ESA GSTP project

Bio-composite structure in space applications

Executive Summary Report

ITT AO/1-8938/17/NL/LvH
Ref: Item 17.133.05
Contract: 4000122778/18/NL/LvH

Prepared by:

Régis Voillat, M.Sc., Aerospace Project Manager, regis@bcomp.ch, +41 26 558 84 02
& **Julien Rion**, PhD, CTO, julien@bcomp.ch, +41 76 346 26 53
Bcomp SA
Passage du Cardinal 1
1700 Fribourg, Switzerland

Ralf Usinger, Manager Innovation & Industrialization, ralf.usinger@ruag.com, +41 44 306 20 95,
RUAG Schweiz AG | RUAG Space
Schaffhauserstrasse 580
8052 Zürich, Switzerland

1 Introduction

1.1 Edition list

Issue/Rev	Date	Modifications
1/0	13/08/2020	Initial edition

1.2 Scope of the document

This document concisely summarizes the work done and findings obtained during the 2018-2020 GSTP project “Bio-composite structure in space applications” to non-experts in the field.

1.3 Acronyms and abbreviations

AD	Applicable document
AHP	Aluminium honeycomb panel
(A)HC	(Aluminium) honeycomb core
BCBB	Bio-composite breadboard
BCPSS	Bio-composite pyro shock sample
CFRP	Carbon fibre reinforced polymer
CME	Coefficient of moisture expansion
CTE	Coefficient of thermal expansion
CoM	Centre of mass
CVCM	Collected volatile condensable material
D4D	Design for demise
FEM	Finite element model
FFRP	Flax fibre reinforced epoxy
HVI	Hypervelocity impact
FFRP	Flax fibre-reinforced polymer ↳ “Bio-composite”
gsm	g/m^2
HLS	High level sine
LLS	Low level sine
L	Longitudinal
T	Transverse
tex	g/km (unit of textile measurement)
Tg	Glass transition temperature
PFA	poly(furfuryl alcohol) / furan resin
prepreg	Pre-impregnated fabric
PU	Polyurethane
RD	Reference document
RML	Remaining mass loss
S/C	Spacecraft
SBB	Standard breadboard
SPSS	Standard pyro-shock sample
TBD	To be defined
TRL	Technology readiness level
UD	Unidirectional
UTS	Ultimate tensile strength
Vf	Fibre volume fraction
Wf	Fibre weight fraction

2 Background and objectives

In the framework of the Clean Space initiative, ESA has shown an interest in bio-composites (here: flax fibre-reinforced thermosets, or **FFRP**) based on two main drivers:

1. The search for more sustainable materials
2. The search for more demisable materials based on the requirements from the space debris mitigation policy ("Design for Demise" or D4D principle)

In 2015, Bcomp had already shown that bio-composites based on flax fibres and epoxy resin could be a viable material for spacecraft structures at TRL 4, while demonstrating their exceptionally low thermal expansion, high specific stiffness and strength retained at cryogenic temperatures, and viscoelastic behaviour improving on vibration damping over CFRP and aluminium.

The goal of the present GSTP was to develop and produce a demonstrator FFRP spacecraft structure for a generic LEO mission with a low environmental impact, and well-demisable at re-entry.

A cradle-to-gate Life Cycle Assessment (LCA) was to be conducted to compare the environmental impact of the alternative NFRP structuring with the benchmark.

By the end of the project, Bcomp's bio-composites solutions for S/C structure would reach TRL 6 at material level, and TRL 5 at component level as per ECSS-E-HB-11A.

3 Materials selections

Bcomp's choice of flax bast fibres for composite reinforcement is based on their exceptional specific stiffness compared to most available lignocellulosic fibres (hemp, sisal, kenaf, jute, among others) and a particularly well-established supply chain from European sources. On top of the obvious environmental advantages of using a biological material – such as reducing the depletion of fossil resources, low process energy, CO_2 sequestration from photosynthesis – European flax has further environmental benefits:

- Low demand in irrigation, drawing water almost exclusively from rainwater
- On-field dew retting instead of water retting: fungi are responsible for fibre extraction, significantly reducing freshwater ecotoxicity.
- Low fertilizer demand thanks to dew retting, which returns nutrients to the soil.
- Very little competition with food crops, but rather well-suited for crop rotation.

Bcomp's flax fibre reinforcements for composites come in two product families:

ampliTex™ are the common fabric architectures – UD, woven, biaxial – meant to replace synthetic fibres in standard composite laminates. They benefit from long and highly aligned fibres (low twist and low crimp), high coverage, and a high degree of consistency between batches. Like carbon fibres, ampliTex™ reinforcements also benefit from the thermal contraction of flax fibres, yielding epoxy laminates of near-zero thermal expansion.

powerRibs™ is a patented technology meant to be used as a surface ply in open or half-rigid mould processes. They readily and efficiently produce a mesh of ribs on the surface of the laminate, increasing the moment of inertia and thus flexural stiffness with minimal weight penalty. powerRibs™ directly benefit from the ability of natural fibres to be assembled as thick, self-standing round yarns. A full-flax laminate with the right combination of ampliTex™ and powerRibs™ can match the flexural stiffness of typical full carbon monolithic laminates at the same areal weight.

Figure 3-1 Flax stems laid out on the field for dew retting (source: www.hungarolen.hu)

Figure 3-2 Selected Bcomp flax fibre reinforcements for the demonstrator ampliTex™ and powerRibs™.

4 Structure selection and breadboard design

A typical, large spacecraft architecture is organised around a primary "backbone" structure surrounded by a secondary structure of flat panels enclosing the volume and supporting equipment. The primary structure encounters mostly in plane tensile, compression and shear forces, while the secondary side panels must provide stiffness in out-of-plane flexure to avoid catastrophic resonance under the high energy vibrations from the launcher.

An analytical assessment based on simple sandwich mechanics considerations confirmed that replacing CFRP/AHP with ampliTex™ FFRP/AHP in the primary structure would lead to unacceptable mass penalty in order to meet the in-plane stiffness requirements. However, the flexural stiffness requirements of side panels could be met when replacing an aluminium AHP side panels with FFRP/AHP with very little-to-no weight penalty. The reference structure panel was thus chosen to be an SVM Lateral Panel for the Sentinel-1 structure, as shown in Figure 4-1**.**

Scaled-down breadboard panels were designed to be tested in vibration testing, thermal cycling and shock tests, to verify the mechanical performance, thermal stresses and vibration/shock propagation damping provided by the viscoelastic nature of flax fibres.

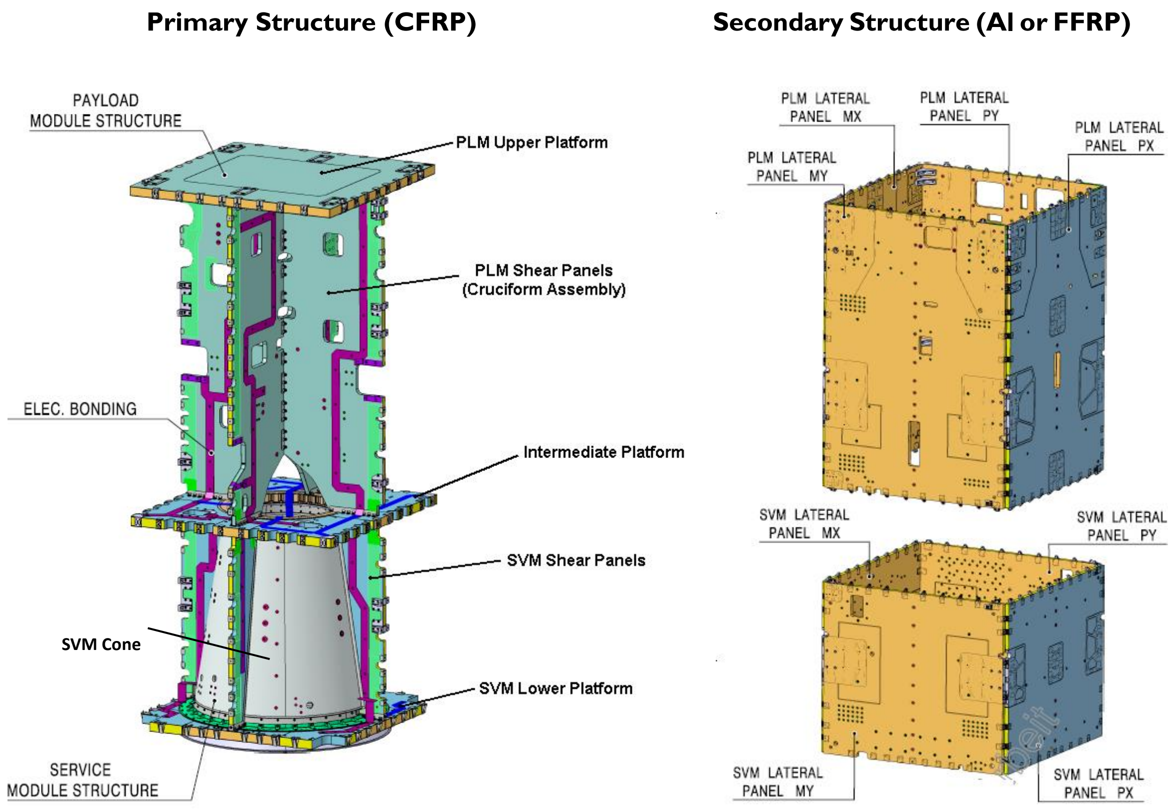


Figure 4-1 Sentinel-1 satellite primary and secondary structure components. Source: RUAG Space

To further improve on demisability, a novel design feature was explored, benefiting from the *powerRibs*™ technology for the stiffening of thin laminates: single-shelled recessions called "*powerRibs*™ windows" were introduced in areas of the panel that were not used for equipment mounting. They consist of the removal of the top sheet and HC, leaving only the bottom sheet to be reinforced in out-of-plane flexure by the *powerRibs*™ at the bottom. The intent was to provide targeted weak points for the early ingress of plasma heat fluxes into the satellite's internals before the side panels would have the chance to demise completely.

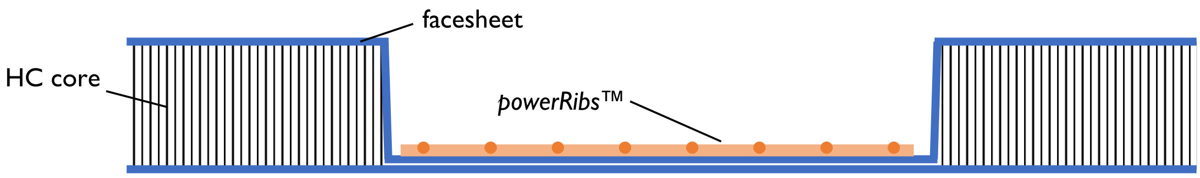


Figure 4-2 Cross-section view of the *powerRibs*™ reinforced recessions as a novel D4D concept.

In order to reproduce simply supported edges boundary conditions in testing, the choice was made to attach the panels on their perimeter using "flexible" blades to be clamped to the vibration table.

Equipment dummy masses were included as simple, solid aluminium blocks, to reproduce the inertial loads of real satellite equipment such as battery assemblies, control systems, etc.

The breadboards were designed, built and tested thanks to the expertise and facilities of satellite structure specialists at RUAG Space.

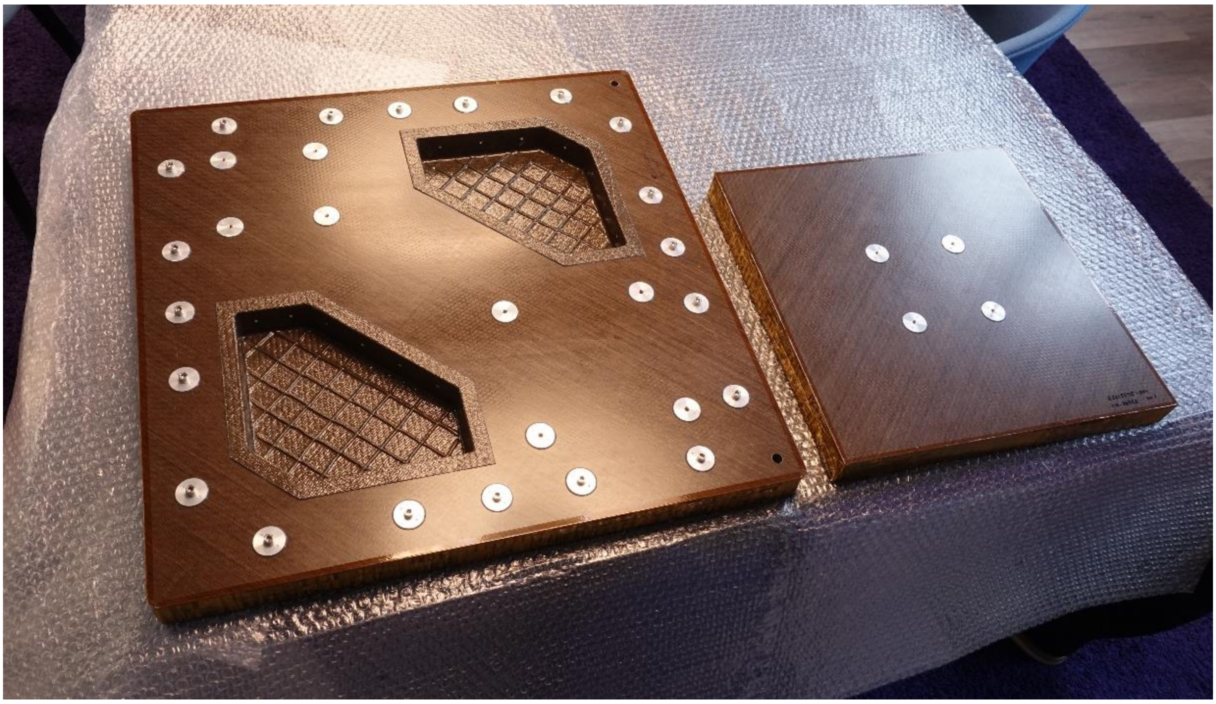


Figure 4-3 Vibration and shock test bio-composite panels side-to-side.

5 Tests and simulation

Vibration testing across a range of frequencies and acceleration levels was used to verify the panel stiffness, strength and resonant behaviour, as well as to identify potential damage caused by thermal cycling between -70°C and +90°C. When mounted with two masses of 12 kg and 5 kg respectively, the bio-composite panel could handle vibration loads up to 25 g at 100 Hz without suffering any damage.

A finite element model (FEM) simulation was developed, and its predictions were verified to a high degree of accuracy by the vibration test campaign, allowing for its use for the design of larger and more complex structure panels.

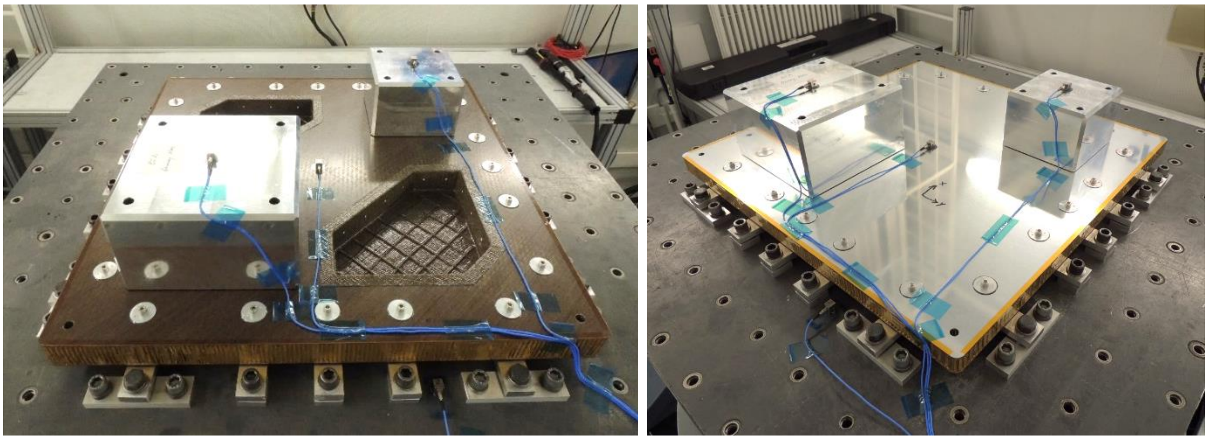


Figure 5-1 Bio-composite and standard aluminium breadboards in vibration testing.

Pyro shocks were simulated electromechanically. The shock tests demonstrated a comparatively better damping behaviour of the bio-composite solution over the aluminium reference, and hence its potential for equipment protection during launch and separation events.

6 Material test campaign on FFRP

A large test campaign was conducted on samples of FFRP material produced under conditions equivalent to the breadboard's facesheets. The goals were to provide mechanical data for the FEM, to verify certain requirements for the breadboard that only required testing at material level, and to provide additional information on material properties for the records.

A total of 15 different tests was conducted. A summary of the most important results is presented here.

- The complete in-plane tensile (longitudinal, transverse, shear, Poisson) and flexural response of the FFRP plies was characterized at varying fibre fractions, allowing for accurate analytical and FEM predictions.
- The tension-tension cyclic fatigue behaviour was measured, demonstrating a endurance that was qualitatively situated between that of GFRP or aluminium (relatively poor) and CFRP (relatively good).
- Thermal vacuum outgassing requirements were only met under the conditions that the FFRP laminate was subjected to a vacuum bakeout procedure of 72h at 130°C. It is likely that a pre-treatment of the dry ampliTex™ reinforcement would eliminate the need for a post-cure bakeout, with a more efficient process (TBC).
- In a controlled hygrothermal aging test, coating solutions were investigated to protect the FFRP against moisture uptake due to its relatively high hygroscopicity. It was found that coatings, besides adding weight to the structure, could only serve to slow down the uptake of water, reaching equilibrium given enough time. Hence, the preferred protection method against an aggressively humid environment would be to store under a controlled atmosphere (inert gas or vacuum). Climate-controlled ambient conditions (50% RH at 23°C) do not cause the material to deteriorate at any significant degree, but water vapour release on orbit shall be considered. Long term storage conditions remain TBD in future tests.
- FFRP samples were exposed to high doses of UV/VUV radiation corresponding to the LEO spectrum. The only visual cue for degradation was a darkening of the illuminated surfaces. Flexural strength was reduced by only -6.0% in non-coated and -2.4% in coated samples, and stiffness was left unchanged.
- Thermal vacuum endurance (600h at 110°C) and cycling (±120°C) was verified, causing no measurable change in fibre strength and stiffness properties, and only leading to a slight embrittlement of the epoxy matrix that is not compromising to the overall structural integrity.
- Longitudinal and transverse thermal conductivity, as well as the coefficient of moisture expansion, were measured.
- A very low RF attenuation was measured at all relevant communication frequencies between 1 – 40 GHz (up to K_a band), not exceeding -2 dB at any laminate thickness up to 4.0 mm.
- Samples were subjected to destructive plasma wind tunnel testing to study ablation, i.e. demise behaviour under experimentally simulated conditions that are relevant to uncontrolled atmospheric re-entries. Compared to CFRP, the flax fibres are considerably more prone to spall, leading to a much faster ablation rate. However, when compared to aluminium alloys, its time-to-demise falls short by approximately half an order of magnitude.

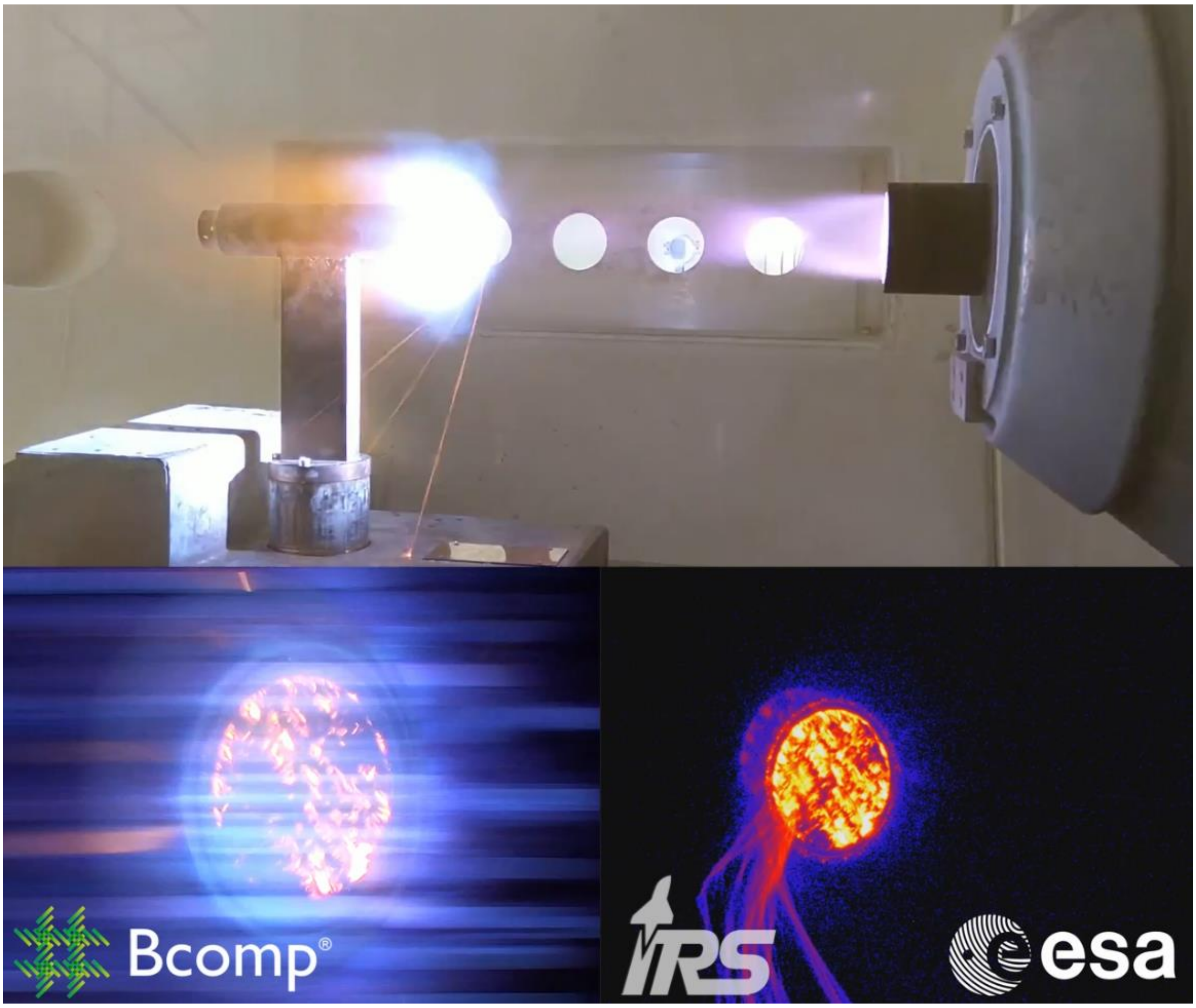


Figure 6-1 Side view, HD close up and IR video of the plasma wind tunnel test at IRS Stuttgart. It shows fibre spallation that greatly contributes to a fast ablation rate compared to CFRP under the same re-entry simulation conditions.

7 Life Cycle Assessment

A study was conducted to compare the environmental performance of the novel bio-composite panel (BCBB) against the reference aluminium structure (SBB). This work was subcontracted to sustainability consultants at Quantis, Switzerland, and its methodology is compliant with ESA Handbook, "Space system Life Cycle Assessment (LCA) guidelines".

The system boundaries were limited to the production of the secondary structure panel as it comes out of the manufacturing plant, since the distribution and use stages are almost equivalent between the two technologies.

This comparative study did not show a very clear advantage from one solution or the other when considering all impact indicators. On individual indicators, the BCBB had clear advantages (metal and abiotic resource depletion, marine ecotoxicity), clear disadvantages (ozone depletion, marine eutrophication, freshwater ecotoxicity), and unclear differences that were highly sensitive to assumptions (global warming, air acidification, freshwater eutrophication, gross water consumption, among others).

The sensitivity analysis revealed that a better understanding of the impact caused by the processes involved in the manufacturing of the structure panels was key to improving both the LCA and the actual impact. In particular, the environmental impact was dependent on the bake-out process required for the outgassing behaviour of the FFRP facesheets for the BCBB, and strongly dependent on the acid passivation process required for a good bonding of the aluminium facesheets onto the honeycomb core in the SBB (Figure 7-2).

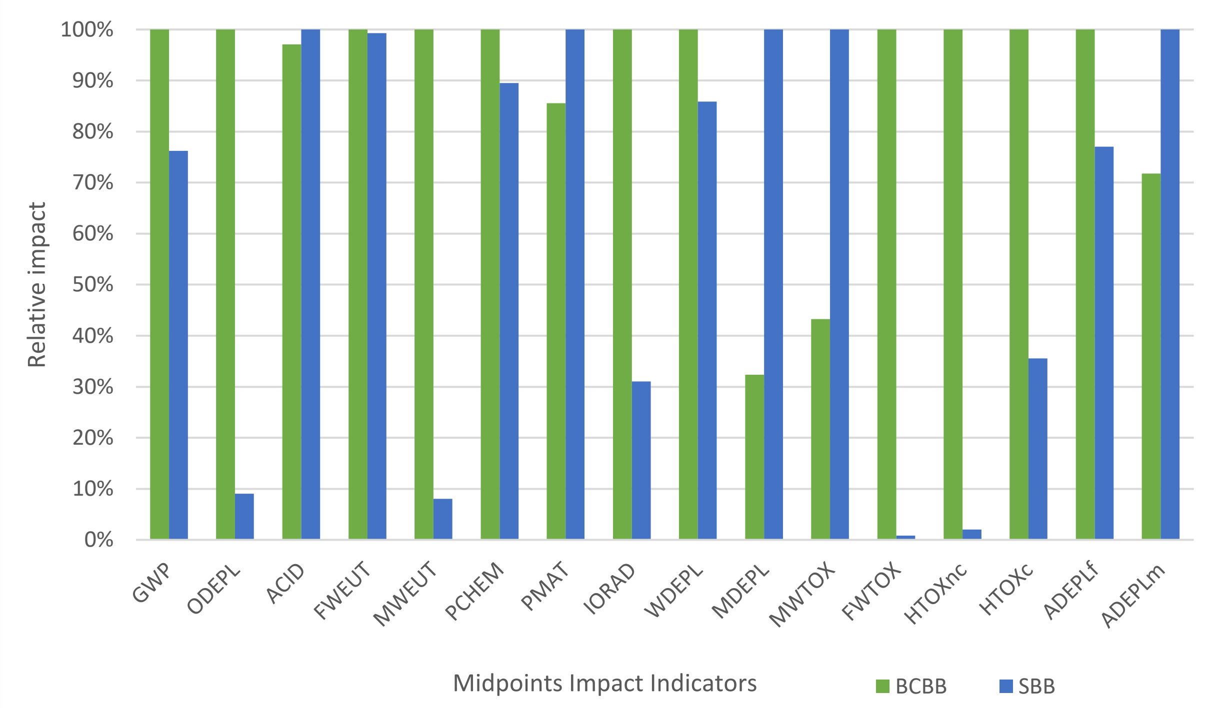


Figure 7-1 Impact assessment of BCBB and SBB on Midpoint Indicators in relative values

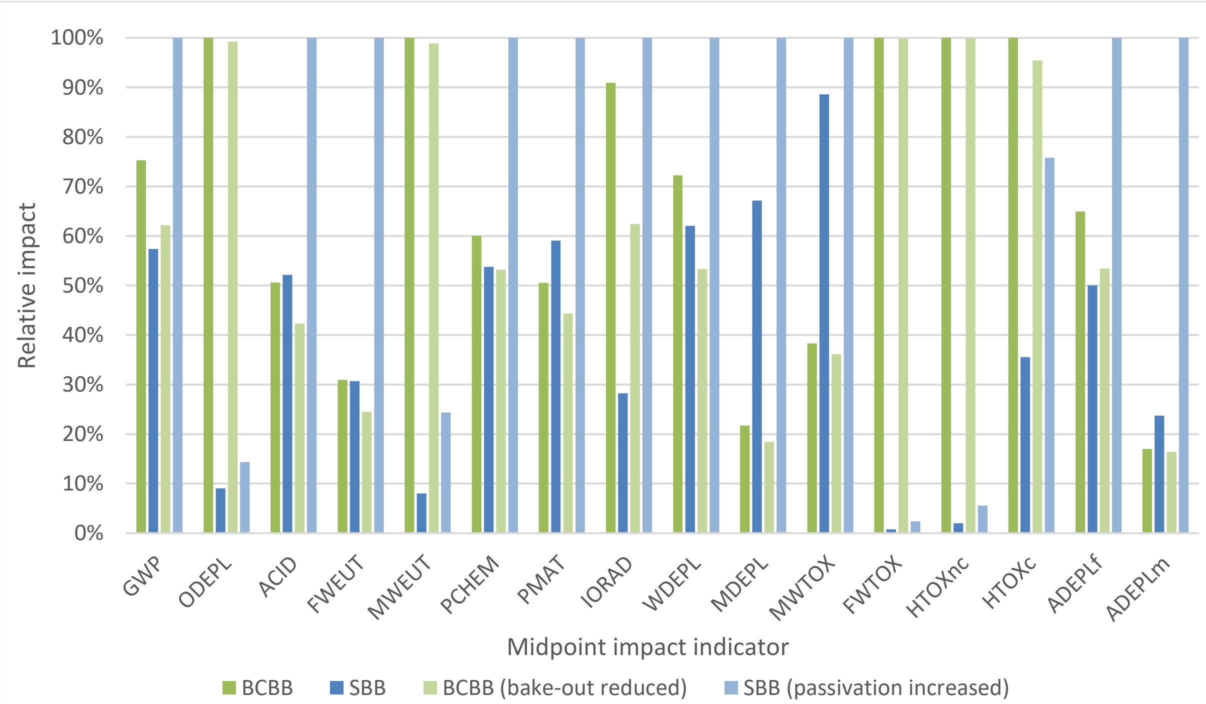


Figure 7-2 Impacts of sensitivity analysis for all considered impact indicators

8 Conclusions

Under ESA GSTP funding, Bcomp Ltd. and RUAG Space jointly designed and built a spacecraft structure demonstrator panel from ampliTex™ flax fibre-reinforced composite facesheets (FFRP) and aluminium honeycomb core (AHC) under the same specifications as a standard aluminium / AHC panel. The reference design, structural and environmental requirements were taken from the Copernicus Sentinel-1 satellite's secondary structure for LEO missions.

Novel design features were introduced as a new opportunity for Design for Demise, allowed by the natural fibre-based powerRibs™ thin-shell composite reinforcement technology: single-shelled recessions in the sandwich panel surface, intended to act as targeted demisable points for the early ingress of heat fluxes into the satellite's internals upon re-entry.

The good demisability behaviour of FFRP was demonstrated in plasma wind tunnel testing. Compared to carbon fibre-PEEK composites (CFRP), its ablation rate under the same heat flux conditions was exceptional thanks to its propensity for spallation, whereas CF strands tend to remain in place as the matrix demises around them. Compared to aluminium alloys – which have phenomenologically different demising processes – the approximate time to demise is generally slower with FFRP.

A large test campaign was conducted at material level on FFRP. Besides providing an in-depth understanding of their mechanical properties for analysis and simulation, key assets of these materials were revealed, such as relatively good mechanical fatigue endurance, high UV/VUV resilience, and a very low RF attenuation at all relevant frequencies for radio-communication (up to K_a band).

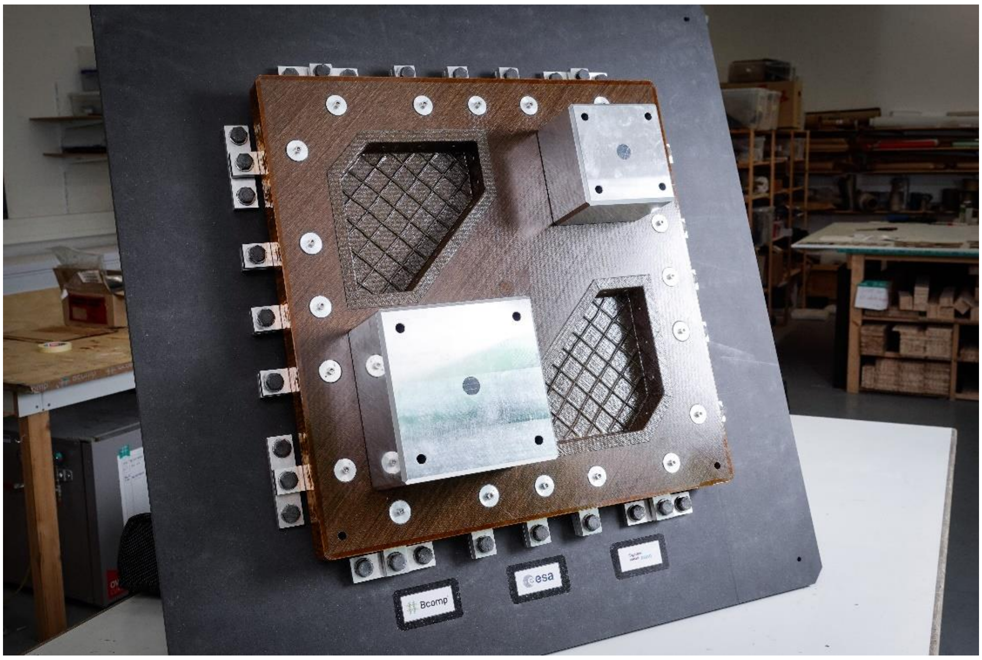
The natural hygroscopicity of flax fibres – and incidentally FFRP – is source for concern regarding long term storage, surface water sensitivity, geometrical stability, and water vapour release in vacuum. The equilibrium water content of FFRP under ambient conditions was found to be around 3% by mass. The coefficient of moisture expansion was measured and found to be low in the fibre direction. The relatively high-water vapour release remains a shortcoming and may require that the materials be stored in an inert gas container prior to launch in applications sensitive to water vapour release on orbit. Organic coating solutions to help reduce the moisture uptake were deemed unnecessary if the parts were to be stored in a controlled environment. The long-term storage requirements remain a point of verification for further qualification.

The stiffness, strength and thermal fatigue resistance requirements of the demonstrator panel were met to support and protect the satellite's structure and mounted equipment for launch. The low-level vibration tests also verified the validity of a finite element model for structural predictions to a high degree of accuracy. Known to be viscoelastic, the superior vibration damping properties of FFRP compared to aluminium were also verified in electromechanical shock tests.

Where out-of-plane (flexural) rigidity is the design driver, FFRP/AHC panels can meet the stiffness requirements with little-to-no weight penalty over an aluminium/AHC panel under the condition that the core thickness is increased to account for the lower in-plane modulus of the facesheets. Theoretical analysis also suggests that such panels would provide an improved protection against hypervelocity impact events over aluminium panels (to be verified in testing).

An ESA-compliant cradle-to-gate life cycle assessment (LCA) was conducted to compare the environmental impact for the production of the bio-composite structure with the standard solution. Despite the greatly reduced process energy and low resource-demand for the production of raw FFRP compared to aluminium alloys, the LCA revealed that there was no clear environmental advantage to a complete FFRP/AHC over an Al/AHC panel due to the heavy contribution of processes in the overall impact. This study and its sensitivity analysis revealed key potential improvements in the actual process chain for both technologies – as well as for the LCA model itself – and provided valuable data for future LCA in the field.

With the project successfully concluded, Bcomp ampliTex™ and powerRibs™ flax fibre composite solutions for LEO satellite structures can now be considered mature at TRL 6 as per ECSS-E-HB-11A. At component level, the FFRP/AHC panel is validated at TRL 5, and a full-scale demonstrator would bring it to TRL 6 as well.



9 Future developments

FFRP provides many advantages over CFRP as a composite reinforcement: a significantly lower environmental impact at material level, much better demising behaviour, improved vibration damping and radio-transparency. However, the lower specific modulus often implies a heavy weight penalty in structures designed to meet the same in-plane stiffness requirements, making straightforward material replacement compromising.

Future developments shall focus on making the best of the assets of FFRP in key applications:

- Thanks to their very good thermal compatibility, flax/carbon hybrid solutions may be designed to greatly improve the re-entry demisability of structures where CFRP remains the limiting factor, while incidentally improving on vibration damping, with minimal compromise on stiffness and weight.
- The radio-transparency of FFRP, along with their relatively high specific stiffness compared to most radio-transparent materials, may be key to the development of lightweight structures for RF applications: antennae structures, radomes, etc.

Regarding material characterization for space applications, future validation will also require verifying the long-term storage requirements, as well as investigate fibre pre-treatment in order to prevent the need for a post-cure bakeout to meet the thermal vacuum outgassing requirements, as was already shown with previous variants of FFRP. This would most certainly be favourable practically, economically and from an environmental impact perspective.