Composite material designs for lightweight space packaging structures

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ABSTRACT

This paper presents a study on advanced material designs suitable for lightweight space packaging structures. During this study, several material designs were proposed, evaluated and in the end three packaging structures were designed, manufactured and validated through a test campaign. The material designs proposed consisted in hybrid laminates composed of a composite substrate and integrating metallic foils with high atomic number (Low Z - High Z - Low Z concept) and metallic coatings to increase the structure's protection against harsh space conditions. The packaging structure design selected was a 2U CubeSat. A FEM analysis was performed on two different designs which showed good mechanical resistance under static loads, and regarding the modal analysis, the natural vibration frequencies of the CubeSat were in the imposed limits (outside of the critical range of 1-125 Hz). To reproduce the dynamic environment encountered during launching stage, vibration tests were performed. The structures were validated through a test campaign (vibration tests) and their first vibration mode overcomes 100 Hz, results predicted by the FEM analysis.

KEYWORDS: *polymeric composites, space structures, metallic coating, CubeSat, FEA*

1 INTRODUCTION

Nowadays the use of fiber reinforced polymer composite materials in space applications and beyond is increasing. The application of fiber-reinforced composites (FRC) as structural materials has grown continuously during the last 50 years owing to their unique combination of low density, high stiffness

and strength as well as toughness [1], and they are considered the next generation of materials for space-borne applications [2].
In order to design a material for space applications, an important aspect that must be considered is the total mass of the structure. The launching cost depends on this fact [3], and launching a satellite can cost about $20,000–$50,000/kg [4], so the materials should be as light as possible.
During the designing phase of structural materials and structures for space applications it is important to take into account the space environment regarding vacuum, radiation and thermal cycling, to ensure the durability of the material in harsh conditions. For example, satellites experience several types of mechanical, thermal, and electromagnetic disturbances during their development, manufacturing, and launch to their final operating position in space [5].
One of the usual materials used in space applications is aluminum, it is a good structural material and even if it is lighter than other metallic materials, it is heavy compared to advanced composites. Aluminum is used as radiation shielding in space structures, it is supposed to attenuate the energy and flux of radiation to a level below a certain threshold that is safe for the space structure electronics and payload [6].
Other aspects that have to be considered for aerospace materials are found in ECSS-E-HB-32-20 Part 1A/2011 "Space engineering: Structural materials handbook – Part 1: Overview and material properties and applications" [7] and the main considerations are: the outgassing rate (which has to be as low as possible), microcracking resistance (the materials have to provide high resistance to microcracking due to micrometeoroids impact), dimensional stability (a low thermal expansion coefficient) during exposure to high/low temperatures (thermal cycling), gamma radiation resistance, atom flux attack resistance, proton and electron shielding, UV and VUV shielding. Also, according to ECSS-E-HB-32-26A/2013 "Space engineering. Spacecraft mechanical loads analysis handbook" during spaceflight, the spaceflight hardware is subjected to static and dynamic loads like: static acceleration, low-frequency dynamic response, high-frequency random vibration environment, high-frequency acoustic pressure environment, shock events [8]. Cho et.al. [5] studied the dynamic responses of a satellite which integrates composite materials in case of random excitation by finite element analysis and vibration testing, their results can enhance the knowledge of the vibration characteristics and physical behavior of a monocoque type satellite structure.

2 RESEARCH GOAL AND METHODOLOGY OF WORK

The goal of the present study was to design and manufacture an advanced structural material which integrates a metallic coating, material design suitable for a space packaging structure and as a final result, a demonstrator packaging structure had to be manufactured.
The driving factor of developing an advanced material for packaging applications was radiation shielding capability ensured by a multifunctional design. The packaging structure used for this study was the skeleton mechanical structure of a nanosatellite - 2U CubeSat.
The CubeSat concept was developed in 1999 as a collaboration between California Polytechnic State University (Cal Poly) and Stanford University's Space Systems Development Laboratory [9]. The CubeSat is a small satellite, equipment with reduced weight and smaller size than a conventional satellite and in the last years it was widely used for all type of missions. System requirements and recommendations for QB50 Programme was consulted [10].
Two CAD designs were realized along with a study on advanced material designs suitable for this type of space structure. Numerical simulations (static and modal analysis) were performed to provide an optimum CAD and material design. The manufacturing technology chosen to manufacture the demonstrator structure was the autoclave technology. Irradiation tests were performed to assess the shielding capability of the proposed material designs.
After manufacturing the final packaging structure, a test campaign was performed to provide information regarding the behavior of the manufactured space structure in vibration conditions.

3 RESULTS AND DISSCUSIONS

3.1 Composite space packaging structure geometry

Different CAD designs were modeled using SolidEdge ST4 software. Two designs were evaluated, which were composed from two components (one cap and body) or three components (two caps and body). CAD designs were used as input data for the FEM analysis along with the structural material designs. The final and optimum CubeSat design selected for manufacturing was composed of three components, two caps and the CubeSat's body. The experimental model was proposed to be manufactured as a solid model and after the manufacturing process to be mechanical processed using a pattern to get the skeleton version. In Fig. 1 can be observed the evaluated CAD models.

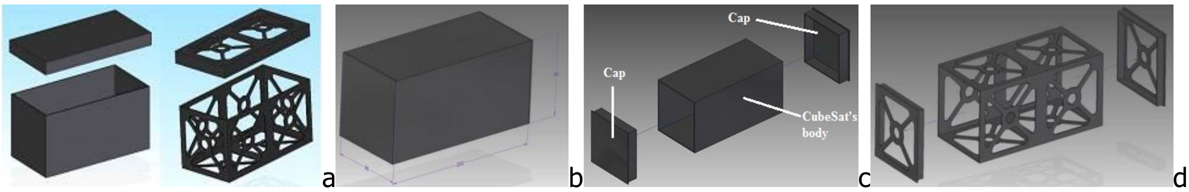


Figure 1. CAD models of the 2U CubeSat structure. a) CubeSat design with two components (one detachable cap); b, c) CubeSat – Final solid model with two detachable caps; d) CubeSat – Final skeleton model with two detachable caps

3.2 Structural material designs

The study on advanced structural material designs was focused on developing a hybrid material which included metallic coating on polymeric substrate which ensure protection against harsh environmental conditions from space. Also, the material designs proposed were integrating the concept Low Z – High Z – Low Z, which ensure radiation shielding. This concept was studied by others researchers and it was concluded that materials with low atomic numbers attenuate protons, but electrons and photons are attenuated more by elements with high atomic number (like tungsten) [11,12]. Three categories of materials were investigated during this study: materials for the substrate, materials for Low Z – High Z – Low Z concept and suitable metallic coating materials.

To manufacture the structure substrate, two types of polymeric composite material precursors were taken into consideration: prepregs Gurit EP 127-C20-45 T2 (thermoset matrix: epoxy-cyanate ester blend, reinforcement: 60% carbon fiber) and HexPly M49/42%/200T2X2/CHS-3K (thermoset matrix: epoxy resin, reinforcement: 58% carbon fiber). The substrate represents the Low Z material.

Materials considered as an effective particle radiation shielding for the Low Z – High Z – Low Z concept were: tungsten (Z=74), tantalum (Z=73), stainless steel and aluminum (the last two being some low-priced and not so effective solutions). Also, except metallic foils was studied the integration of metallic powders like Al-Si alloy powder (88%Al, 12%Si), Ni powder (purity >90%, Z=28), Mo powder (particle diameter 45µm, Z=43).

Different types of coatings were analyzed: metallic materials (Zn, Al, Cu), intermetallic compounds (Ni-Al: 95-5), alloys (Monel, Babbitt) and functionally graded materials - FGMs composed by different layers of metallic materials (like Zn/Ni-Al: 95-5, Zn/Ni-Al: 95-5/Cu, Zn/Monel). The FGM coatings are characterized by a gradual variation in volume, chemical composition and structure, which leads to a gradient of properties in the material so multifunctional surface coatings can be obtained.

The autoclave technology was chosen to manufacture the samples for the irradiation tests and for the demonstrator CubeSat. Also, to coat the composite structures the thermal spray coating technique was used.

3.3 Numerical simulations (static and modal analysis)

Static analysis

Numerical simulations (static and modal analysis) were realized using NASTRAN and ANSYS programs and were made on two material designs. For the FEA analysis were used the particularities of Vega launcher in terms of maximum loads and accelerations. The numerical simulations were performed to determine the mechanical resistance of the structure under static loads, taken from the User Manual of Vega launcher [13]. Also, it was simulated the natural vibration frequencies to ensure if the structure is outside of the critical range of 1-125 Hz.

The first design consisted in a CubeSat structure with a substrate made of 8 plies of HexPly M49 with a symmetrical integrated aluminum foil (0,009 mm thick) and coated with one layer of Zn with a total thickness of 100 µm. The first numerical simulation was made on the skeleton version of the CubeSat composed of two components (the detachable cap on the sideway of the structure).

The second design was a CubeSat structure made by 8 plies of EP 127-C20-45 T2 which integrates a Ta foil (0,08 mm thick) and a FGM metallic coating with a total thickness of 100 µm, coating composed of one Zn layer (50 µm), and one Monel layer (50 µm). The second numerical simulation was made on the skeleton version of the CubeSat composed of two detachable components (caps). In Fig. 2 and Fig. 3 can be observed the distributions of the global maximum yield indices and the yield indices of the metallic coating using the Tsai-Wu theory [14]. In both cases it was determined that maximum values of the yield indices are very low compared with the yield limit of 1, which shows that structures have a good mechanical resistance for the imposed requirements.

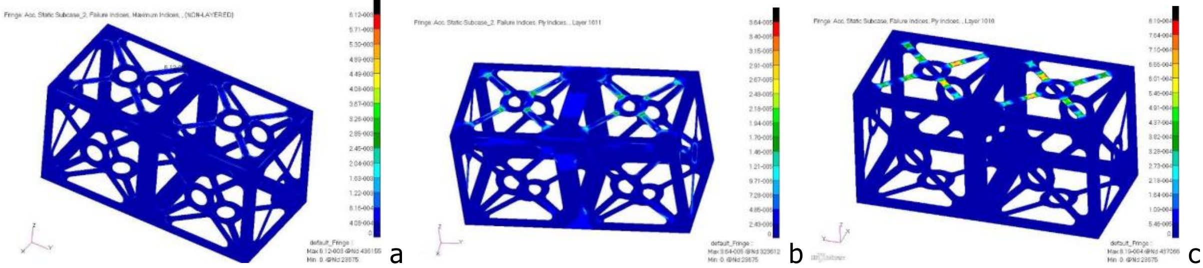


Figure 2. FEM simulations on 2U CubeSat – first design

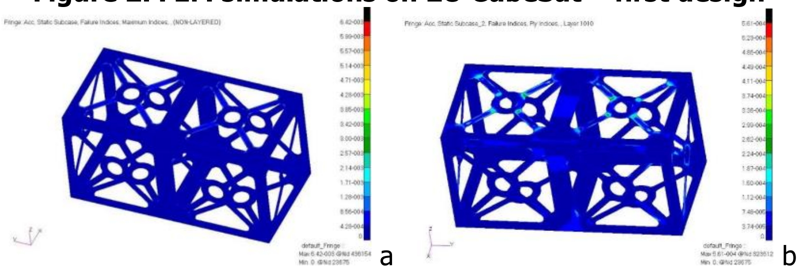
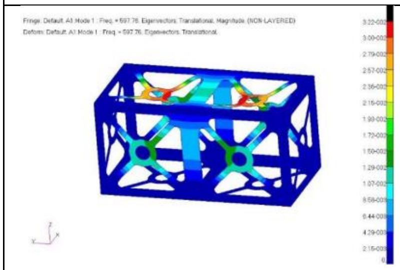
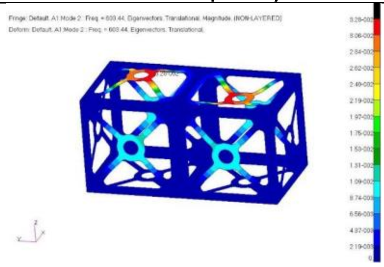
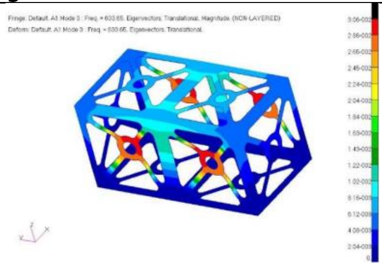
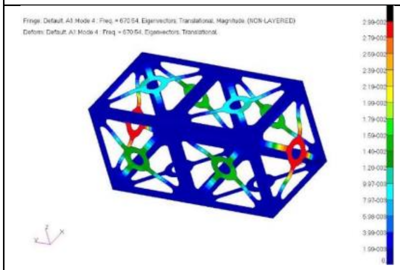
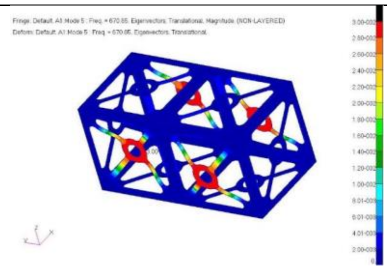
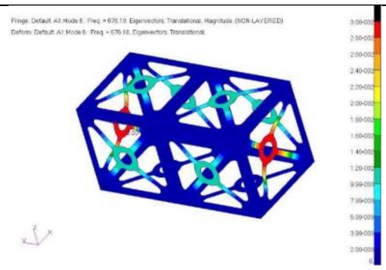
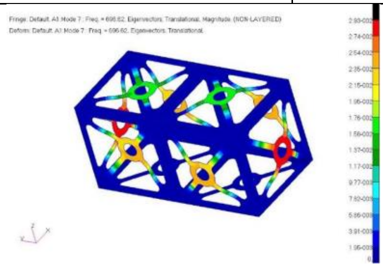
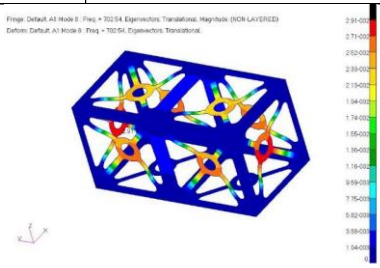


Figure 3. FEM simulations on 2U CubeSat – second design

Modal analysis

Table 1. Natural vibration frequency for the first design

Natural vector and frequency – first design		
 **F1=598 Hz**	 **F2=603 Hz**	 **F3=634 Hz**
 **F4=671 Hz**	 **F5=671 Hz**	 **F6=676 Hz**
 **F7=696 Hz**	 **F8=703 Hz**	

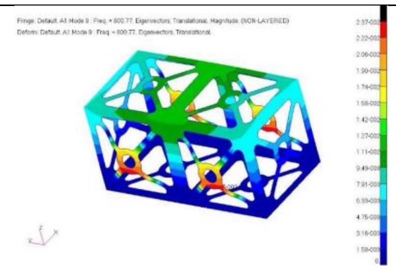
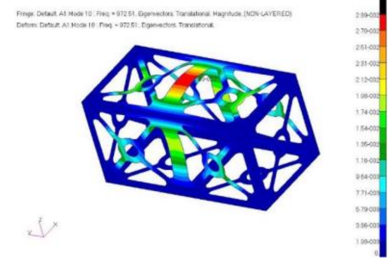
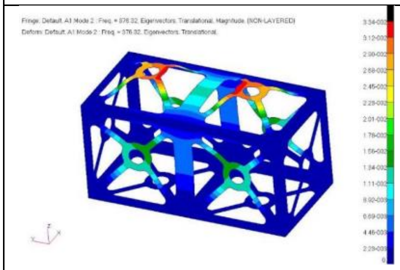
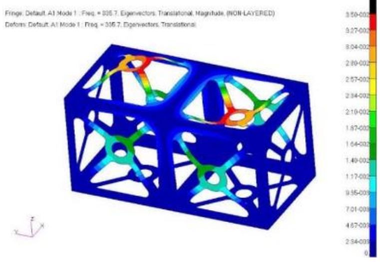
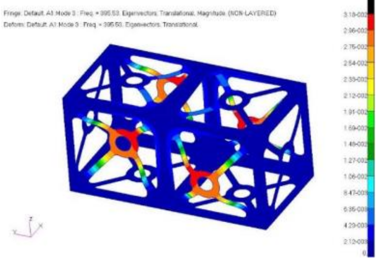
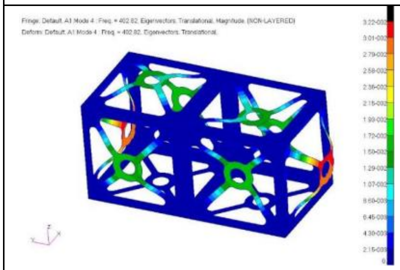
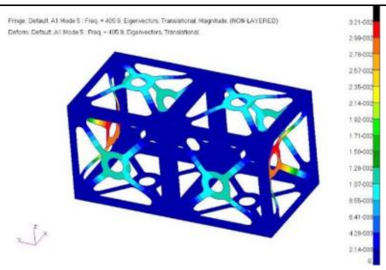
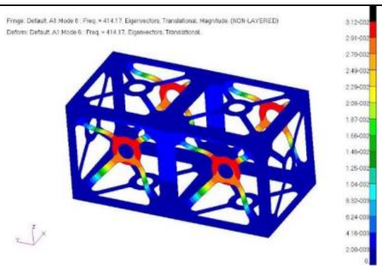
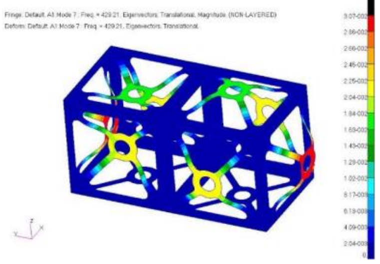
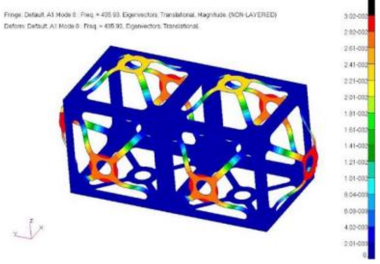
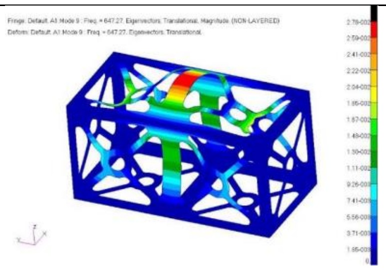
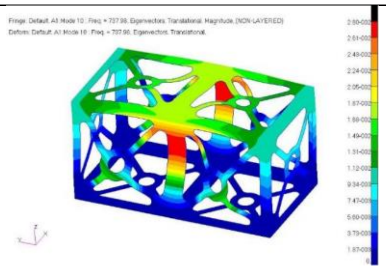
Natural vector and frequency – first design	
 F9=801 Hz	 F10=973 Hz

Table 2. Natural vibration frequency for the second design

Natural vector and frequency – second design		
 F1=336 Hz	 F2=376 Hz	 F3=395 Hz
 F4=402 Hz	 F5=406 Hz	 F6=414 Hz
 F7=429 Hz	 F8=436 Hz	
 F9=647 Hz	 F10=738 Hz	

The modal analysis is used to determine the modal parameters of a structure (frequency, damping and modal shape), for all the natural frequencies in the area of interest. The goal of this analysis is to ensure the modal reaction. In this analysis, every forced dynamic deflection of a structure can be represented by a weighted sum of the structure's natural vibration modes. The natural vibration modes for the two CubeSat designs are presented in Table 1 and Table 2.

In case of the first design, the natural frequencies modes 1, 2, 4, 5, 6, 7, 8 are defined by localized deformation on the faces, without affecting the frame of the CubeSat, natural frequencies modes 3, 9, 10 present natural vectors characterized by deformations on the faces and the frame of the structure. In case of the second design, the natural frequencies modes 4, 5, 6, 7, 8 are characterized by localized deformations without affecting the CubeSat's frame, mode 1, 2, 3, 9 and 10 are characterized by deformations on the faces and CubeSat's frame.
Regarding the mission requirements observed in User Manual of Vega launcher, it was concluded that the natural frequencies of the CubeSat's structures falls within the required limits (1-125 Hz). The natural frequencies of the second structural design are lower compared with the first structural design, the reduction is mainly caused by the difference of elastic modulus and density of the integrated metallic foils for the Low Z – High Z – Low Z concept (aluminum foil versus tantalum foil). Due to the fact that the majority of the localized deformation are on the faces of the CubeSat's it was selected as final optimum design the second structural design which has two caps and integrates tantalum foil and FGM metallic coating (Zn-Monel).

3.4 Mold design and manufacturing process

The CAD model of the final CubeSat structure was used as input data for the mold design. Three types of molds were proposed along with different materials suitable for the manufacturing process: **Wood**, **Necuron 702**, **Steel**. The material chosen for the mold manufacturing process was Necuron 702, it is a board made of epoxy resin suitable to manufacture molds for polymeric composite structures reinforced with fibers with cure temperatures in the temperature range 130-142°C. This material was selected due to its good compatibility with the composite material used to manufacture the demonstrator structure, its good and easy machinability and easy to handle (it is a lightweight material). Thus, two molds were designed for the manufacturing process of the CubeSat: one mold used for the caps and one mold used to manufacture the CubeSat's body. The molds were designed to allow the manufacturing of two components simultaneously (Fig. 4). Mold components were cut and milled from a Necuron 702 board, the active surfaces of the molds had to be flat surfaces with a reduced roughness to avoid the adhesion between the advanced composite material and the surface of the mold and to obtain even surfaces of the structure. To reduce the roughness of the mold, the surfaces were polished with fine sandpaper (P1200) and coated with a gelcoat – Necuron V7.

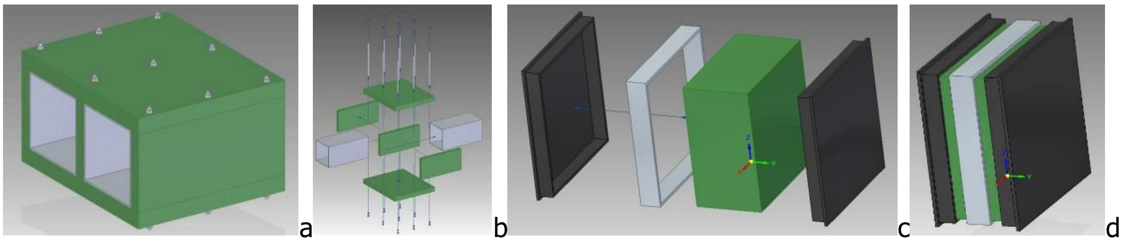


Figure 4. Molds designed to manufacture the CubeSat. a, b) CAD model of the double mold used for the CubeSat's body – 2 bodies; c, d) CAD model of the mold used to manufacture the CubeSat's caps

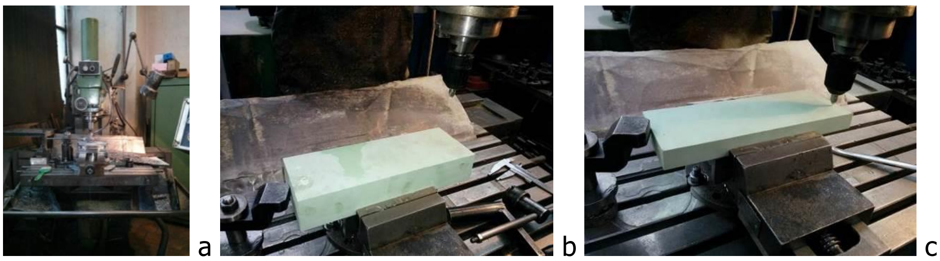


Figure 5. Manufacturing of the Necuron 702 mold components

3.5 Manufacturing and processing of the final packaging structure

Before starting the manufacturing process, the Ta foil (99,95% Ta with thickness of 0,08 mm) for the Low Z – High Z – Low Z concept was sandblasted with F33 corundum to ensure a physical bonding with the prepreg plies, afterwards it was degreased with acetone.

For the manufacturing of the demonstrator, the prepreg EP 127-C20-45 T2 was chosen due to its good mechanical properties and the possibility to use it in space applications with service temperature range (in cured state) between -55°C to +185°C [15]. To manufacture the final lightweight space packaging structure, the autoclave technology was used. First, the mold surface was cleaned with acetone and a release agent was applied, then four plies of EP 127-C20-45 T2 were placed on the mold surface, a Ta foil was placed on top of prepreg plies and another four plies of prepreg. Afterwards, the vacuum ensemble was realized (peel ply, release film, breather, vacuum bag) and it was connected to the vacuum lines of the autoclave. To manufacture the vacuum ensemble for the CubeSat's body, two internal vacuum bags were necessary to be connected to an exterior vacuum bag to ensure the pressure on structure's walls. The curing cycle was selected considering the instructions form the material's technical sheet and the properties of the mold (temperature resistance max.142°C), and it is showed in Fig. 6. Fig. 7 presents the manufacturing process of the CubeSat's components, body and caps.

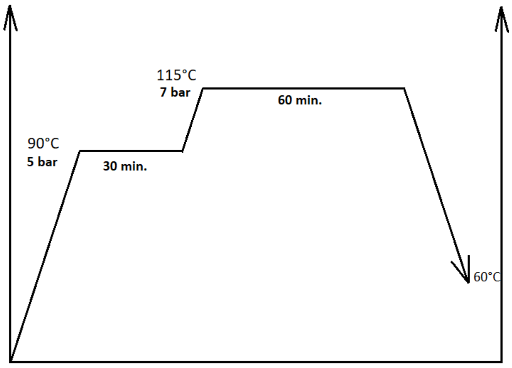
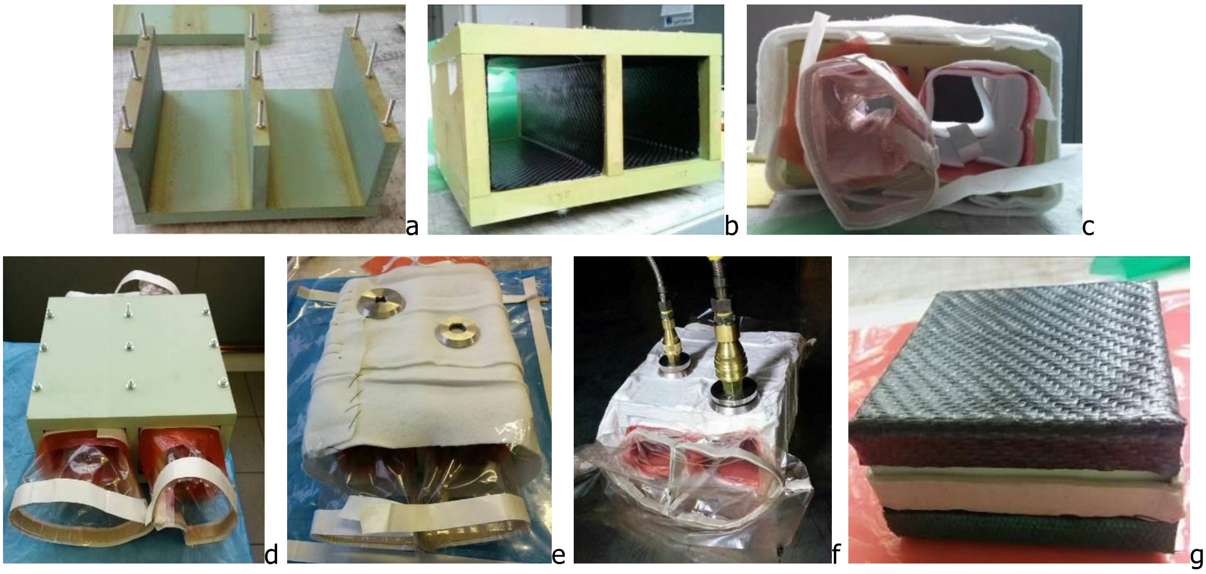
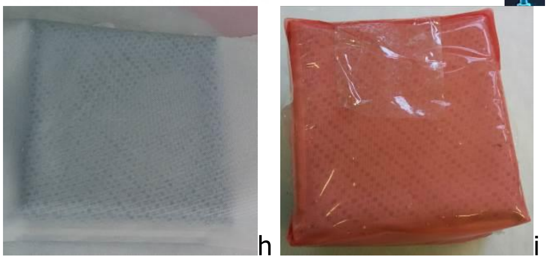


Figure 6. Curing cycle of the CubeSat structure chosen according to material's technical sheet [15]

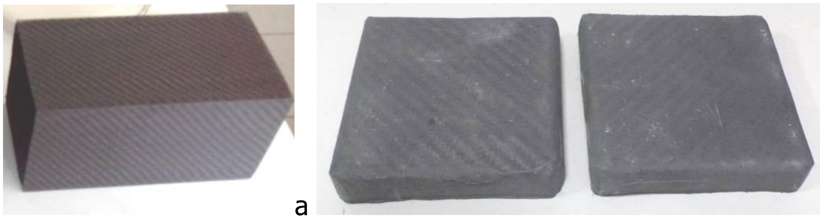
After the curing cycle, the components were allowed to cool over night from 60°C until ambient temperature to avoid the internal tensions in the structures when they are released from the molds. Fig. 8 presents the CubeSat's components – solid model. Three solid models of the CubeSat structure were manufactured. Skeleton version of the CubeSat was realized using a water jet cutting machine – process showed in Fig. 9.





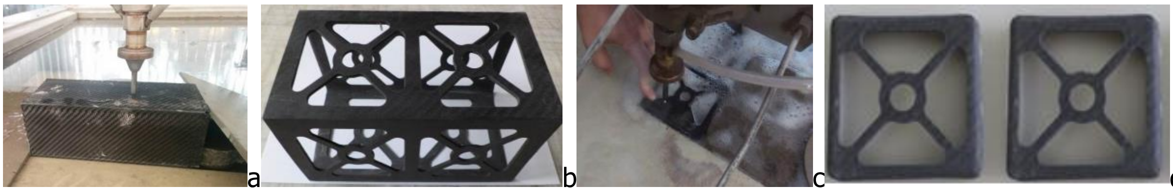
h i

Figure 7. Steps of the manufacturing process of the CubeSat's body and caps. a) CubeSat's body mold assembling; b) prepreg plies placing; c, d, e) vacuum bag ensemble; f) vacuum lines coupling; g, h, i) CubeSat's caps manufacturing process



a b

Figure 8. The CubeSat's components. a) the CubeSat's body; b) the CubeSat's caps



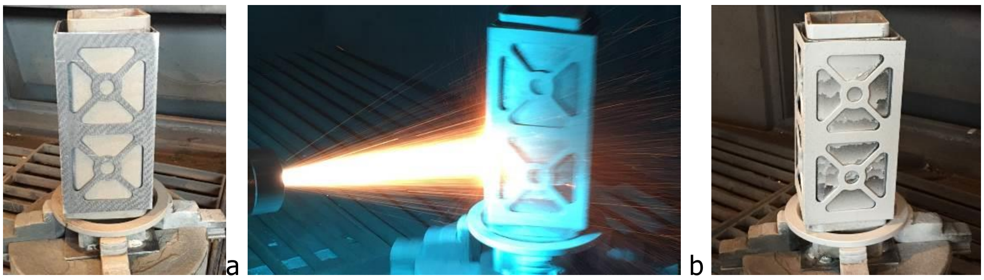
a b c d

Figure 9. a) CubeSat's body during the water jet cutting process; b) the CubeSat's body – skeleton version; c) CubeSat's cap during the water jet cutting process; d) the CubeSat's caps – skeleton version

The skeleton version of all CubeSat's components was sandblasted using a Pioneer equipment and F30 electro-corundum (process parameters: pressure 4 bar, distance 100 mm, 6 times), the objective of this iteration is to ensure the adhesion between the metallic coating and prepreg precursor. The structures were then coated with three different metals: Zn, Babbitt and a FGM coating made of Zn and Monel (Fig.10). To coat the structures, the thermal spray coating technology was used. After the coating process, the CubeSats were assembled with rivets A3 (dimensions Ø=3.2 mm, l=10 mm) (Fig. 11). Table 1 presents the coating process parameters.

Table 3. Coating process parameters

Material	Pressure [bar]	Distance [mm]	Tension [V]	Intensity [A]
Zn	5	100	22	157
Babbitt	2,5	100	28	157
Monel	2,5	100	28	160



a b c

Figure 10. a) CubeSat's body after the sandblasting; b) CubeSat's body during the coating process; c) CubeSat's body after the coating process

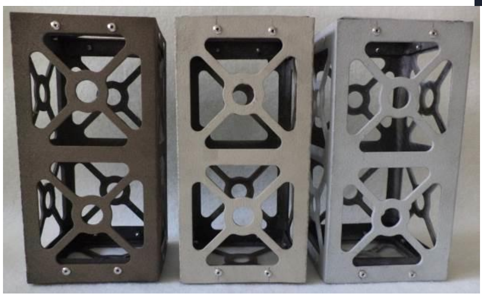


Figure 11. Assembled CubeSats

3.6 Test campaign of the packaging structure

The test campaign consisted in vibration tests and irradiation tests.

Vibration test campaign

For the vibration tests, a TestPOD was designed and manufactured from metallic sheets (Fig. 12), to keep the CubeSat structure on the shaker in the same position as in the rocket during the launching stage. As is specified in ESA standards, an incomplete or improper on ground testing approach significantly increase space project risks leading to late discovery of design or workmanship problems or in-orbit failure [16].

The vibration tests were focused on reproducing the dynamic environment during the launch of the satellite. The CubeSat structures were subjected to various testing profiles to observe if they meet the qualification requirements for mechanical space structures.

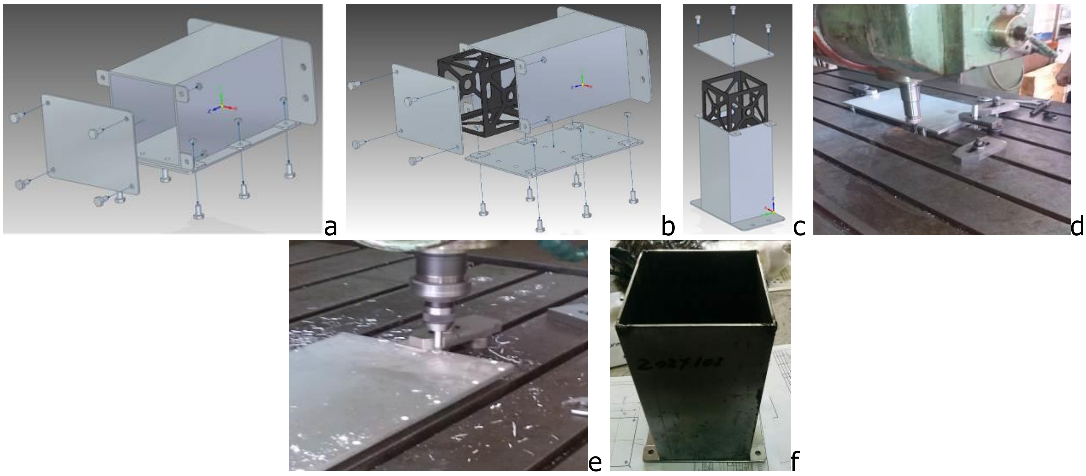


Figure 12. CAD design and manufacturing process of TestPOD structure: a, b, c) TestPOD design; d, e) manufacturing of the TestPOD; f) final structure

The vibration tests were performed on three axes (OX, OY, OZ) using a TV 50303 shaker and consulting the QB50 qualification requirements. Vibration survey tests performed were:

- Resonance survey test;
- Quasi-static tests;
- Sinusoidal vibration tests;
- Random vibration tests.

In Fig. 13 is presented the mounting of the TestPOD on the shaker.

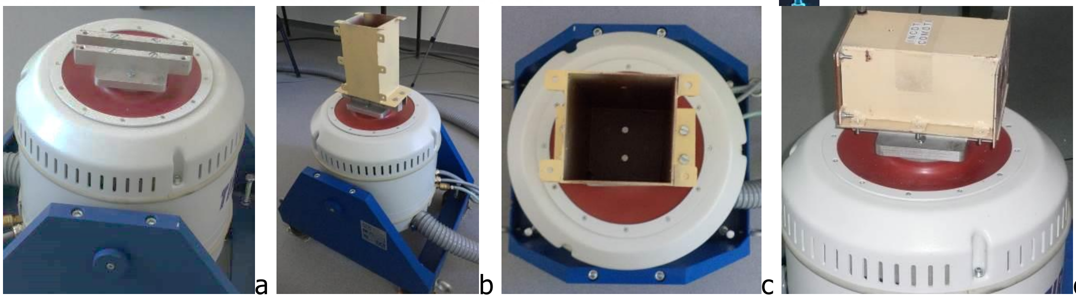


Figure 13. TestPOD mounting on the shaker

A resonance survey test had to be performed before and after running each test to ensure the stability of the structure and for passing the test, the lowest natural frequency of the CubeSat shall be >90 Hz. The resonance survey was performed in the frequency range of 5-100 Hz and an amplitude of 0,15 g. For the quasi-static tests, the shaker method was used. As a general rule for the quasi test a low excitation frequency must be used, where the frequency must be a third from the first natural mode. Quasi-static tests were performed for 120s at a testing frequency of 15 Hz due to the fact that at this frequency the shaker can produce the acceleration of 10,8 g, according to the qualification level of QB50. Sinusoidal vibration tests were performed at qualification level in the frequency range of [5Hz – 1,3g, 8Hz – 2,5g, 100Hz – 2,5g] with a rate of 2 oct/min, and random vibration tests were performed in the frequency range of 5-2000 Hz with a RMS acceleration of 8,03g for a period of 120s. Resonance survey tests were performed before and after each test, and they showed that no major differences between the response frequency of the structures weren't observed, sustaining the fact that the structures didn't showed major changes after each testing phase. The results of the sinusoidal test showed a minor change between the response frequencies (approximately at 60 Hz) which can be caused by the mounting bracket of the TestPOD, not by the natural vibration mode of the structure. Resonances between frequencies range of 5-100 Hz weren't observed.
Random vibration tests are important for the designing and validation phases of space structures [17]. Random vibration test on OZ axis for the CubeSat structures showed high frequencies resonances on frequencies 1380 Hz, 1648 Hz, 1930 Hz. It was concluded that the registered resonances were generated by the TestPOD, not by the CubeSat structures. Excepting the resonances on OZ axis, the random vibration tests can be considered valid.

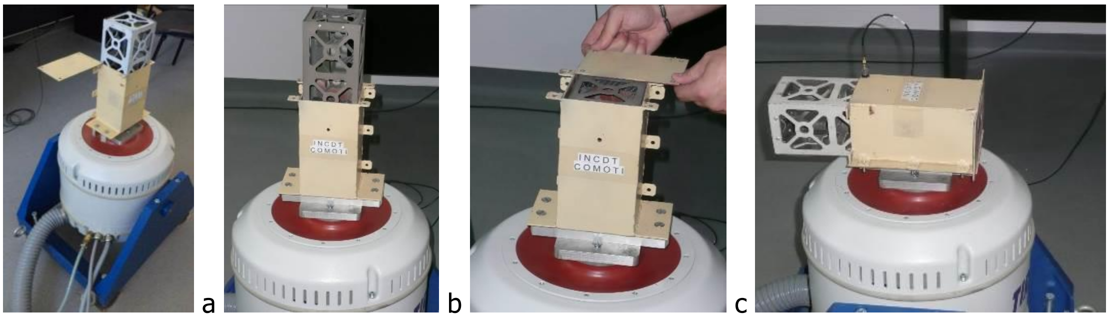


Figure 14. Structures fitting on vibration device

Irradiation tests

The irradiation tests with proton beam and electron beam were realized. The purpose of the tests was to determine the radiation shielding capability of the material designs. To perform these tests, the standard ISO 15856:2010 [18] was consulted in terms of simulations of radiation exposure of non-metallic materials. To reproduce low Earth orbit (LEO) conditions in term of electron irradiation environment the energy ranges have to be between 40 keV to 5MeV and in term of proton irradiation it has to be between 100 keV and 200 MeV.
The proton irradiation tests were performed using the accelerometer HVE FN Tandem Van de Graaff de 9MV (proton beam energy of 15,8 MeV), respective electron irradiation tests using the electron linear accelerator ALID-7 (electron beam with average energy of 6 MeV). For the tests were used references made of carbon reinforced composite and hybrid composite samples coated with metallic materials (Zn, Babbitt, Zn/Monel) and integrating Low Z – High Z – Low Z concept. In both cases the sample were used as target for the particle beam for 30s.

In case of proton irradiation, it was observed that the beam's energy penetrates the reference laminates but it does not penetrate the hybrid laminates. In case of electron irradiation, it was observed that even in case of the reference samples the electron beam is attenuated after targeting the samples (shielding percentage of approximatively 10%), and the hybrid samples can attenuate the electron beam up to 50%.

4 CONCLUSIONS

As a result of this study, advanced material designs were developed for a lightweight space packaging structure, in this case for a nanosatellite 2U CubeSat. The advanced material design consists in advanced polymeric composite (cyanate-epoxy blend reinforced with carbon fibers) which ensures high resistance when operating at negative and positive temperatures (-55ºC…+185°C) also, the design integrates a Low Z – High Z – Low Z concept (a tantalum foil) and metallic coatings. Two designs were validated through static and modal analysis, the 2U CubeSat structures made of carbon fiber reinforced polymer showed a good mechanical resistance under static loads and the natural vibration frequencies of the CubeSat were in the imposed limits, outside of the critical range of 1-125 Hz. Three CubeSats were manufactures with different coatings (Zn, Babbitt, Zn/Monel). All three coated CubeSat structures were submitted to vibration testing. The structures were validated and the first vibration mode was higher than 100 Hz. Proton and electron irradiation tests (charged particles found in space) were completed, and it was observed that the proposed material designs have shielding properties. The material designs provided in this study will be used as a starting point for further researches regarding advanced material designing for space structures.

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