ADVANCED COMPOSITE FOR SPACE APPLICATIONS: DESIGN AND STRUCTURAL ANALYSIS OF CFRP ELECTRONICS HOUSING

Voicu Raluca[1*]

[1] *National Research & Development Institute for Gas Turbines COMOTI,*

**Head of Composite Materials Laboratory,*

Adress: 220 D Iuliu Maniu Ave., 061126, sector 6, Bucharest, Romania

E-mail: raluca.voicu@comoti.ro

Abstract
Hosting a payload straight up to escape Earth's gravity requires a phenomenal expenditure of energy, and every gram of weight saved in either launch space vehicle or payload weight translates in to lower overall costs. Satellite payload includes also among others electronic unit housing structures, traditionally made in aluminium alloys. The paper presents the geometrical design study for a satellite electronic housing, three types of CAD models along with materials structural new concept design validated by FEM analysis, to be developed by autoclave technology in advanced composite materials. Mechanical stresses study included static and dynamic loads calculations. Optimized CAD3 model and structural design were validated for manufacturing, with increasing stiffness of the frame with box beam, considering natural vibration frequency higher than 100Hz during launching. The proposed CFRP composite electronics housing was designed in order to fulfil the multiple requirements set for the housings providing large mass savings. An experimental model, calculated to withstand both launch and on orbit space environments, ready to be tested in vibration regime was manufactured using autoclave technology.

Keywords: carbon fiber reinforced composite materials, structural design, stress analysis, high thermal conductivity carbon fiber, space structures

1. INTRODUCTION

Today, when the entire industry suffers from "the low weight syndrome," which continuously aims for lighter materials, lighter vehicles, lower energy and fuel consumption, higher performances, reduced pollution, low costs and full satisfaction, composite materials seems to be the best candidate material to these needs. Starting from these considerations and requirements, new developments in the space industry indicate a much higher usage of composite materials in spacecraft structures. In space vehicles, size may not matter, but weight does. The launch cost is determined overwhelming by the mass factor, and in the same time the launch cost has a major relevance for the mission cost. For a Low Earth Orbit (LEO) defined up to 1500-200km altitude satellite launch costs are estimated at 20,000 $/kg [1,2] and therefore weight is closely managed during design. Much work has been done over the last years in improving the efficiency of spacecraft, composite materials including the polymeric PMC composites which are the lightest, already being deployed in many space structures. Composite materials are best candidates where stiffness is critical such as launch in satellite structures i.e. bus, payload, and instrument structures, in launch vehicles i.e. fairings/shrouds, payload and motor adaptors, structural decks, avionic panels but also in telescopes, antennas, optical structures. Furthermore, as a result of the trend in space engineering towards cost reduction the application of non-space-qualified electronics in satellites has become a common practice [3, 4]. Ionizing particles in the harsh space environment could damage the non-radiation-hardened electronic devices, potentially impairing the satellite's main functions [5]. In order to provide the devices with sufficient protection *an electronics housing structure* should attenuate the incident radiation. Traditionally, the electronics housing structures are made of aluminium alloys. The considered reference for the design study was part of ESA's Advanced Equipment Design (AED) studies [6-8]. The present work presents the results obtained with respect to geometry design optimization for a microsatellite composite electronic housing, taking as reference (only for fixed

dimensions) the ADPMS (Advanced Data and Power Management System) unit in aluminium, already deployed on Proba 2, the second satellite in the European Space Agency's series of PROBA low-cost satellites that are being used to validate new spacecraft technologies while also carrying scientific instruments, the next being Proba 3 to be launched in 2017. Proba 2 (sun monitoring mission) was launched in November 2009 using Rockot launcher, designed for 2 years nominal life mission on low earth orbit altitude between 700 and 800 km, Sun-synchronous Inclination 98.298 degrees. The Proba 2 [9] the ADPMS housing was in size about 460 x 154 x 250 mm, made out of aluminium alloy. The driving factor of developing a composite electronic housing for microsatellite, was weigh reduction (30-45% lighter than aluminium structure designed to the same functional requirements), ease of a accessibility for electronics, proved materials structural concept and manufacturing technologies, along with validation through tests for critical space requirements assessment (at least equal to aluminium reference). Both geometrical and materials structural designs development in the paper were done in an iterative process, targeting weigh reduction and space harsh conditions resistance. Within the geometry design, three design solution were proposed having as input data: fixed dimensions (460 mm x 154 mmx 250mm, wall thickness of 2mm) and unswerving to mass reduction and accessibility conditions. Following that the optimum geometrical design was validated by FEM analysis (launching regime) using special materials structural design concept, which was developed to be able to withstand both launch and on orbit space environment, with performances comparable to the one's obtained on the equivalent aluminium housing.

2. METHODOLOGY OF WORK

Three designs were developed for the composite space structure, CADs elements being presented in figure 1. Design geometry of the electronics housing made in carbon fiber reinforced polymeric composite (CFRP) was performed using 3D SolidEdge ST4 software.

The static and dynamic structural behavior has been studied using Finite Element Method. Using the CAD models of the micro-satellite housing structure, components have been modeled parametrically by finite element meshing. For composite designs, L shape part around 21000, for U shape part around 22200 cub elements were used. For head part closing the housing the modelling was performed using around 8800 cub elements. The edge elements dimension was set to 3mm with the possibility of variation in function of the local geometrical details. The electronic unit shell elements (plates) were used. All aluminium parts were modeled using 4 knots *tetrahedral* linear elements for meshing. For modal analysis [15] it was chosen a simple criterion that requires that the first fundamental frequency of the microsatellite electronic housing must be higher than 100 Hz, so as to avoid interference with frequencies of vibration of the launcher. In the lateral vibration range a first fundamental frequency bigger than 50 Hz is accepted, but in the paper the value is set to 100 Hz. Hence, the main requirements for the satellite structure were related to: first fundamental frequency (>100Hz), random vibration resistance (for lunching stage) and LEO harsh environment (e.g. impact strength, thermal cycling, radiation resistance, etc.). Furthermore, the final structural materials concept design was developed following optimizations resulted from FEA analysis and based on results obtain during laboratory characterization campaign performed on different materials samples. Previous to structure development, appropriate tools were designed using 3D SolidEdge ST4 software and manufacturing was performed on 5 axes CNC machines, obtaining a composite Necuron 702 assembly tool. Moreover, the lightweight space mechanical structure components manufacturing was performed using autoclave technology. The paper presents in conclusion, the first experimental model (after preliminary FEA and laboratory tests validation) ready to be tested in vibration regimes.

3. RESULTS AND DICUSSION

3.1. Requirements for composite space electronic housing

The requirements for the CFRP composite housing were derived from ESA space standards (ECSS-E-ST-32C Rev. 1 – 2008 "Space engineering Structural general requirements", ECSS-E-ST-32-08C-2008 "Space engineering. Materials", ECSS-E-ST-32-10C Rev.1-2009 "Space engineering Structural factors of safety for spaceflight hardware", ECSS-E-ST-20C-2008 "Electrical and electronic") in conjunction with the requirements specification of the ADPMS aluminium reference housing. The specific requirements were defined taking into account all stages: on ground (Temperature, humidity,

atmosphere, biological, transport loads, test), Launch Environment (vibrations, accelerations, shocks, thermal flux, lightening impact, rain, birds), on orbit space environment- (low earth orbit LEO conditions) (temperature, vacuum, radiation, space debris, micrometeorites, atomic oxygen, micrometeoroid, cosmic rays, debris). A detail of space conditions (mainly on LEO orbit) will be detailed in the section regarding the material design concept, where each material choice within the space structure is explained. Furthermore, the main specific requirements for the composite space housing developed in the current work are summarized in Table 1.

Property	**Stage**	**Requirement**
Dimensions	on ground/launch /on orbit, LEO (<1500km [10])	Fixed to 460 mm x 154 mm 250 mm, wall thickness 2 mm *
Weight	launch /on orbit, LEO (<1500km [10])	reduction of 25 % compared to the aluminium reference
Accessibility (electronic units)	on ground/on orbit, LEO (<1500km [10])	High accessibility
First fundamental frequency	launch	set to be >150Hz
Random vibration	launch	qualification level Maximum 15g RMS
Strength, impact (space debris, micrometeorites) resistance	launch /on orbit, LEO (<1500km [10,11])	equal to reference housing
Thermal conductivity	on orbit, LEO (<1500km [10,11])	
Thermal cycling resistance	on orbit, LEO (<1500km [10,11])	[-70/+100 ºC]
Radiation shielding *	on orbit, LEO (<1500km [10,11])	UV (< 200 nm) SR EN ISO 14092:2002 [11]
Electromagnetic compatibility (EMC)	on orbit, LEO (<1500km [10,11])	equal to reference housing
Resistance to ultrahigh vacuum and gas particles environment (~10^{-6} Torr)/ 10^6 particle/cm^3	on orbit, LEO (<1500km [10,11])	LEO, at 800 km altitude: • ultrahigh vacuum: 10^{-9} mbar; outgassing [ASTM E595] • gas particles [O,He,O+,H] 10^6 particles/cm^3 • AO-flux: 4.5x10^{-16} atoms/cm^{2}s
Cost Minimized	on ground/launch /on orbit, LEO (<1500km [10])	

Table 1: Specific requirements for the space structure: advanced composite electronic housing structure developed within the present work [12]. * The goal in radiation protection was to provide shielding against spatial radiation in Low Earth Orbit that is comparable to the aluminium design with 2 *mm* wall thickness

An optimized structural materials design, including low outgassing and weight loss resin, high strength and stiffness reinforcement, peak composite phases volume fraction, optimum fiber orientation within the composite reinforcement network, metallic radiation shield, etc., was developed. The space mechanical structure developed is four times higher strength, stiffness and impact resistance compared with the aluminium reference. Likewise, it exhibit high fatigue endurance limit (up to 60% of the ultimate tensile strength), lower weight (35% lighter than aluminium structures), radiation resistance (focus on critical γ radiation), tailorable thermal and electrical conductivities by using special materials structural configuration, and is designed to provide the same functional requirements. The developed electronic housing structure is obtained at a net shape following manufacturing process (no need of final machining operations, thus cost reduction), and has high dimensional stability and no problems related to thermal expansions which appear on metallic structures during the service at thermal cycling exposure in the range [-70/+100 ºC].

3.2. Design: composite space electronic housing geometry

The design stage of the composite space electronic housing geometry, had as input data the set of requirements that must fulfil the final space structure, the key factor being to obtain a considerable mass saving as previously mentioned in Table 1 using less metallic elements, to obtain the proper tolerances with respect to inner and outer dimensions of the space structure, to correlate all design solutions with the manufacturing and technological steps used within the composite space structure demonstrator development. The reference used as entry data was the Proba 2 aluminium electronic housing and the dimensions were set fixed, 460 mm x 154 mm 250 mm, wall thickness of 2 mm [9]. Three CAD design solutions were proposed for the advanced composite microsatellite electronic housing. The next section presents the CAD parts for each of the three design solutions and the assembly solutions with rivets. Blind TRIPO rivets made in aluminium are used for all three solutions in the assembly operations. For first and second designs 4.2 mm diameter rivets were used as for the third design 3.2 mm diameter rivets.

The three designs are summarized in the figure 1, where both CAD elements, explode and closed configurations are presented.

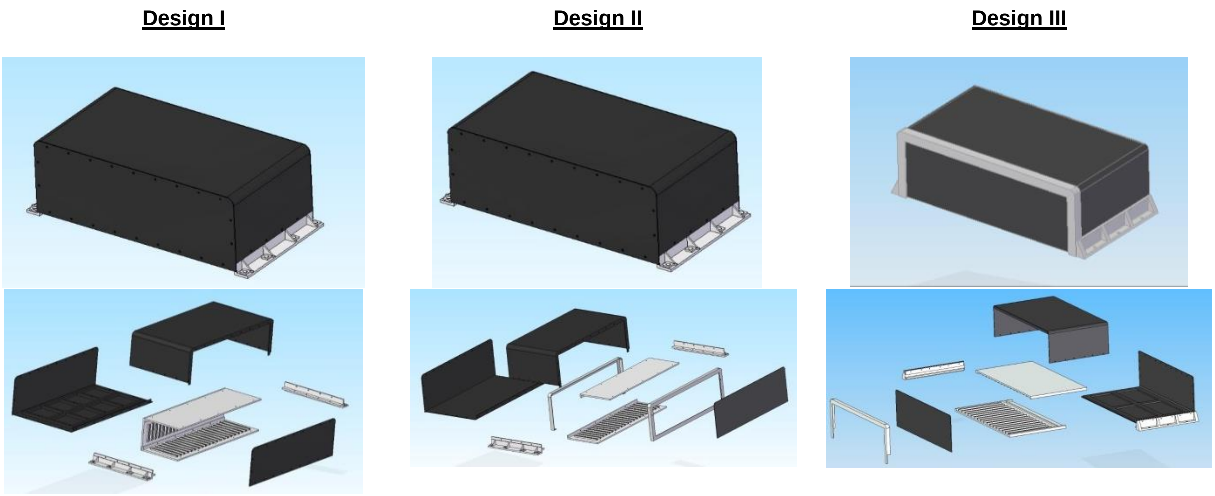


Figure 1: The three designs for the composite space electronic housing CAD elements, line 1: closed and line 2: exploded configurations

All three designs for the CFRP electronic housing, were validated through FEM analysis, in terms of vibration behavior and structural strength, following materials design assessment.

3.3. Materials structural design concept

For materials structural design concept, both on LEO orbit environment and multi-functional structure performance requirements were considered. The proposed concept has been validated by FEM analysis. Starting from FEM analysis an optimum design with aluminium reinforcement ribs has been developed and validated, whereas furthermore the final validation of both optimum design and materials concept will be done in future work performing experimental laboratory and scale tests. Main criterion of materials selection was weight reduction and strength. Figure 2 presents a sketch of one composite panel of the electronic housing, described as a laminate with simply-supported edges subject to a large number of constraints [13].

Advanced composite materials CFRP type (the lighter composites), with higher specific strength compared to the AA6082-T6 aluminium alloy reference material (2 mm thickness set) were selected and their performances were assessed throug experimental tests. Unidirectional carbon fibers were chosen for reinforcement phase assuring mechanical strength, stiffness and thermal, electrical tailorable properties. The matrix was a tthermoset cyanate ester resin with a total mass loss of less than 1% and a collected volatile condensable material of less than 0.1%, rradiation resistant and dimensional stability during on orbit service of the space structure.

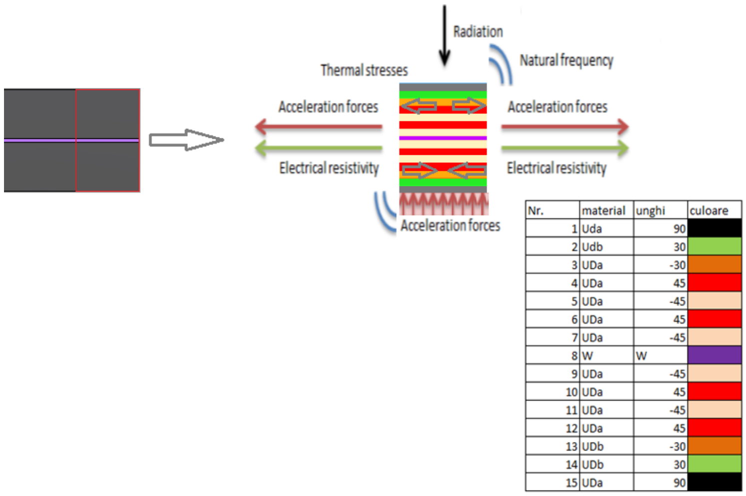


Figure 2: The composite model (panel), subject to different nature constraints (LEO environment)

The composite space structure has to be stiff and mechanical strength in vibration regime is critical (lunching stage). Although on orbit loadings are slight, impact strength is assessed for on orbit impact with space debris and micrometeorites. Performances and overall dimensional stability in cycling conditions (from -70 to +100 ºC) is an important issue. Critical zones are considered the metallic insertions-composite interfaces. Metallic ribs and mounting rails (in AA 6082-T651) are designed in the structure to assure local reinforcement for vibration resistance, increase thermal conductivity performances (AA 6082-T651: 180 W/m.K), assure electronic units integration and mounting the housing to the satellite. Residual stress concentrations can develop at these interfaces, where the composite has a near zero CTE. Unidirectional K1100 carbon fibers reinforcements were selected for thermal energy management, whereas M55J high modulus carbon fibers for structural purposes. Conductive carbon fibers are targeted in the composite structural design concept to assure heat dissipation when electronic units are the source. For both reinforcements the resin for the composite matrix was a cyanate ester. Both composite materials are represented in figure 3 with UD_a and respectively UD_b codes. The colours used are related to fiber orientations and sequence within the composite structure.

For particle radiation protection, the so-called Low Z – High Z – Low Z concept was applied. In this concept, a material having low atomic weight is on both sides of a material with the high atomic weight (see colour violet in figure 3). Several materials were considered for effectiveness in stopping electrons but also providing required thermal conductivity and mechanical characteristics, i.e. wolfram, gadolinium, stainless steel (for costs saving). The ease of manufacture, minimized production costs, keep dimensions tolerances were kept in high priority, the freedom of design being thus constrained. The technology used for the space structure manufacturing was the autoclave technology. The materials structural design concept for the composite electronic housing is summed in Figure 3. For use of example the optimized design validated by FEM analysis is presented. Table 2 summarize the components of the electronic housing space structure and materials.

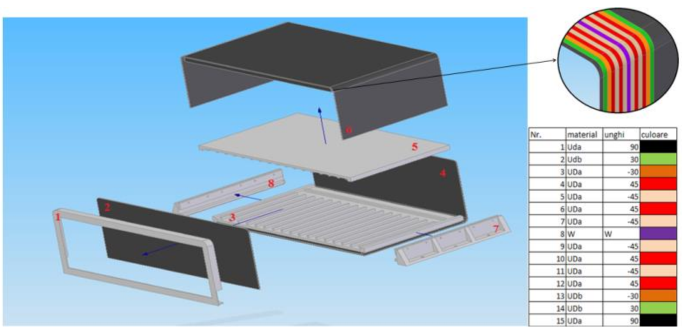


Figure 3. Parts of the composite electronic housing space structure (Optimized CAD model following FEA results): 1- frontal frame; 2- CFRP frontal panel; 3- Lower electronic components integration

plate; 4- CFRP L shape panel (back, low); 5- Upper electronic components integration plate; 6- CFRP U shape panel (upper, lateral); 7/8- Left/right stiffeners, ribs and rivets

Table 2: Electronic housing structure components including Composite* panels structural concept

	Part	**Material**
1	frontal rib	AA 6082-T651
2	frontal panel	Composite*
3	mounting rails for electronic units (lower)	AA 6082-T651
4	L panel (back and low)	Composite*
5	mounting rails for electronic units (upper)	AA 6082-T651
6	U panel (upper and lateral)	Composite*
7	Rib right	AA 6082-T651
8	Rib left	AA 6082-T651

The assembly will be made using blind tripo aluminium rivets, assuring strong fixing (vibration regime during lunching). As mentioned previously, the so-called Low Z – High Z – Low Z concept was applied, mainly for particle radiation protection. In figure 3, a zoom within the composite panel structure is defined. The materials used as precursors for composite laminate are: UD a- prepreg Hexply 954-2A/M55j (0,15 mm ply thickness) 60%vol. fibre de carbon ; UD b - prepreg Hexply 954-2A/K1100 (0,15 mm ply thickness) 60%vol. fibre de carbon ; Tungsten foil (0,08 mm thickness, special treatment for roughness assuring link to composite precursors). The colours are related to fiber orientation at different angles in the structure. The composite panels structural concept presents also week points, a special care will be taken with respect to regions where composite panels are joint. In this respect but also for increasing vibration resistance and assuring thermal conductivity in high vacuum conditions, aluminium stiffeners ribs were used. These metallic ribs are detailed in figure 4.

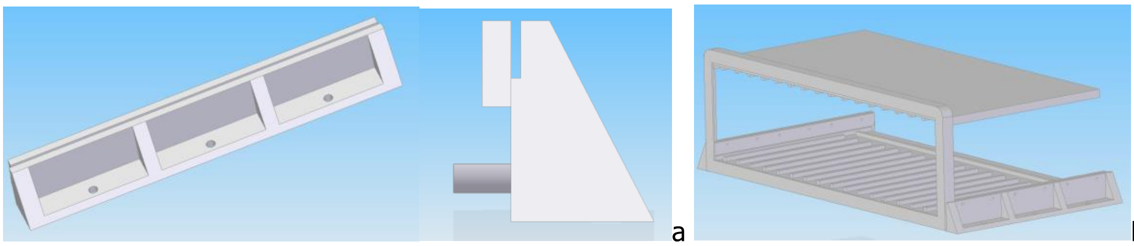

a b

Figure 4: a) Ribs right/left; b) ribs assembly, stiffeners for Optimized CAD model following FEA results

The ribs assembly has contact point with the composite panels (assuring radiation shielding, heat dissipation). The aluminium rivets with 3,2 mm diameter, assure the final assembly operation of ribs assembly to the composite panels structures, assuring a stiffer fixation and lower weight than safety screws.

3.4. FEM analysis for design validation

As mentioned, the biggest stresses and loadings are encountered at lunching stage using carrier rocket launcher. To prevail gravitational field using a limited amount of fuel the rocket will have to develop a considerable acceleration at which will be add the likely influence of atmospheric turbulence and vibrations encountered on the path generated by the combustion of fuel in the combustion chambers of the engine. Thus, the first step is to perform a static analysis that comprises all these influences for preliminary assessment of the composite electronic microsatellite housing

components. For Ariane 5, a model proposed by M. Sedighi and B. Mohammadi [14] involves 11g on OX, longitudinal rocket direction (lunching direction) and de 6 g on OY, lateral direction. The static nonlinear analysis on four configurations: design 1 (aluminium and composite); design 2 (composite); design 3 (composite). For aluminium and composite parts were used different methodologies for minimum safety coefficient calculation, the maximum Von Mises stress reported to the reference of yield stress and respectively the maximum stresses obtained on three directions reported to the maximum failure stress of composite plies on the three directions: "warp", "weft" , "thickness"/length, width, thickness. Table 3 presents the launching loads, static regime.

Table 3: Static Loads [14]

	Longitudinal	Lateral
Acceleration (g=9.8 m/s^2)/Static	7 g	1.5 g
Acceleration (g=9.8 m/s^2)/Static and Dynamic	11 g	6 g

For AU2GN (AlCu2Mg1.5Ni) aluminium alloy design, figure 5 presents maximum Von Mises equivalent stress level of 30 MPa in the region of L shape part joint to metallic ribs mounting rails used to mount the housing to the satellite, whereas details of the displacements are shown in Figure 6.

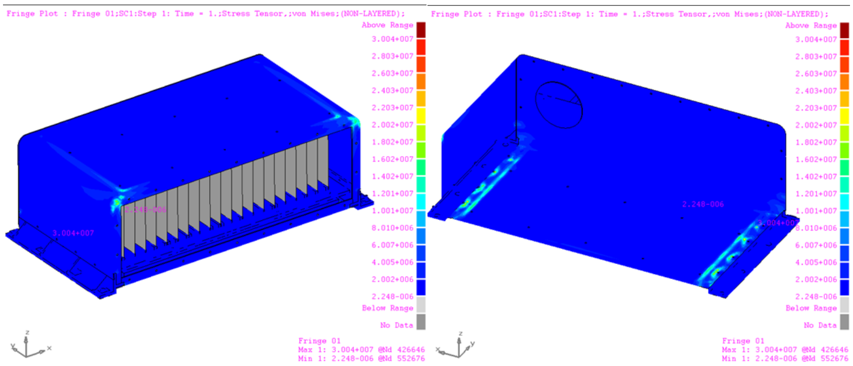


Figure 5: Maximum Von Mises equivalent stress on aluminium design

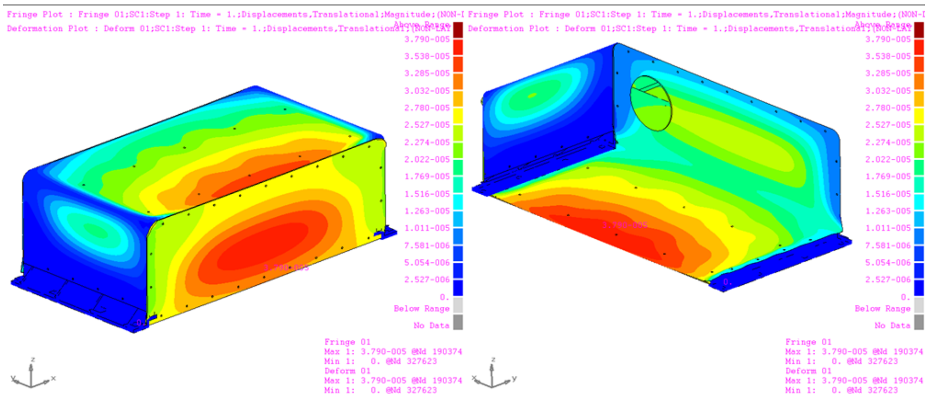


Figure 6: Displacements a) upper isometric view b) lower isometric view for maximum 3.8x10^{-5} m displacement

For the composite designs (design 1, 2 and 3), figure 7 presents the safety coefficient obtained using Hashin fabric theory for composite materials failure behavior assessment, whereas figure 8 describes the failure mechanism for composite electronic housing plies and figure 9 the maximum stress level for plies on all "warp" and "weft" direction.

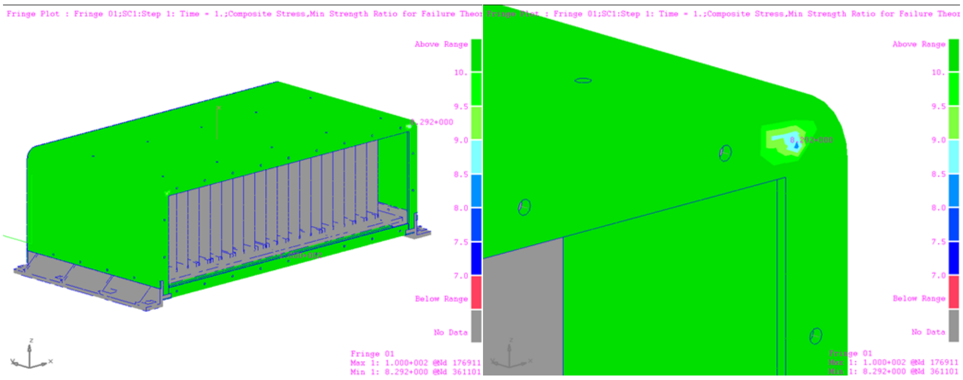


Figure 7: Minimum Safety factor distribution for composite Design 1 (SF minim 8.3 at composite electronic housing edge corner)

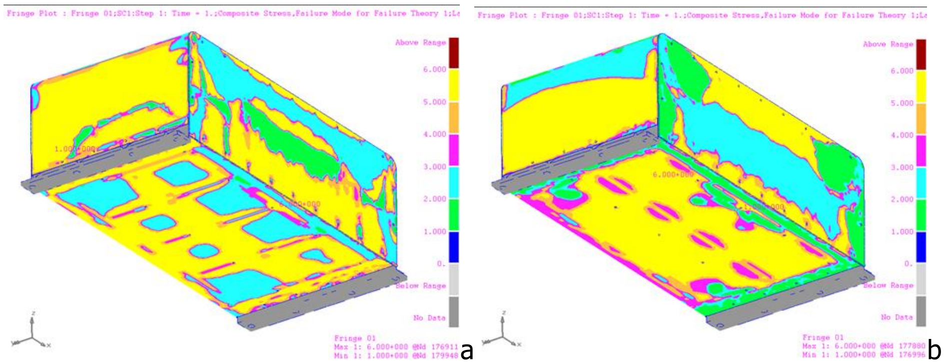
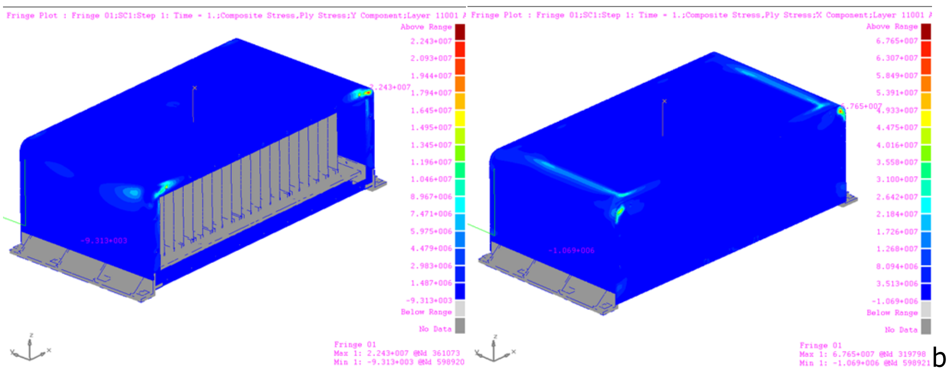


Figure 8: Failure mechanism for composite electronic housing Design 1 a) at first inner ply ; b) at external ply level



a

Figure 9: Maximum stress level for plies on all a) "warp" and b) "weft" direction

Results for static analysis with respect to safety coefficients on the three designs (Design 1 - aluminium, Design 1, 2 and 3 composite) are summarized in Table 4.

Table 4: Safety coefficients for static nonlinear loading * composite design

Safety coefficients				
Design	Design 1(aluminium)	Design 1*	Design 2*	Design 3*
Aluminium (sigma 0.2/ Von Mises)	11.3	136	59	5.6
Composite (Hashin)	--	8.3	5.2	5

One of the important issues rises on the structural analysis of a microsatellite structure is the behavior of structure under the dynamic loads during launching period. If the natural frequencies of the structure and the applied load frequency be in the same range, resonance phenomenon happens which could cause the severe damages on the structure and the components. First analysis was performed on electronic unit plates the results showing a 480 Hz first fundamental frequency (higher than 100 Hz). With respect to aluminium design 1, figure 10 shows the first two vibration modes, the first fundamental frequency is 405 Hz.

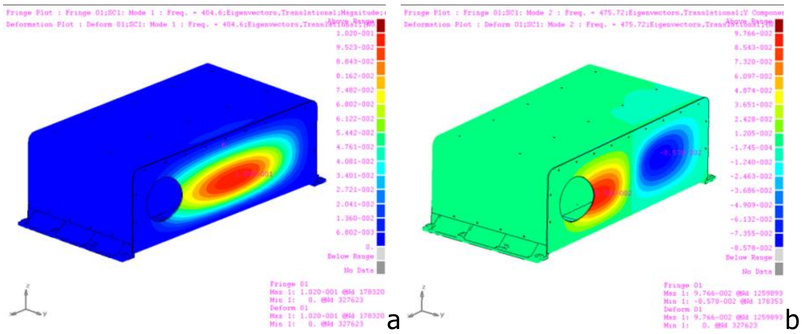


Figure 10: First two vibration modes at resonance of the aluminium design 1

For the composite Design 1, figure 11 shows the first three vibration modes, the first fundamental frequency is 99 Hz (lower than 100 Hz).

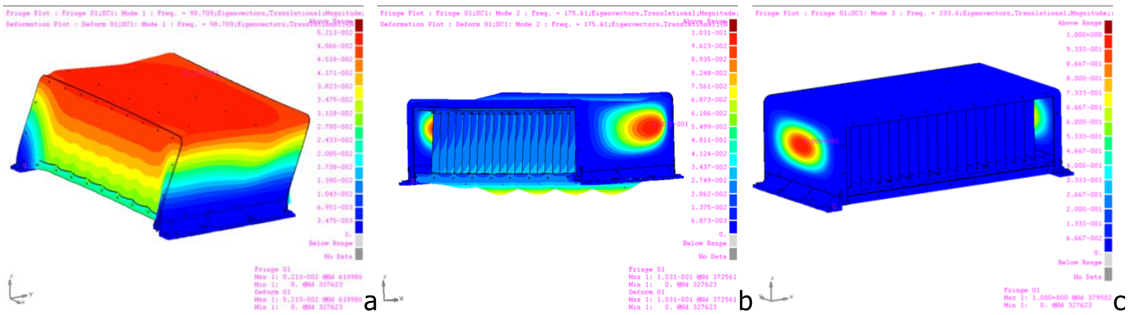


Figure 11: First three vibration modes at resonance of the composite electronic housing Design 1

The first vibration mode is a displacement on Oy axes, the second on Oz axes and the third is a vibration of lateral panels on Ox axes. For the composite Design 2, figure 12 shows the first three vibration modes. The first vibration mode is a displacement on Oy axes of the entire housing structure, the second on Oz axes and the third vibration mode is a lateral displacement on Ox axes.

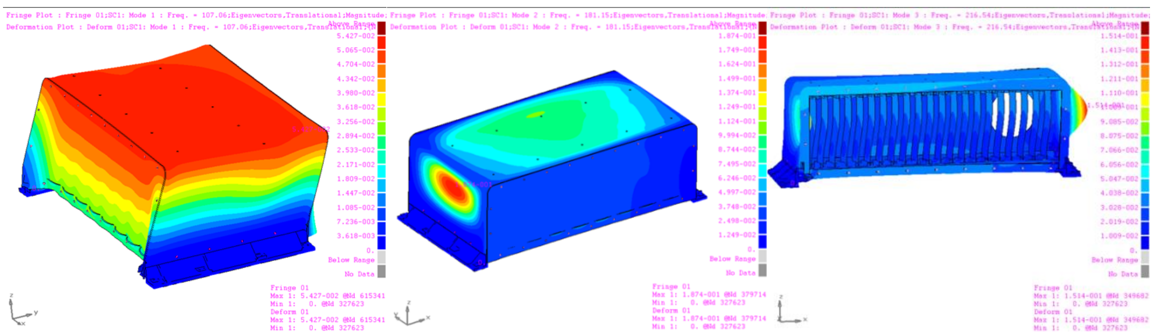


Figure 12: First three vibration modes at resonance of the composite electronic housing Design 2

The electronic unit plate in composite electronic housing structure Design 2, the first vibration mode is at 452 Hz, higher than 100 Hz. For the overall assembly of the electronic housing structure Design 2 first fundamental frequency vibration is at 107 Hz , close to 100 Hz. Figure 13 presents the first three vibration modes at resonance of the composite electronic housing Design 3.

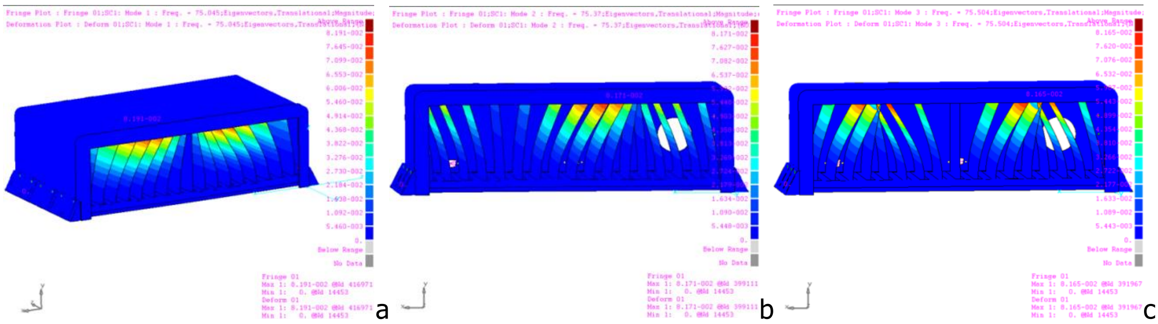


Figure 13: First three vibration modes at resonance of the composite electronic housing Design 3

Results of modal analysis, showing the vibration frequencies at resonance including the electronic unit panes, on the three designs (Design 1aluminium, Design 1, 2 and 3 composite) are summed in table 5. A first fundamental frequency higher than 100 Hz is critical requiremnent, in order to avoide resonance issues with luncher vibration frequences, whatever the fixing position of the electronic housing structure will be chosen at integration and mounting the housing to the satellite.

Table 5: Summary of modal analysis

Nr. frecv.	CAD 1 Aluminium	CAD 1	CAD 2	CAD 3	CAD optimized
1	404	99	107	86	115
2	475	175	181	98	135
3	477	234	216	117	250

3.5. Optimization and manufacturing of an experimental model

The only design that is not passing this criterion is the composite Design 3. Nevertheless, this design being the lighter an optimization was done with respect to increasing stiffness in critical local zones of the structure, and thus was set the final design for the composite electronic housing structure validated through FEM analysis as shown above. Based on FEM analysis and experimental results, following mechanical and structural materials design optimizations, an experimental model for the electronic composite space structure was developed. Appropriate tools and moulds were designed and made by CNC machining in Necuron 702 (an epoxy cast board with thermal resistance up to 140˚C). As machined L part mould component is shown in Figure 14.

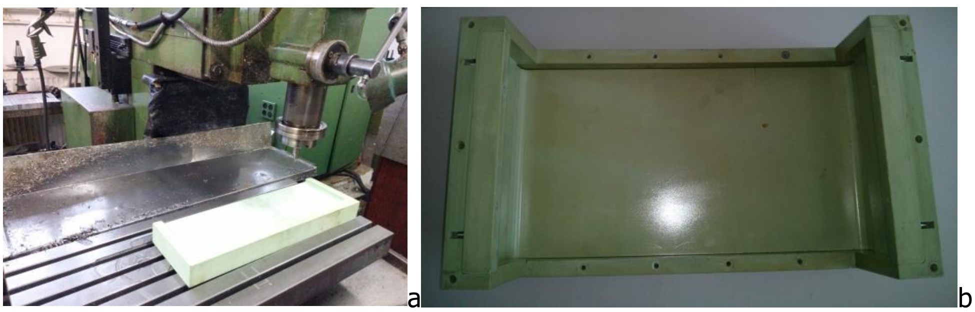


Figure 14: final L part mould component

Moreover, the lightweight space mechanical structure components manufacturing was performed using autoclave technology (curing cycle applied: heating rate 3˚C/min. to 140˚C-2 hours-

cooling rate 4˚C/min.to 60˚C. Figure 15 presents the experimental model ready to be tested in vibration regimes.

Figure 15: Experimental model ready to be tested in vibration regimes

4. CONCLUSIONS

Three geometry designs for a microsatellite composite electronic housing structure were developed in order to replace the existing reference made in aluminium alloy, targeting weight reduction, increased performances. All proposed designs were subjected to finite element modelling showing that for static regimes all designs are qualified, all safety coefficients were in the safety range, whereas for vibration regime, an optimization was performed on the lighter composite design 3 and stiffness was increased (resulting an optimized final design).

The optimized geometrical design (3) along with the material structural new concept design, were validated using FEM analysis in static and dynamic regimes (microsatellite lunching stage). A microsatellite composite electronic housing structure first experimental model was manufactured using autoclave technology for scale validation in both vibration regimes (lunching stage and on-orbit functioning relevant tests.

Compared to the metallic reference, the developed structure is lighter (25% weight reduction), and preliminary results showed that the CFRP composite housing structure, fulfils part of requirements, mechanical performances mainly for lunching stage (FEA results) and on-orbit environmental resistance (laboratory experimental tests). Experimental laboratory and scale tests results for both optimum design and materials concept will be subject of o further paper.

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