA/DoD Technology Readiness Levels (TRL) [14]. TRL is often used for space missions as a proxy for development cost and risk. This tradespace, shown in Figure 5, is appropriate for technology roadmapping and portfolio...
planning, but inappropriate for evaluating the use of a technology in a mission-specific application. In those cases, the utility of a given technology should be evaluated using mission-specific requirements and objectives.

![Figure 5. Tradespace of rigidizable gossamer technologies for space applications.](image)

Attractive technologies are in the upper right-hand corner, where high technology readiness meets high utility. This is often called the “utopia point.” Legacy non-gossamer structures are included in the tradespace to compare gossamer rigidizable technologies to mature technologies in use today. The values corresponding to this analysis are shown in Table 2.

**Table 2. TRL and Utility of rigidizable gossamer technologies for space applications arranged by process.**

<table>
<thead>
<tr>
<th>Process</th>
<th>Technology</th>
<th>TRL</th>
<th>Utility</th>
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</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Stretched Metal Laminates</td>
<td>9</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Photolyzable Structures</td>
<td>9</td>
<td>Low</td>
</tr>
<tr>
<td>Chemical</td>
<td>UV Setting</td>
<td>5</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Gas and Vapor Curing</td>
<td>3</td>
<td>Med</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermosetting</td>
<td>4</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Glass Transition</td>
<td>8</td>
<td>Med/High</td>
</tr>
<tr>
<td>Physical</td>
<td>Solvent Boiling</td>
<td>4</td>
<td>Low</td>
</tr>
<tr>
<td>--</td>
<td>Legacy Non-Gossamer</td>
<td>9</td>
<td>Med/High</td>
</tr>
</tbody>
</table>
Conclusions
Within the set of rigidizable gossamer technologies, Thermosetting, UV Setting, Glass Transition, and Photolyzable structures are pareto optimal and should be pursued further with additional investment. Evaluating gossamer technologies alone suggests that Glass Transition technologies are the best balance of TRL and utility and should be pursued further. However, including legacy non-inflatable deployable structures in the evaluation shows that Glass Transition technologies are generally less attractive than existing non-gossamer technologies. This suggests that absent a near-term need to employ rigidizable gossamer structures, an investment should be made in increasing the readiness of Thermosetting and UV Setting technologies, and investments in Glass Transition technologies should be isolated to increasing mission-specific utility. Furthermore, this analysis suggests that dominated technologies such as Gas & Vapor Curing and Solvent Boiling should not be pursued.
References


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