Small Satellites and Structural Design

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Abstract

The cost to orbit for 1 kg of mass, using an Atlas launch vehicle, is currently around $20,000 and represents the high end of the range of launch costs. The latest technology represented by a SpaceX Falcon launcher, an ISRO Polar Satellite Launch Vehicle (PSLV) or a small satellite launcher such as the Electron all are significantly less costly. Nevertheless launch cost even by the most efficient launchers into low Earth orbit (LEO) remains quite expensive. In the case of very large space craft such as a high throughput satellite for telecommunications with mass of 5000–10,000 kg, the savings that might come from a highly efficient structural frame that reduces the overall mass by 100 kg, or alternatively allows the payload to be 100 kg larger, might be worth

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something like $2 million dollars per satellite launched. Even for small satellites such as a 3 unit cubesatellite, a very light weight, high strength frame that is thermally stable, and is not adversely affected by high radiation levels, clearly has good value. At this size, however, it is more common to use a lower cost material such as aluminum alloy.

Frame designs for small satellite are getting increasingly more sophisticated. It is possible that a primary frame or even a secondary structure such as a solar cell panel to allow the inclusion of an additional heat sensor, star tracker, or other safety feature or capability to be integrated into the harness design.

Some designs might even allow the addition of a passive de-orbit device that allows the small satellite to more quickly deorbit. In short, some design features for primary or secondary structures are optimized by determining and adding features that reduce both the mass and available usable volume of a small satellite.

The addition of new additive manufacturing capabilities to the arsenal of capabilities available to those who design and manufacture small satellites can increase the performance, cost-effectiveness, or safety of a project.

This article addresses all aspects of a small satellite's design in terms of its mass, strength, volume efficiency, thermal and radiation protective qualities, reliability, and overall structural aspects and efficiency as measured by all of these factors. It analyzes what aspects have been improved over time and what the prospects are for the future to increase structural design and performance. This article analyzes the status and future direction of research related to primary structure related to small satellites. This primary structure is key to a satellite surviving launch and deployment, its operational integrity throughout the spacecraft lifetime up to its end of life. Also considered is the nature and performance of its secondary structures. The structural integrity of these secondary systems are also necessary to support the successful operation of subsystems or components such as solar panels, thermal blankets, radiation shielding, instrument mounts to be properly anchored so as to operate reliably, and so on. Progress is being made on primary and secondary structure design and performance. In many instances, the design of the small satellite and its structural elements are being integrated with essential elements of the spacecraft to reduce mass, increase volume for payload systems, or otherwise increase efficiency. These innovations are sometimes known as multifunctional elements when structures, panels, wiring harnesses, sensors, and other devices are integrated together in the design.

Keywords

Additive Manufacturing · Cubesat · Carbon/epoxy composites · Components · Integrated components · Kits · Longitudinal and Transverse Strength · Micro-lattices · Multifunctional structures · Opportunity costs · Primary structure and secondary structure · Reliability · Resilience · Shear strength · Small satellite · Spacecraft structural units · Systems engineering · Thermal performance

1 Introduction

The first satellites that were launched were, in fact, small satellites. They were virtually all small platform carrying experimental packages to test out new space technologies. The first emphasis was on testing radio, sensors, and experimental devices and the buses or platforms that carried them were not of particular or special concern. This was particularly the case with regard to the rocket systems of the U.S.S.R. that had developed very powerful rocketry. Some of the earlier soviet satellites in the Sputnik and especially the Molniya series resembled craft that looked more like washing machines than delicately engineered spacecraft designed to reduce mass. In the USA, which had less capable launchers, the design focus was different. The US designers of spacecraft, very early on, began to conceive of satellites buses that had the greatest strength but also required the least amount of mass. The shift from all governmental space operations to commercial systems in US programs, such as Relay (RCA), Telstar (AT&T), Syncom (Hughes), and Early Bird (Intelsat and Hughes), led to research and development to create spacecraft buses that were structurally sound but as light in mass as possible (Pelton 1974).

This led to the development of carbon-epoxy composite structures for the primary structure of a satellite. This type of composite for the primary structure was found to be very strong and the lightest in mass in comparison to such materials as steel, titanium, or metal alloys. These very strong fibers were also extremely resistant to thermal expansion and shear characteristics and still retain compressive strength in both longitudinal and transverse dimensions. As will be discussed later, these primary structural elements can be designed to incorporate other key elements of the satellite's design such as wiring harnesses, sensors such as sun or thermal sensors, etc. Table 1 shows these characteristics for a commercial available carbon fiber/epoxy resin material that is readily now available. Such composites are not only used for the design and construction of spacecraft, but also automobiles, aircraft, and other products where aspects such as strength, durability, and light weight are desirable construction qualities (Carbon/Epoxy Composite 2019).

The use of carbon fiber/epoxy resin composite materials, because of their light weight, thermal stabilities, longitudinal and transverse strength qualities, and durability, became quite common for satellite structure. Indeed this type of composite has been used in the structural elements in the manufacture of a very large number of satellites. Indeed these types of carbon/epoxy are finding their ways into components for aircraft, automobiles, and many dozens of other products. The smallest satellites such as cubesats, pocketques, or chip satellites

Table 1 The strength, shear, and thermal expansion characteristics of carbon/epoxy resin composites

Property	Units	Value
Coefficient of thermal expansion – longitudinal	$\times 10^{-6}\ K^{-1}$	2.1
Coefficient of thermal expansion – transverse	$\times 10^{-6}\ K^{-1}$	2.1
Compressive strength – longitudinal	MPa	570
Compressive strength – transverse	MPa	570
Density	$g\ cm^{-3}$	1.6
Shear modulus – in-plane	GPa	5
Shear strength – in-plane	MPa	90
Ultimate compressive strain – longitudinal	%	0.8
Ultimate compressive strain – transverse	%	0.8
Ultimate shear strain – in-plane	%	1.8
Ultimate tensile strain – longitudinal	%	0.85
Ultimate tensile strain – transverse	%	0.85
Volume fraction of fibers	%	50
Young's modulus – longitudinal	GPa	70
Young's modulus – transverse	GPa	70

The above characteristics are those of RS Stock No. 764-8700, RS Stock No. 764-8703, RS Stock No. 764-8716, and RS Stock No. 764-8707, but they are generally indicative of carbon fiber/epoxy resin composite materials

typically end up not with composites but more likely something like a metal alloy such as a light weight but relatively strong aluminum alloy which is sufficient to the design, since these smallest of satellites tend to be volume limited and not mass limited.

2 Optimized Design of Small Satellites and Structural Design

An optimized design might not be used to reduce the mass of the small satellite but to add additional features or capability. Altering the mass of a small satellite's structural features can thus be seen in the context of an opportunity cost. A better primary structure in terms of lower mass, greater volume, acceptable longitudinal or transverse strength, and or thermal qualities might also be evaluated in terms of allowing additional capability to be added to a small satellite design. Less mass associated with structural design could be reinvested to increase a small satellite's performance, safety features, reliability or ability to de-orbit at end of life.

Indeed a good satellite designer, despite its mass and dimensions, always considers the aspect of "opportunity cost." This is to say that if I can reduce the cost, performance, or mass of a satellite in one aspect of its design, can I produce or can I reinvest that additional mass or volume, etc. to achieve a better result. If I have less mass associated with structure can I increase another capability such as power or processing speeds to produce better overall results in terms of performance of the mission objectives. Systems engineering and assessing opportunity costs are a closely related activity, especially in the world of small satellite design.

The best small satellite structural design is not just limited to its mass, strength, and thermal qualities. The other crucial element is the extent to which it allows the efficient assembly and performance of all the components essential to a small satellite's performance. When one acquires a solar cell panel, that panel could be designed as a structural element of the small satellite and it might also integrate a magnetotorquer or sun sensor or thermal sensor into its design so that the ultimate payload might be more capable. In short, the design of a small satellite such as a cubesat involves volume efficiency as well as mass efficiency. Of the two, volume efficiency is more important, but not if volume efficiency risks reliability and resilience.

3 Small Satellite and Kits and Standardized Structures

There are several ways that one might approach the design, manufacture, test, and deployment of a small satellite. One might start with the idea of doing the entire design and manufacture of a small satellite on a vertically integrated basis either in-house or through a general contractor. This entity will design and try to optimize all aspects of small satellite design, particularly if it is for a large-scale constellation where thousands of small satellites are to be launched. In this case, the idea is to have a structure that is high in longitudinal, transverse, and shear strength, thermally stable, as low in mass and volume as possible, and perhaps adaptable to accommodate elements such as wiring and sensors, and hopefully also low in cost of manufacture and assembly.

The other approach is to acquire subsystems and components from reliable suppliers who specialized in a particular area such as solar panels, magnetotorquers, digital processors, thermal blankets, sun sensors, star trackers, or suppliers of payload systems for telecommunications, networking, remote sensing, data relay, etc. Even prime contractors tend to obtain particular components rather than manufacture every aspect of a satellite.

In the world of small satellites and especially very small units such as at the level of cubesats or qubesats and most particularly when the project is a one off or very limited number of satellites, the ordering of components or kits from specialized suppliers can make a good deal of sense.

Suppliers such as Pumpkin or Innovative Solutions in Space (ISIS) for instance can provide small satellite structures from 1 units up (Pumpkin for instance can provide 1 unit, 6 unit, and 12 unit structural frames). These kits for a cube satellite tend to be manufactured in materials such as an aluminum alloy. The skeletonized structural frame pictured in Fig. 1 by Pumpkin is fabricated from a strong alloy known as Aluminum 5052-H32. This alloy is described as having corrosion resistance and good workability to create a skeletal structure and resistance to metal fatigue and ability to be easily welded. Despite its modest weight, it at least has moderate strength. Since it is used in gas tanks, aircraft fuel lines, appliances, and

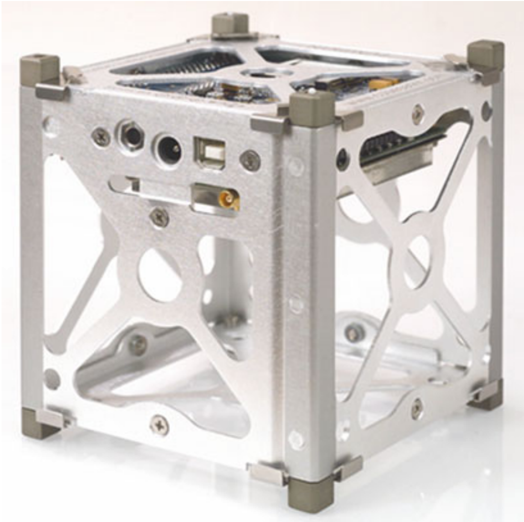

Fig. 1 A skeletal cubesat frame from an aluminum alloy. (Graphic courtesy of Pumpkin)

other applications, its cost is not high. Only in larger microsats and minisats is it common to go to carbon/epoxy composites. See Fig. 1.

The same is true of femtosats (i.e., chipsats) and picosats (i.e., pocketqubes). The systems engineering task in terms of designing the structural elements of these types of small satellites is finding ways to conserve available volume much more than mass. The logic of using kits or assembled units at the level of femtosats and pocketqubes is increasingly clear because the designers of such types of small satellites have already been forces to conserve mass and volume while also meeting structural requirements for strength, shear, thermal integrity, etc. Supplier of kits and launch intergrators for PocketQubes are limited. These include Alba orbital, KSF Space, and GAUSS Srl (see Fig. 2).

The following are some of the suppliers of primary structural systems for satellites at the cubesat level (typically 1 unit up to 6 units and now in some cases up to 12 unit structures). The trend line is that continuing progress has been made in the development of new standards and cost effective structures. Recently, 12 unit structures have been developed by several providers and on the other end more options are beginning to occur with regard to pocketQube units that are 5 cm × 5 cm × 5 cm small satellites that are available for quite small experiments. The fact that the International Space Station is now equipped with dispensing systems that can handle everything from pocketQubes to 12 unit cubesats and thus small satellites from 200 mg to around 90 kg has helped this standardization of structural systems and help lower the cost of such types of smallsats (NASA State of the Art 2018).

- Complex Systems and Small Satellites (C3S)
- Endurosat
- GOMspace

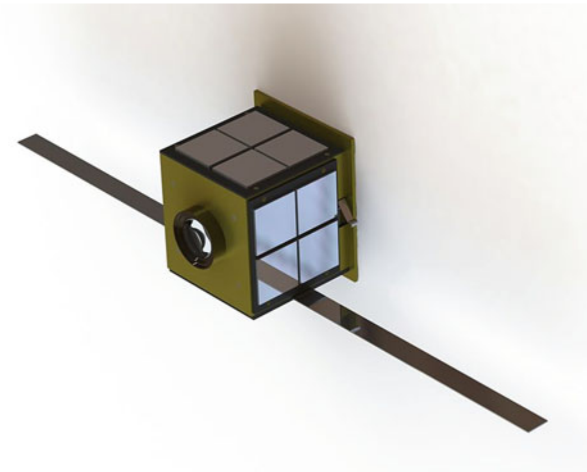

Fig. 2 A pocketqube picosat with camera. (Image courtesy of Alba orbital)

- Innovative Solutions in Space (ISIS)
- NanoAvionics
- Pumpkin
- Radius Cubesat Structures

There are of course other providers and the above list is not intended to be exhaustive. This is the current list of global suppliers for cubesat structural suppliers that appears in the NASA State of the Art of Small Satellite Technology report in their section on Structures, Materials, and Mechanisms (NASA State of the Art 2018).

4 Small Satellite Structure and Additive Manufacturing

One of the key newer elements in the manufacture of small satellites is the introduction of additive manufacture to the building of everything from cubesats to minisats. Additive manufacture can provide a number of advantages to this process.

There are several ways that so-called 3D printing can provide advantages in this regard. If the outside structure and wiring harness for a small satellite are integrated, this can expand the size of the internal volume to accommodate a larger payload. In some designs, the external panels could embed wiring, sun and heat sensors, and even magnetotorquers. This can not only make a small satellite more efficient in terms of payload size, it can also speed up production in the case of small satellites for large-scale constellations (Becedas and Capparros 2014).

The development of suitable standards for materials that can be extruded from additive manufacturing and more adaptable 3D printers with double extruders are now able to cope with the design and manufacture of composite-based satellite structures. This type of double extruders can facilitate the ability to embed functional features into the structure. This can for instance include wiring or sensors and thus create so-called multifunctional structures.

Yet another aspect of additive manufacturing with regard to small satellites that could create yet another benefit is with regard to the minimization of orbital space debris at end of life in terms of its destructive forces on one hand. This new form of manufacturing technique can easily allow for new design possibilities, shapes, and geometries. Such shapes and designs were difficult to achieve in a cost-efficient manner without using 3D printing techniques. These new shapes and geometries might be also designed to facilitate additional atmospheric drag, facilitate release of gases at end of life, or enable ease of repurposing as reusable modules. This type of approach might be compatible with experimental design concepts that have been explored by the US Defense Advanced Research Projects Agency (DARPA) in the context of so-called Satlets.

On the other hand, there is the possibility of using additive manufacturing to create more efficiency shielding techniques for small satellites against potential collision with debris or micro-meteorites as will be discussed below.

5 MicroLattice Structures as a Part of Small Satellite Panels

There are other structural materials other than composites that can make sense for small satellite and their structural design. One of these new possibilities involves the use of metallic lattices or even so-called metallic "micro-lattices" These lattices can play a role in the interior design of structural panels for small satellites. The creation of very light weight but strong metallic lattice structures is one of the possible structural components that are made possible and cost efficient with additive manufacturing techniques. In lieu of foam or other such materials, metallic micro-lattices can be stronger, more resilience, waste less material, and even cost less when fashioned by a 3D printer optimized for this type of design.

With the latest additive manufacturing technique, a metallic micro-lattice could be intentionally designed for a specific need. It is possible to create "negative Poisson rates." This could allow, for instance, the increased resistance capabilities of a structure, or even to help its protection against collision with a micro-meteorite. This type design could also add to the shear resistance of a small satellite structural panel (Gong et al. 2014).

The capability to make lighter and lighter structural elements via 3D printing continues to improve. The micro-lattice variant that has been designed by Boeing is rather amazingly shown to be 99% air and 1% metal (The lightest metal 2015) (see Fig. 3).

Spacecraft that design orbital space debris shielding in order to lessen the impact energy of debris or micro-meteorites create several layers of shield separated by gaps that could be filled with micro-lattice rather than foam. This may be more the case for microsats and minisats where volume considerations are not quite a severe.

The current approach that is used in most small satellites is typically based on the employment of honeycomb panels. Such honeycomb panels have limited impact

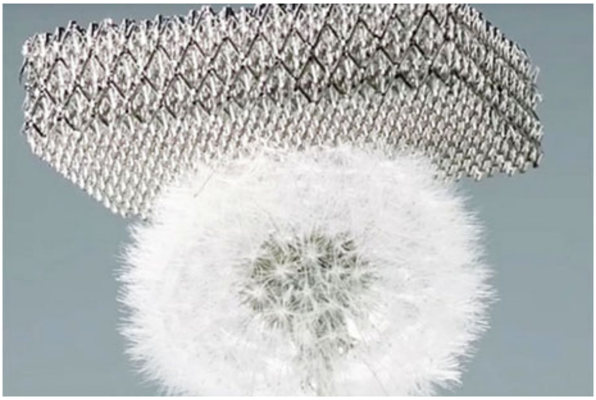

Fig. 3 A super low mass micro-lattice variant suspended on top of a dandelion. (Graphic courtesy of Boeing)

mitigation characteristics. Further the volumetric demands of these honeycomb panels would be challenging to include within the limited volume of a true small satellite such as 1 unit CubeSat standard. The use of metallic micro-lattices is for the future design of debris collision mitigation system. This approach may prove most promising for larger small satellite designs that might be manufactured so that they could be deployed for a large scale LEO constellation.

6 Conclusion

The materials used for the primary structure of truly small chipsats, pocketQubs, cubesats, and up to six unit cubesats will most likely remain metallic materials such as aluminum alloys similar to those discussed in this article. On the other hand, larger small satellites such as microsats and minisats in the range of 10 kg up to 1000 kg may tend to use carbon/epoxy composites. The challenges for the future is the extent to which primary structural elements or even secondary structural elements such as solar cell panels will be designed as highly space efficient components to include harness wiring, sun sensors, thermal sensors, or other quite small units such as magnetotorquer in order to maximize volume for the smallsat payload.

Efficient system engineering will continue to seek to improve small satellite design. This will mean eliminating the inefficiencies of the spacecraft “bus” so as to increase the payload that supports the prime mission for which the spacecraft is being deployed. The idea of considering each and every one of the components of a spacecraft bus as “excess mass” and an impinging occupier of internal volume must be seen as an ‘opportunity cost’ that is taking away power, mass, or volume that could be devoted to the real purpose of a small sat mission. The design of new and improved materials that can be lower in mass and volume, while maintaining longitudinal, transverse and shear strength and be resistant to change as thermal conditions should rise or fall is a clear objective.

The new capabilities that come from additive manufacturing offer a way to pursue these objectives and also reducing the cost of fabrication and material consumption. There are research studies that are seeking to use these new manufacturing techniques to improve the production of multifunctional components or systems, reduce mass, preserve volume for the payload, preserve structural strength and thermal stability, and as find better ways to cope with problems and issues that arise from orbital debris or micrometeorite collisions, as well as to better ways to protect small satellites against collision or to allow these small satellites to be recycled for use within new spacecraft.

Research in materials, structural design, additive manufacturing, thermal and radiation protective materials, multifunctional systems, micro-lattices, recycling of satellite components, and more can help make small satellites better. These innovations can create cubesats that are more cost-effective, more resilient, and better prepared for hazards in outer space include orbital debris collisions, thermal variations, coronal mass ejections, and other design and operational issues.

7 Cross-References

► Flight Software and Software-Driven Approaches to Small Satellite Networks
► High Altitude Platform Systems (HAPS) and Unmanned Aerial Vehicles (UAV) as an Alternative to Small Satellites
► Hosted Payload Packages as a Form of Small Satellite System
► Network Control Systems for Large-Scale Constellations
► Overview of Small Satellite Technology and Systems Design
► Power Systems for Small Satellites
► RF and Optical Communications for Small Satellites
► Small Satellite Radio Link Fundamentals
► Small Satellite Antennas
► Small Satellite Constellations and End-of-Life Deorbit Considerations
► Spectrum Frequency Allocation Issues and Concerns for Small Satellites
► Stability, Pointing, and Orientation

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