Arbosat - Towards a new class of sustainable structural materials for spacecraft structures based on enhanced wood

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ABSTRACT

After completing their missions, LEO satellites are typically deorbited to burn up in Earth's atmosphere. However, aluminum, one of the most widely used structural materials for small satellites, undergoes chemical reactions during thermal decomposition that may adversely affect our ozone layer. To address this challenge the Arbosat team is developing a sustainable alternative to aluminum based on enhanced wood material. The approach involves utilizing standard wood, an ubiquitous carbon-neutral and renewable natural composite, processed through a novel thermo-hydromechanical treatment (no chemical additives). By leveraging wood with its unique inherent properties, the result is a high-performance composite structure with excellent mechanical strength and stiffness, low outgassing, and good resistance to space conditions such as radiation, vacuum, and extreme temperatures. It is imperative that along with the material and process development activities a comprehensive test program is conducted. This involves laboratories test campaigns but also IOD/IOV activities. Also, the impact of such a new class of structural spacecraft material on the overall system design is studied in parallel activities. Within this conference paper the current status of the development and testing activities is summarized. Moreover, an outlook is given how the usage of enhanced wood material might impact on the design of space systems as we are used to.

INTRODUCTION

The rapid democratization of space has led to a massive increase in satellite constellations. While ”Space Sustainability” often refers to debris mitigation and orbital management, the chemical footprint of satellite re-entry is an emerging field of concern. Standard space-grade aluminum alloys, when subjected to the extreme heat of re-entry, undergo thermal decomposition into aluminum oxides (alumina). Recent atmospheric studies suggest these particles may catalyze ozone depletion and alter the radiative balance of the mesosphere. The Arbosat project, a collaboration between Swiss Wood Solutions AG (SWS) and ETH Zürich | Space, seeks to mitigate this by introducing densified wood as a structural spacecraft material. Wood is naturally carbon neutral, renewable and burns up cleanly into organic ash and gases without forming harmful metallic oxides. Currently various workstreams are proceeding to bridge the gap between material characterization for space applications and system-level implementation for spacecraft and launcher design.

IMPACT

Current industry standards for spacecraft and launcher structures rely heavily on Aluminum AA6061/AA7075 or Carbon Fiber Reinforced Polymers (CFRP). While having high performance, these materials present significant challenges at the end-of-life (EOL) phase of space assets. They can also contribute significantly to the overall cost structure of space projects as well as can put a certain risk on the supply chain.

Impact of Alumina on Environment

Research indicates that aluminum re-entry produces microscopic alumina oxides particles that remain suspended in the upper atmosphere. These particles increase the albedo of the mesosphere and provide surfaces for heterogeneous chemical reactions. In accordance with our hypothesis, wood being an organic cellular composite, undergoes complete combustion (ablation) into water vapor, carbon dioxide, and traces of nitrogen oxides, all of which are already naturally present in the atmosphere.

Impact on Sovereignty and Supply Chain Resilience

Aside from sustainability aspects, Arbosat addresses strategic sovereignty. Traditional aerospace materials are often subject to ITAR restrictions or rely on global supply chains that are vulnerable to geopolitical shifts. Wood is a ubiquitous and inexpensive resource. Utilizing a low-CAPEX manufacturing process allows for a distributed, resilient manufacturing base for spacecraft structures that is entirely independent of export control restrictions and costly manufacturing infrastructure.

ENHANCED WOOD MATERIAL SYNTHESIS

The core of the Arbosat technology is the transformation of naturally grown wood (softwoods or hardwoods) into a technical-grade material through thermo-hydromechanical (THM) processing. This allows to overcome traditional limitations of wood in space, such as inadequate mechanical properties, outgassing and low dimensional stability, while leveraging its unique benefits, including RF transparency, high specific strength and ultimately cost benefits.

THM Treatment Mechanics

The THM process developed by SWS involves in its main steps:

1. Softening: Utilizing moisture and heat to reach the glass transition temperature of lignin.

2. Densification: Uniaxial compression to collapse the cellular lumen. This increases typically the density from 0.65 g/cm^3 to 1.4 g/cm^3.

3. Curing: Cooling the wood under specific pressure to ”lock” the polymer chains in their densified state without chemical resin.

Figure 1: Wood below before densification, above after the THM process was applied

Comparative Mechanical Properties

First series of mechanical tests on maple samples were performed. This involves measuring the Young’s modulus and the tensile strength along the fiber direction (longitudinal) and perpendicular (transversal) to it. The following table summarizes first test results.

Table 1: Young’s modulus and tensile strength for native and densified maple

Wood species	E-Modulus [MPa]		Tensile [MPa]	
	long.	transv.	long.	transv.
Maple (native)	11.700	680	80.3	7.3
Maple(densified)	27.400	3100	190.6	19.5

The increase in value due to the densification process is significant. The Young’s modulus and the tensile strength in longitudinal direction for example increased by around 140% after densification. The same trend has been observed for the transversal direction.

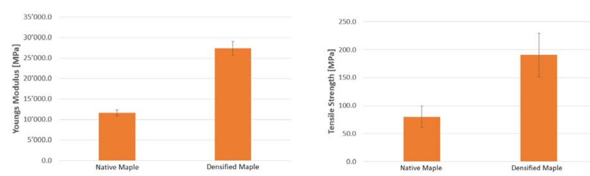

Figure 2: Young's modulus and tensile strength of native and densified maple wood samples in longitudinal direction

As seen in the following Ashby map, the resulting material exhibits a specific stiffness (E/ρ) that competes with aluminum. It has to be remarked that it is even possible to significantly enhance the specific modulus by choosing other wood species like spruce.

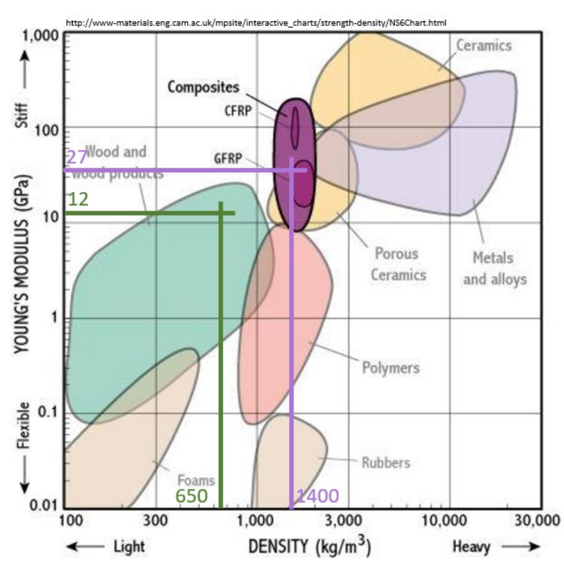

Figure 3: Ashby map of different materials

The properties of densified maple (pink line) match those of composites (pink area) and compete with aluminum. This contrasts with the properties of native maple (green line) which is in the region of wood and wood products (green area).

Orthotropic nature of wood

While aluminum is isotropic, the orthotropic nature of wood is leveraged in the design phase by aligning the load paths of designs with the fiber orientation of the wood, or creating specific veneer lay-ups (e.g. quasi-isotropic) as we are used from fiber reinforced composite development.

Outgassing

Outgassing tests in accordance with the ECSS-Q-ST-70-02C standard were performed. The first test campaign included four sample types that have been tested: native maple veneer, densified maple veneer, densified and heat-treated maple veneer and heat-treated balsa wood. The results are summarized in the following table.

Table 2: Outgassing in accordance with ECSS-Q-ST-70C

Wood species	CVCM [%]	WVR [%]	TML [%]
Maple (native)	0.01 ± 0.00	8.04 ± 0.09	7.32 ± 0.12
Maple(densified)	0.01 ± 0.01	6.67 ± 0.03	6.20 ± 0.02
Maple (densified & heat treated)	0.01 ± 0.01	3.90 ± 0.02	3.34 ± 0.01
Balsa (heat treated)	0.05 ± 0.01	5.47 ± 0.06	4.90 ± 0.07

As is obvious from the tracked data the harmful CVCM values are well in line with the applicable values for spacecraft and launcher materials. Related to the nature of wood there is a certain amount of water that is released in vacuum. This amount can be reduced a lot by densification and heat treatment. The calculated RML (TML – WVR) value is negative and results from the increased sample weight after treatment, which is caused by the elevated moisture content during post-conditioning compared to pre-conditioning.

SYSTEMS ENGINEERING CONSIDERATIONS

Implementing wood as a structural spacecraft material potentially requires a paradigm shift in the current way how spacecraft and launcher systems are designed and developed but also opens the floor for new solutions. A few aspects focusing on system design are discussed in the following paragraphs:

Impact on the system design

It is imperative that the impact of enhanced wood as a structural material on the overall system design of spacecraft and launcher systems has to be assessed. In order to account for this, one workstreams that is currently followed in the frame of an ESA project is to understand more about the system impact of such a new class of materials by conducting a specific study at system level. This involves but is not limited to the screening of satellite and launcher systems for suitable candidate parts, derive applicable requirements and ultimately come up with a first design of the most promising applications leveraging wood as a structural material. This study is not just limited to engineering considerations. Also, a Life Cycle Analysis (LCA) is performed to have a comprehensive understanding of the environmental impact. Within this study manufacturing constraints as well are evaluated.

RF Transparency

Experimental data shows that densified wood has a dielectric constant between 2.0 and 3.5, depending on the wood species and densification level. This potentially allows for S-band and X-band communications through the structural walls, potentially increasing the usability of SmallSats by removing the failure point of deployable antennas.

Thermal Management Subsystems

The low thermal conductivity of wood prevents the structure from acting as a ”heatsink” for high power electronics. While this simplifies the thermal isolation of cold components, it necessitates active thermal paths (e.g., heat pipes or specialized copper strapping) for power-dense boards. Addressing these localized thermal gradients and developing integrated, scalable thermal management architectures remains a critical objective for future iterations of this technology.

Library of Connection Technologies

The project has already developed a library of joints. Namely:

1. Self-Centering Dovetails: For primary structural alignment of panels

2. Mortise and tenon joint: To connect individual structural members

2. Threaded metallic inserts: Metallic inserts potted into the wood using space-grade epoxy to interface with standard bolts

3. Flexural Hinges: Leveraging the natural elasticity of wood for small-angle mechanisms.

To ensure dimension stability when moisture is released is a critical element to be further investigated.

Monolithic vs sandwich

The technology also provides the possibility to manufacture full wooden sandwich structures. These types of wooden sandwiches consist of face skins made of laminated veneer as well as a very light Balsa core. The vertically aligned balsa wood is sandwiched between the cross-laminated densified veneer face sheets. The lay-up of the face skin can be quasi-isotropic but also other fiber angles are possible.

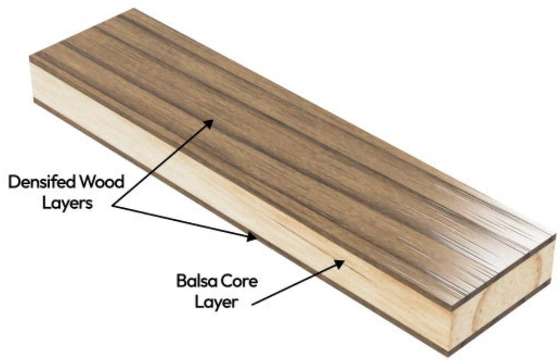

Figure 4: Sandwich design

First engineering samples were manufactured and prove the feasibility of building an “all wood” sandwich. Current development activities are focused on establishing the mechanical properties of these sandwich panels under both static and dynamic loading. Furthermore, ongoing research addresses novel methodologies for structural connection and equipment mounting, specifically focusing on the optimization of load-bearing attachment points and potting inserts within the wood matrix.

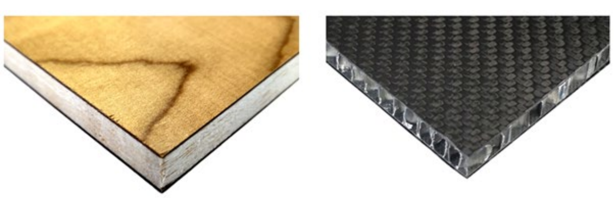

Figure 5: Prototype of a wooden sandwich structure vs. CFRP sandwich

Wooden 1U CubeSat structure

To evaluate the structural viability of densified wood for small satellite platforms, a 1U CubeSat technology demonstrator was fabricated utilizing densified wood components. The structural interfaces between individual frame members rely exclusively on traditional timber engineering principles—specifically, optimized mortise and tenon joints—thereby minimizing metallic fasteners. Threaded fasteners are restricted solely to the integration of the exterior cover plates across the six primary faces.

To rigorously characterize the mechanical and physical performance of this monolithic "all-wood" architecture, a systematic development road map has been established. Immediate experimental efforts focus on quantifying the material's dimensional stability under hygroscopic loading, specifically mapping deformation during moisture absorption and desorption cycles. Furthermore, the structure will undergo quasi-static and dynamic mechanical testing to validate its structural integrity against typical launch vehicle qualification profiles.

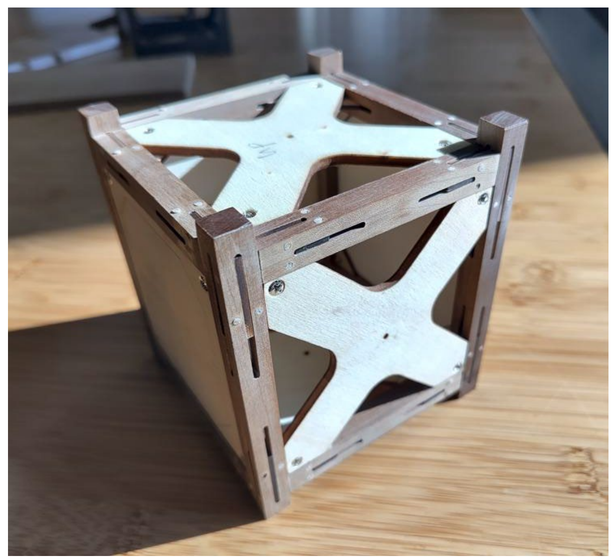

Figure 6: 1U CubeSat all wood structure - technology demonstrator

Results are planned to be published in Q3/Q4 2026.

IN ORBIT DEMONSTRATION/VALIDATION (IOD/IOV)

A first IOD mission is scheduled to fly in Q4 2026 to the International Space Station (ISS) with the objective of quantifying how wood-based structural materials behave under Low Earth Orbit (LEO) exposure. In this experiment a passive 0.2U (100×100×12 mm) payload is exposed for six months to external LEO environment such as vacuum, atomic oxygen (ATOX), UV radiation, cosmic radiation, and thermal cycling. After six months of exposure, the samples return to earth for comprehensive post-flight analysis and a comparison with stored reference samples. The experiment consists of 4 different types of wood samples:

1. Not densified maple: Serves as the reference to assess the effect of space exposure on untreated material

2. Densified maple: Density approx. 1400 kg/m^3

3. Densified beech: Density approx. 1400 kg/m^3

4. Wooden sandwich: Face skins densified maple, core balsa wood

The samples are placed in an aluminum frame with a cover plate and attached to one of the external test racks that are offered by the ISS. The samples are exposed in the flight direction of the space station.

Figure 7: Flight model Arbosat-1 – passive experiment

The experiment will address main open research questions related to the application of modified wood as structural material for space. These are as follows:

1. Deliver the first in-orbit mechanical degradation dataset for modified wood

2. Quantify stiffness retention after LEO exposure

3. Identify dominant degradation drivers

To demonstrate flight readiness a comprehensive qualification and acceptance testing campaign was conducted on the experimental set-up. This included dimensional and mass verification but also thermal cycling, random vibration testing and TVAC bakeout.

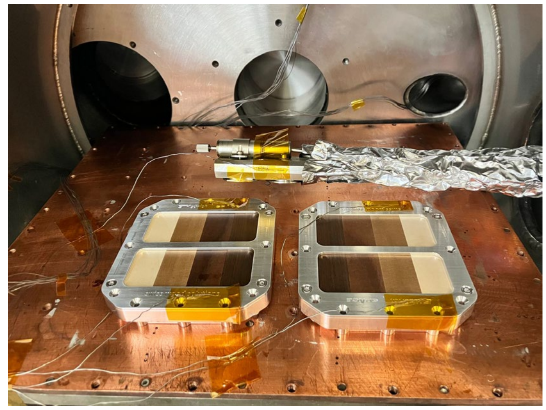

Figure 8: TVAC bakeout Arbosat-1 flight model and ground reference model

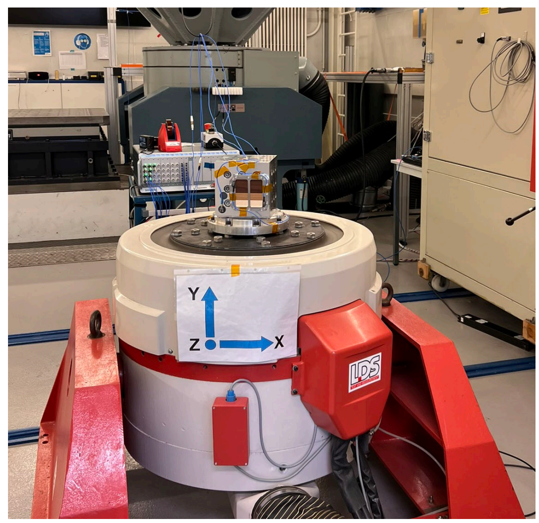

Figure 9: Shaker testing Y-axis – acceptance testing flight model

All tests were done successfully, and the flight hardware was handed over to the launch provider for further integration and testing activities.

ROADMAP AND FUTURE WORK

While no critical flaws have been identified regarding the use of modified wood as a structural material for spacecrafts and launchers so far, this approach remains highly novel. Consequently, a substantial knowledge gap must still be addressed to build confidence and establish a robust flight heritage. To systematically bridge this gap, a dedicated development roadmap has been established to progressively mature the material's Technology Readiness Level (TRL). This comprehensive framework includes material characterization, engineering considerations, and manufacturability, supported by joint projects with dedicated partners.

Immediate efforts within this roadmap are focused on critical material testing and validation. Notably, the upcoming plasma wind tunnel testing will provide vital insights into the demise behavior of enhanced wood during atmospheric reentry. Concurrently, several in-orbit demonstration and validation (IOD/IOV) missions are transitioning into the development phase. These include the concrete plan to launch a fully wooden CubeSat structure, alongside a suite of active and passive experiments designed to quantify the long-term impacts of the harsh space environment on modified wood. Ultimately, these parallel ground and orbital efforts lay the groundwork for adopting sustainable materials in the next-generation space assets architectures.