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STRUCTURAL DESIGN AND ANALYSIS OF A STUDENT CUBESAT 1U

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Abstract

New space is a new frontier in the space market. Private institutions, Universities, and the production of small space devices are the new horizons of this sector. In this sense, the Gama Cube Design team of the University of Brasilia in Brasilia (Brazil) is developing GamaSat-1, a 1U remote sensing cube sat with the purpose of producing new aerospace engineering capabilities in the students of the university as well as inserting the institution in the space market. For the success of the satellite, it is important to align the needs of the project, the available budget, and the current standards in order to ensure the integrity of the systems to the space and launch environment. In this way, this paper studies the design and analysis of the primary and secondary metallic structures of the GamaSat-1 CubeSat using computational tools and Finite Element Analysis by means of software from *ANSYS* ®. Static analyses were performed for the extreme load environment as well as dynamic analyses based on the generalized dynamic load environments obtained from NASA standards. The results showed positive safety factors (according to the von Mises yield criteria) for the studied static load environment, a natural primary frequency of 187.2 Hz and response to vibration spectra that satisfy the normative requirements. Finally, according to the proposal, it was obtained a metallic structure that meets the requirements and specifications raised allowing the integration with other subsystems and with total mass and inertia compatible with known commercial solutions but with lower cost.

Keywords: CubeSat, strucutural design, static and dynamic loads.

1. Introduction

During the design of a CubeSat, several system requirements must be met, as described in the document "CubeSat Design Specification" [1] from California Polytechnic State University. These requirements include the mechanical requirements that are fundamental to ensure the integrity of the satellite and the launch vehicles in the most different environments. In this paper the structural metallic design and the mechanical analyses of the structural systems of the mission GamaSat-I, developed at the University of Brasilia, are presented following the requirements specified in Cal Poly's CDS REV13, NASA's GSFC-STD-7000 and NASA-STD-6016 documents.

GamaSat-1 is a 1U CubeSat nanosatellite project developed by Gama Cube Design, an aerospace project development team at the University of Brasilia in Brasilia, Brazil. The project was born from the need to insert and improve the university's students in the satellite market. The development of the satellite structure was divided into 4 parts and the project as a whole in seven parts and four main reports: MCR, PDR, CDR, and FRR.

In the conceptual project phase, the structural design was developed with the compromise of ensuring the lowest cost both in the choice of materials and in the manufacturing of the prototype, always respecting the normative requirements, the design restrictions and structural resistance. Thus, it was selected the use of aluminum alloy 7075-t6 and the manufacture of the -Z and +Z faces by subtractive manufacturing from a massive block of material in order to obtain a full structure and subtract the need for fasteners.

In the mechanical analysis, the global behavior of the structure was studied under the critical structural load environment listed in the previously mentioned standards, using computational analysis tools available on the ANSYS platform. The static analysis focused on the critical launch phase, using the high and low frequency static and vibro-acoustic load factors of the Space Launch Vehicle (SLV) Minotaur I, which was considered the worst loading environment of the launch vehicles researched. In addition, the dynamic analyses were supported by modal and harmonic response, random vibration and shock spectrum response analyses in accordance with the requirements of GSFC-STD-7000 standard [2].

2. Theoritical Background

2.1 NewSpace

The *NewSpace* is translated as a new frontier of space exploration, where it allows itself to be exclusively carried out by government initiatives and starts to act also private initiatives, with companies and clusters from various countries actively acting in the production of satellites, launch vehicles, and ground segments [3]. With this new phase, together with the accelerated advance of research and development of projects in the space scope, traditional satellite models are undergoing a profound revolution, making room for miniaturized models with lower weight by several orders of magnitude compared to giant geostationary satellites [3].

This new era of technology is now being used on a large scale throughout the world, and Brazil could not be left out, there is today the national project of the VLM (Microsatellite Launching Vehicle) that proposes to carry small useful loads to the space with reduced cost, thus meeting the premises of NewSpace. In addition, at the Federal University of Santa Catarina (UFSC) the *Constellation Catarina* program is being developed with the objective of developing a constellation of Brazilian remote sensing CubeSat, this program generates growth prospects for the new scenario of spatial activities. for students and for professionals in the sector, who are looking at an opportunity to insert Brazil in the development of these fundamental technologies today.

2.2 CubeSat

The "CubeSat" project began in 1999 designed to fulfill the need to advance research on the space environment and have access to space more frequently using small satellites with the proposal to fulfill the requirements of one or several missions, using technology similar to that already used in large satellites, but which took less time to develop and had lower production and operation costs [1].

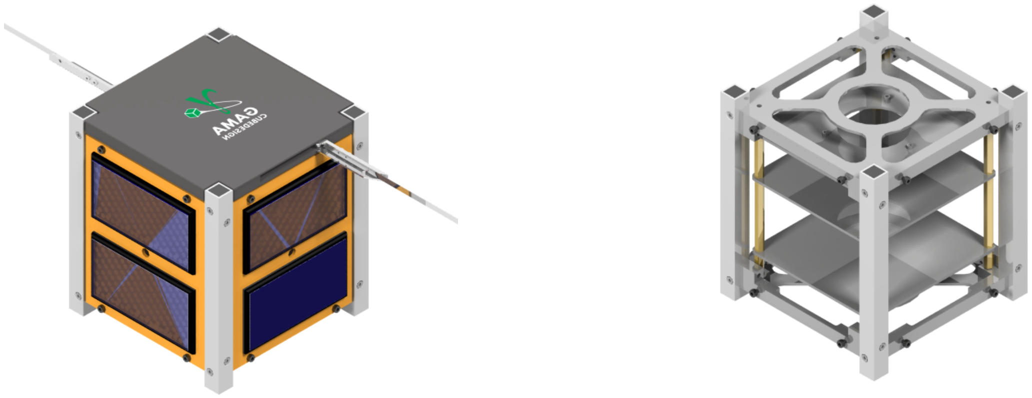
The CubeSats have a standardized design, its concept, in general, emerged in 1998 at the Stanford Space Systems Development Laboratory (SSDL), having dimensions: 10cm x 10cm x 11cm and a volume of approximately 1L, this CubeSat is then called of 1U because it represents only one unit [4]. However, since the beginning of the project, CubeSat variations have emerged and today we can have CubeSat whose units range from 1.5U to 6U, and even new configuretions are always in development . The great advantage of CubeSat was that it made the launching of small payloads accessible and democratized space exploration, which was previously carried out only by large space agencies and government agencies [4].

Currently in Brazil, of the initiatives related to microsatellites, the new Microsatellite Launch Vehicle (VLM) and the CubeSats project "Constelação Catarina" predominate. In addition to these, the country has a national competition held by INPE (National Institute for Space Research) in which teams from several Brazilian universities meet in order to develop new technological capabilities in the space scenario. The missions of this competition are limited to evaluating the knowledge of students in the development of nanosatellites from the area of control and telemetry to that of structural design, one of the most critical for defining the integrity of systems and components to the space environment.

2.3 GamaSat-01

Gama CubeDesign is a team from the University of Brasília, which has the initiative to promote the development of nanosatellites in the academic environment through theoretical studies and practical activities for the development of CubeSats. In this scenario, the team is currently involved in the project of the nanosatellite GamaSat-01, Figures 1 (a) and (b), a remote sensing 1U CubeSat whose main objectives are to participate in the "CubeDesign" competition carried out by the National Institute for Space Research (INPE) and, in the future, to mature the project to make it the university's first operational satellite.

The GamaSat-01 project follows the planning model developed by NASA, which is divided into 7 phases and 4 main reports: MCR, PDR, CDR, and FRR. A fifth report called MOP presents the CubeSat operations manual and will also be done.



(a) (b)

Figure 1 – 3D view of the conceptual design (a) and 3D view of the structural design (b) of the GamaSat-01 nanosatellite.

In the development phase of the structure and design of GamaSat-01, a methodology of iterations between the different subsystems is applied to obtain a coherent final product within the requirements, maintaining the integrity of the Mission.

The architecture of the GamaSat-01 was designed so that its assembly could be facilitated during competitions and that it would meet the required structural requirements, in addition to complying with the standard standards for CubeSats.

The external design is configured to accommodate flat faces where electronic components and other systems will be attached. On the lower and upper faces, the camera and the antenna are placed respectively. The faces are joined to the columns using M3 screws in alloy steel, class 12.9, due to their structural and dimensional properties.

The internal organization of the subsystems is made by shelves arranged vertically along with the structure. These shelves divide the satellite into 3 sections, the upper section is for the control components, the middle section is for the onboard computer and attitude sensors, finally, the lower section accommodates the power and payload subsystems (sensors and cameras).

2.3.1 Mechanical environment

During the orbital launch, the satellite is subject to static and dynamic loads induced by the launch vehicle. For the design and dimensioning of the satellite structure, it must be foreseen that a combination of severe loads will be encountered at every moment of the flight [5].

From the standpoint of static loads, critical conditions are encountered during maximum dynamic pressure, thrust tail off, and just before thrust termination [6]. As for the dynamic load environment, it includes: low frequency longitudinal vibrations, low frequency lateral vibrations, random vibration, acoustic vibrations and shocks [6].

2.3.2 Specification

To protect the launch vehicle (LV) and ensure the safety of the CubeSat and the Poly Picosatellite Orbital Deployer (P-POD), Cal Poly has developed a series of specifications gathered in the CubeSat Design Specification (CDS). As part of the CubeSats community, all participants should ensure the safe operation of their systems by following the minimum requirements and tests set out in this document [1].

For structural design, the CDS specifies dimensions and weight limits to be respected, random vibration and shock analyzes must be performed as part of the validation program.

In addition to this, the technical standard GSFC-STD-7000 is an important document for checking systems and subsystems of spatial projects in different environments and areas of analysis if launch vehicle enviromentis unknown [1], as is the case of the GamaSat-01 project.

2.4 Finite Elements

Finite element analysis (FEA, Finite elemental analysis) is a powerful mathematical tool for the study of structures [7]. The phases for a correct analysis vary as proposed, however, at least they must follow the phase of creating a structural model, proceeding to the model discretization with elements and nodes, insertion of boundary conditions, and finally, post-processing where the results of interest will be acquired and validated from reference values, normally taken from physical tests performed under similar conditions [8].

Is the must important software for analysis by finite element methods, however, in this article, the computational tools of ANSYS ® will be used due to the availability of licenses granted by the latter to the University of Brasília.

3. Methodology

The development of the satellite structure was divided into 4 parts. First, planning was done together with information about the requirements and constraints that must be satisfied. In the conceptual design there was the elaboration of concepts and structural designs that would satisfy the requirements and meet the restrictions imposed on the project. In the preliminary design from the geometry and design specifications already defined it was sought to model the structures and analyze them,through computer-aided engineering (CAE), to verify that the response to the loads was compatible with the proposed requirements and constraints. Finally, in the detailed design, the final structure was refined and validated against the necessary norms and standards.

4. Results

4.1 Structural Design

Guided by the requirements and project constraints defined in the planning phase, and by the premise of obtaining an economically feasible structure that could be put into effect even with the budget constraints that have affected various sectors of industry and research since the crisis generated by the new Coronavirus pandemic in 2020, A structural design based on subtractive manufacturing and aluminum alloys was developed. It is important to note that the development of the structural design was performed in conjunction with finite element analyses (FEA) for verification and optimization of the structure.

The resulting structure is built in two parts (primary and secondary), the primary structure has 10 main parts joined by screw connections and locked by Seeger rings which make up the outer body of the cubsat, Figure 2 (a). It is evidenced that the -Z and +Z faces of the CubeSat are designed to be as a single piece manufactured by subtractive manufacturing techniques to reduce the possibility of joint looseness due to vibrations.

The secondary structure is made up of seven parts, with three shelves responsible for fixing the electrical components and subsystems, and four spacers responsible for fixing the three shelves and spacing them as needed, Figure 2 (b).

The main frames and shelves are entirely designed in anodized 7075-T6 aluminum alloy and the spacers in C26000 brass alloy, the design mechanical properties taken into account for the project [9] are shown in the Table 1. The volume and total mass of the resulting structure were 1.257E-4 m^3 and 0.387 kg, respectively.

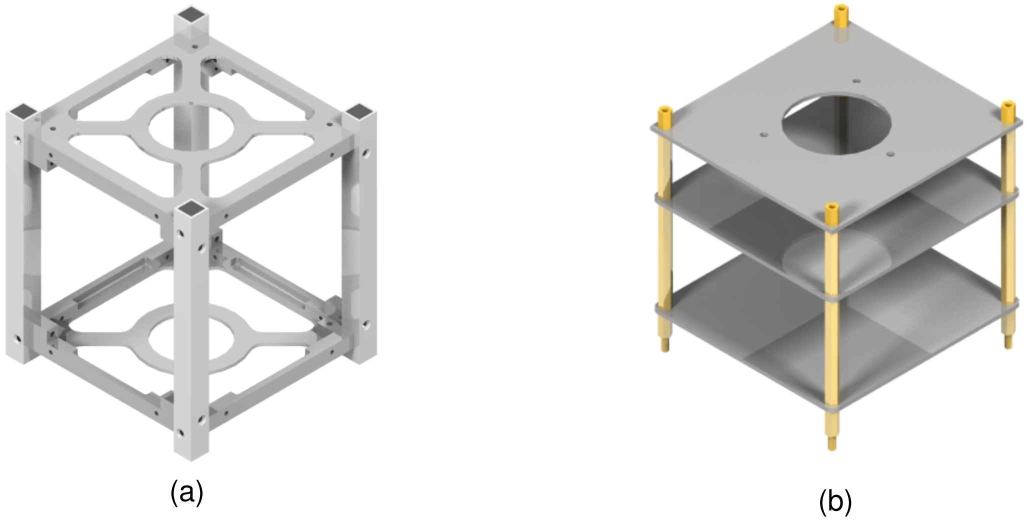


Figure 2 – Primary (a) and secondary (b) structure of the nano-satellite GamaSat-01.

Table 1 – Mechanical properties of main materials [9].

Properties	**Al 7075-T6**	**Brass C26000**
Modulus of Elasticity [GPa]	71.7	110
Poissons Ratio	0.33	0.33
Tensile Strength [MPa]	570	345
Yield Strength [MPa]	505	170
Elongation (Plate) [%]	11	-
Elongation (Bar) [%]	9	28

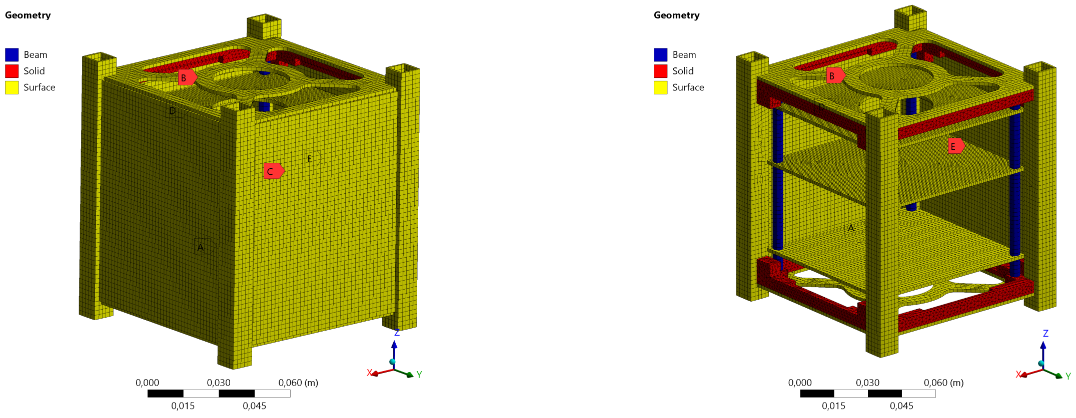
4.2 Structural Analysis

This section explains the analyses performed to verify the integrity of GamaSat-01. Detailed static and dynamic analyses have been performed from finite elements whose results have been oriented to demonstrate structural integrity after launch to ica GSFC-STD-7000 standards.

4.2.1 Finite Element Model

The complete structure (primary and secondary) of the satellite was modeled in design software by which the CG of the body was also computed applying the proper material of each structural component. Then the finalized structure was exported to *Ansys*. In Ansys, the structure was then configured to a finite element model compatible with the structural body analyses and finally meshed observing the available computing power and the required detailing.

The finite element model used to simulate the primary and secondary structure of the satellite is shown in Figures 3 (a) and 3 (b).The principal beams, -Z faces and the partitions where the payload is fixed and subsystems were modeled as shell elements, he horizontal beams as three-dimensional elements and the spacers were modeled as beam elements connected to the side beams and partitions by adjacent nodes. In addition, the model is simplified by assuming that all structural element and subsystem bolts are omitted and replaced with bonded type contacts or others more consistent with the case.



(a) (b)

Figure 3 – Structural model (a) and structural model with details of the internal structure (b) of GamaSat-01.

The inertial properties of the payload components and the main subsystems connected to the partition panels were modeled by lumped mass elements. The boundary conditions are imposed according to the flight environment to which the structure is to be analyzed. The most refined model of the structure consisted of 79642 nodes, 55950 elements and 5 lumped mass.

4.2.2 Static analysis

Static analysis is fundamental to predict the behavior of the cube-sat during the launch phase, where various loads are transmitted to the cube-sat structure. To determine the load acting on the cube-sat, it is necessary to know the load factors. In addition, safety factors must also be applied to limit the loads, these are shown in Table 2 taken from the GSFC-STD-7000 standard [2].

Table 2 – Safety factors applied to limit loads [2].

Failure Type	**Static**	**Sine**	**Random**
metallic yield	1.25*	1.25	1.60
Rupture of metallic element	1.40**	1.40	1.80
Rupture of composite element	1.50	1.50	1.90
Joint and adhesive breakage	1.50	1.50	1.90

*2.00 for analysis without tests **2.60 for analysis without tests.

The launch load environment is composed of a combination of steady-state and transient low-frequency and high-frequency vibroacoustic loads. To determine the combined loads for any given launch phase, the sum of the square root of the low and high-frequency dynamic load factors is superimposed on the steady-state load factor [18], if appropriate of a particular launcher, Equation 1.

$$N_i = S_i \pm \sqrt{(L_i^2 + R_i^2)} \tag{1}$$

Where N_i is the combined load factor, S_i he static load factor in the direction i, L_i ow frequency random vibration factor in the direction i e R_i the high-frequency random vibration load factor in the direction i.

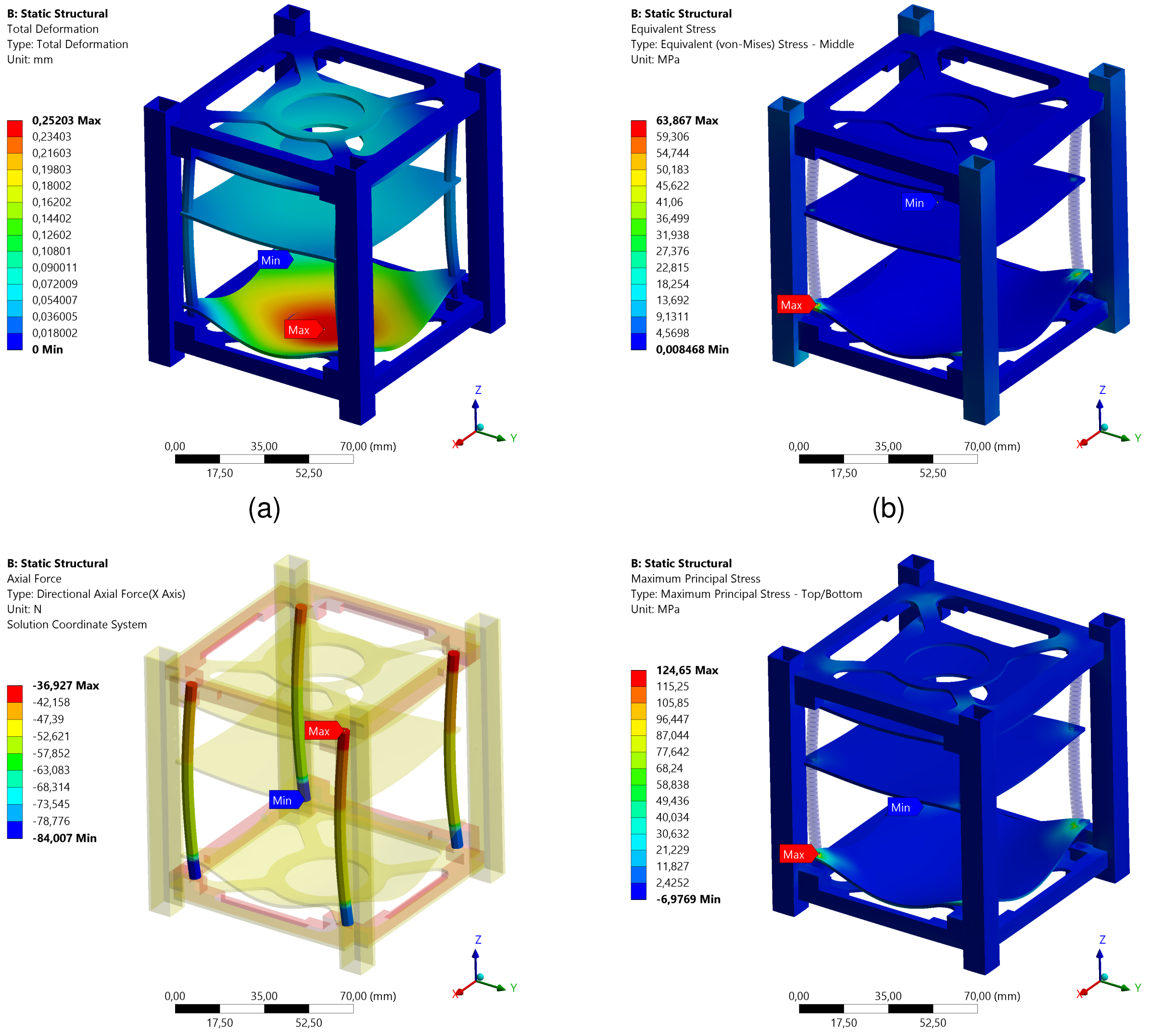
For the present study, the launch loading environment chosen was the Minotaur 1, because it is the launch vehicle with the most critical loading conditions presented by the satellite launcher user guides obtained [10]. The Table 3 shows the load factors of this launch vehicle [11].

Table 3 – Minotaur I Launch Vehicle Load Factors.

Type	Magnitude [G]
S_{Long}	13
S_{Lat}	± 3.3
Li	5
Ri	14.1

From this, the maximum combined load factor in the longitudinal direction was determined ($\mathbf{N_z}$) which is 27.96 G's and the lateral ($\mathbf{N_x} = \mathbf{N_y}$) is equal to $\pm$ 18,26 G's.

The boundary conditions for the static analysis were the maximum combined rocket load factors and the mass of two 1U CubeSats (2.66 kg) inserted above GamaSat-01 in the P-POD. The stresses on the CubeSat structure must not exceed the yield strength of the materials used in order to maintain structural integrity [12]. Therefore, the von Mises stress must be less than the yield strength of the material. The Figures 4 (a) to 4 (d) present the displacement and stress gradients of relevance for the analysis of the response to static loads.



(a) (b)

(c) (d)

Figure 4 – Total strain gradient (a), von Mises equivalent stress gradient (b), axial stress gradient in spacers (c) and maximum principal stress gradient (d) of the primary and secondary structure of the GamaSat-01 satellite.

From these results, we could determine the safety factor (SF) for the structural components of the CubeSat, as presented in Table 4.

Table 4 – Stress values and safety factor of the GamaSat-01 structure.

Component	**Stress [MPa]**	**Admissible Stress [MPa]**	**SF**
Structure	124.65	505	4

Thus, the numerical results obtained indicate that the CubeSat structure is safe for the static loads of the critical phase (launch).

4.2.3 Modal analysis

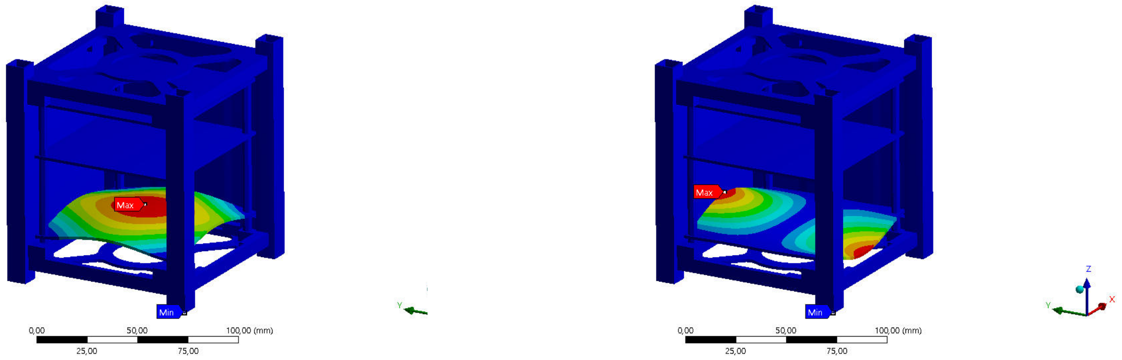
The modal analysis aims to determine the natural frequencies and vibration modes of the system [14, 13]. It is an important analysis to evaluate whether, during the launch phase, the CubeSat structure will resonate due to the dynamic loads produced by the flight environment.

In this analysis, they were attached to the -Z faces of the main beams to match the vertically stacked satellite on the P-POD.

The first ten natural frequencies of vibration of the GamaSat-01 structure and their respective modes are listed in Table 5 and in Figure 5 (a) to Figure 5 (j), respectively. It can be seen from the results that the first ten vibration modes were all in the secondary structure of GamaSat-01.

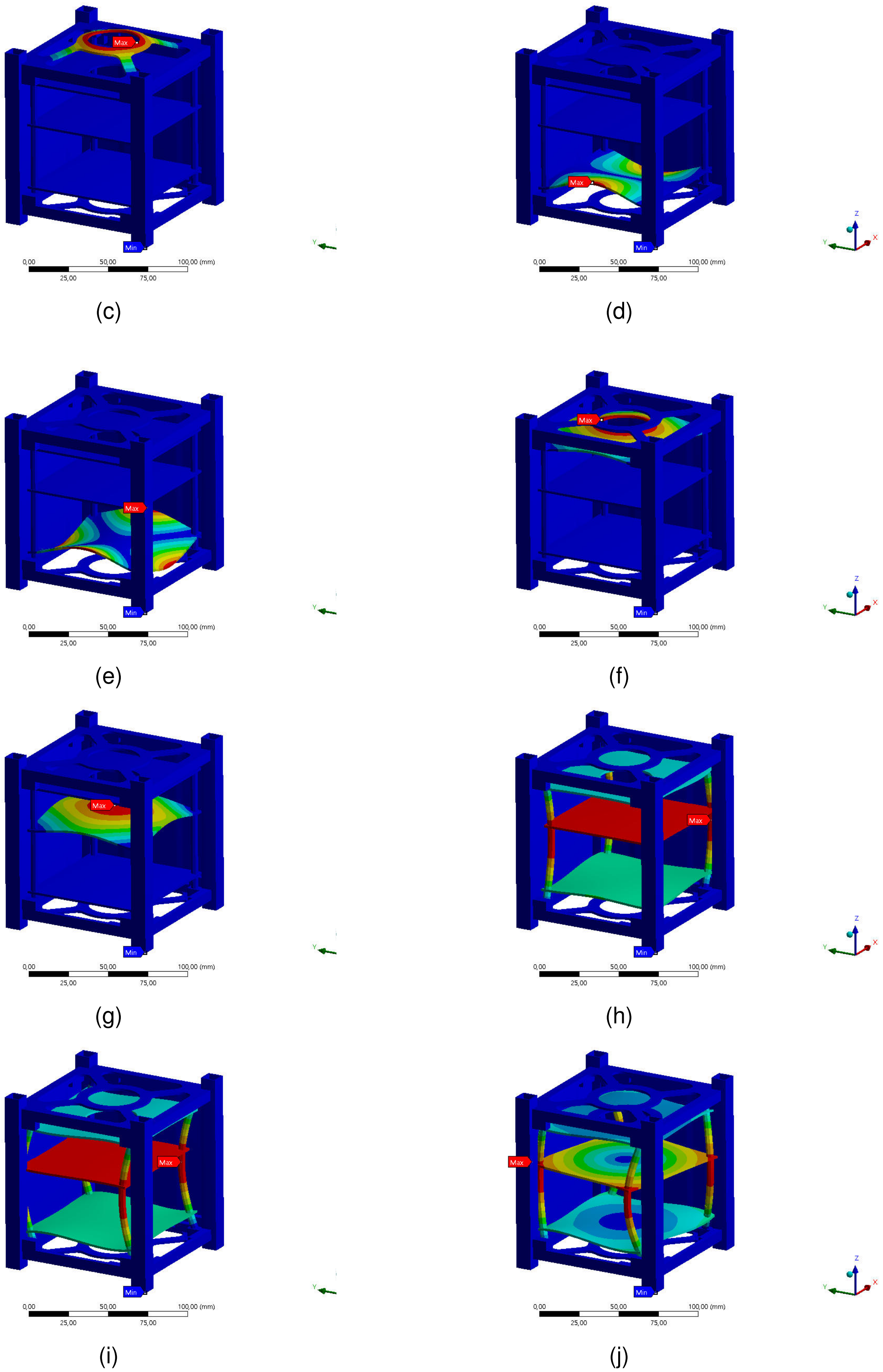
Table 5 – Ten first natural frequencies of vibration.

Mode	**Natural Frequency [Hz]**
1	187.23
2	342.76
3	354.57
4	359.54
5	397.54
6	403.36
7	434.65
8	451.63
9	452.56
10	627.60



(a)

(b)



(c) (d)

(e) (f)

(g) (h)

(i) (j)

Figure 5 – The first ten natural modes of vibration of the structure of the GamaSat-01.

4.2.4 Harmonic response

From the natural frequencies and vibration modes of the structure, it was possible to obtain the harmonic response of the system. The harmonic response analysis of the system consists in analyzing the system output in terms of stress, displacement, or acceleration when subjected to harmonic dynamic loading [14, 13]. For this analysis, the flight condition was considered in which the CubeSat is coupled to the launch vehicle by the P-POD and a sinusoidal base excitation of 300 N (equivalent to the load factor applied in the static analysis) and 0° phase is considered. The Figure 6 shows the system output in terms of voltage. The maximum response is between frequencies 2000 Hz and 2500 Hz.

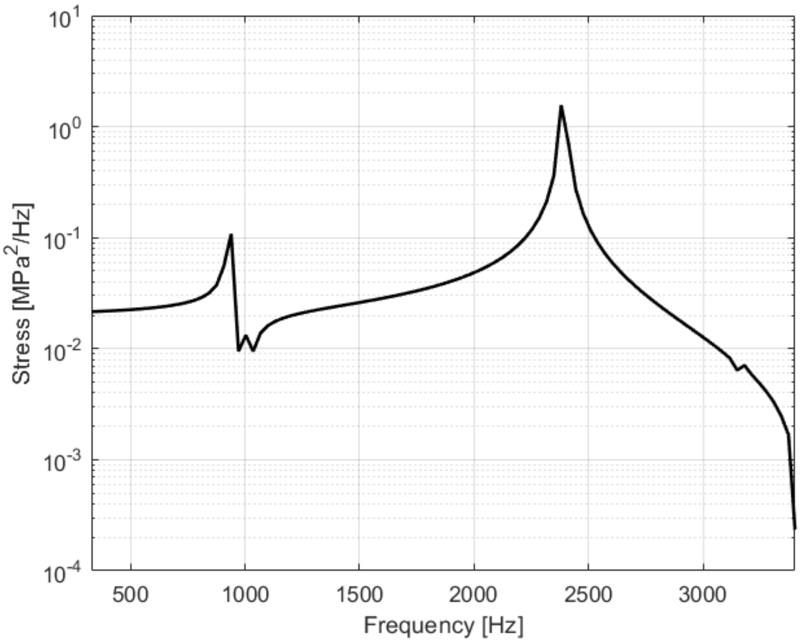


Figure 6 – Response amplitude spectrum for the stress in the horizontal direction.

4.2.5 Random Vibration Analysis

A random dynamic environment is one in which the average properties of the time history signal that characterize the environmental, can be the same each time the environment occurs, but the exact time history signal is not the same, and therefore, the precise value of the signal, at a specific time t, cannot be predicted in advance based on a previous measurement of the environment [15].

A random dynamic environment is certainly found in the orbital launch phase, originating from several factors, mainly aerodynamic loads during the upward trajectory and propellant combustion [15]. Thus, random vibration responses must be studied to assess the structural integrity of the satellite during launch.

In this analysis, the boundary condition was the Acceleration Spectral Density (ASD) which is the commonly used method to specify the random vibration event [16]. Usually, the ASD specific to the launch vehicle to which the satellites are to be launched is used; however, for the present project, the generalized acceleration spectral density was utilized, Figure 7, according to a GSFC-STD-7000 standard [2], because there is, as yet, no launch vehicle specified and consequently no known dynamic load environment.

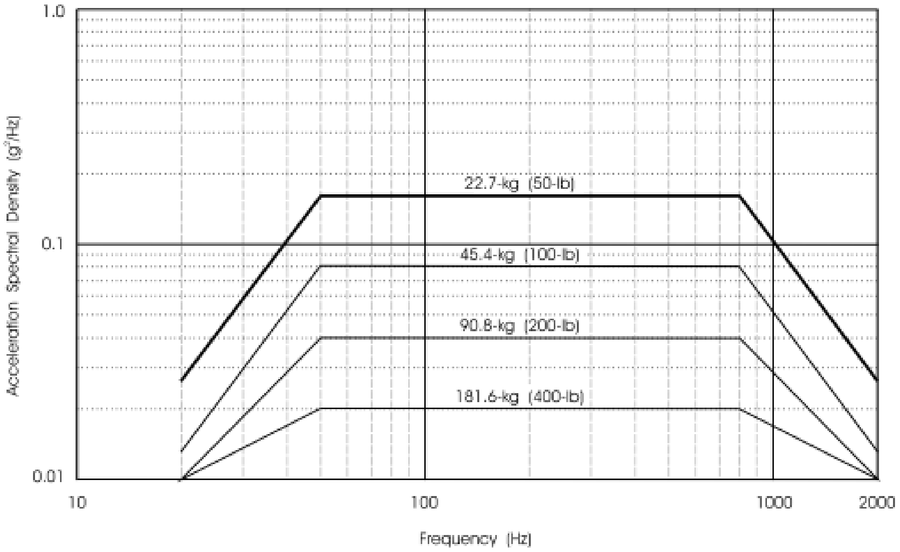


Figure 7 – The generalized acceleration spectral density level (ASD) for components weighing 22.7 kg (50 lb) or less [2].

The signal is placed at the base of the structural system (-Z face of the main beams). The Figure 8 corresponds to the response spectrum for the displacement in the center of the partition where the satellite batteries are fixed. This region was chosen because it has the highest concentration of mass and, consequently, the largest displacement amplitude in the structure [17].

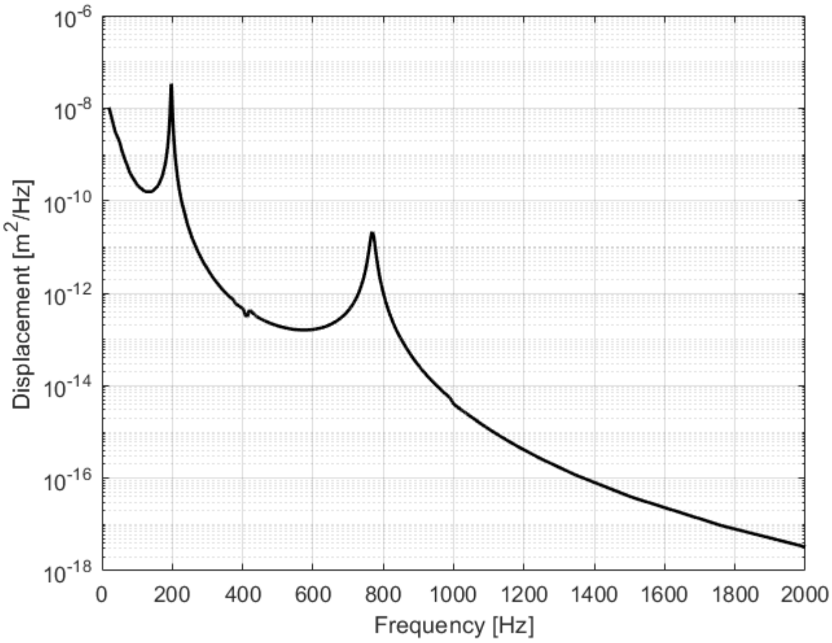
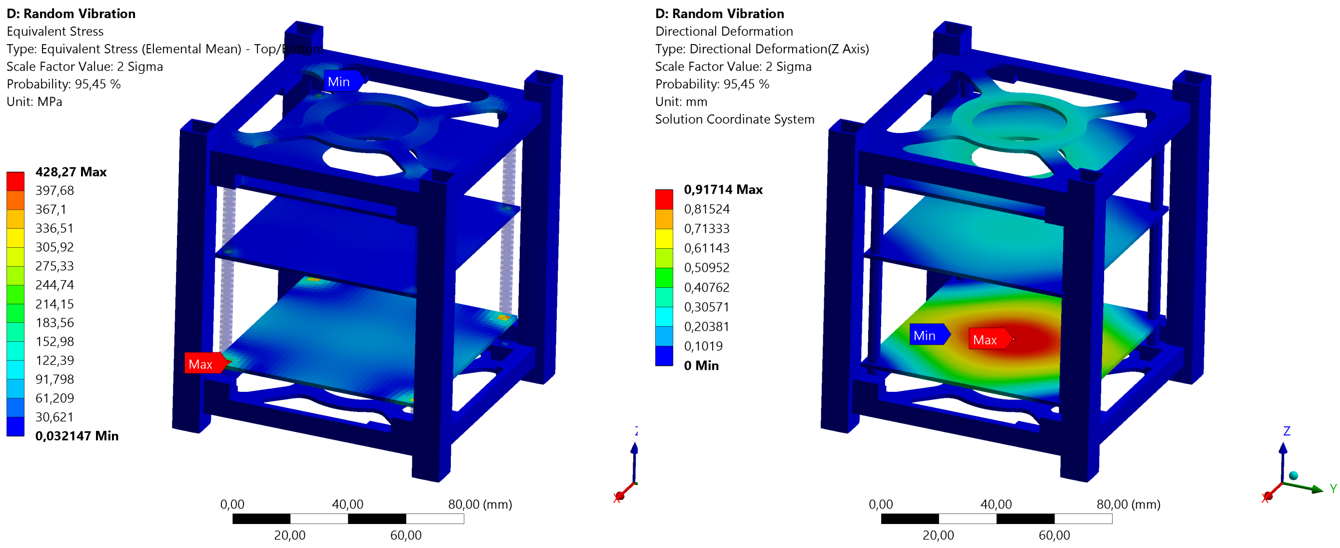


Figure 8 – Response amplitude spectrum for the displacement in the vertical direction at the central node of the plate.

The Figures 9 (a) and 9 (b) show, respectively, the von Mises equivalent stress and displacement response spectrum in the Z-axis direction (vertical) of the satellite coordinate system. The maximum stress occurs at the joint between the spacers and the battery shelf, and that is the critical loading region.



(a) (b)

Figure 9 – Von Mises equivalent gradient (a) and displacement gradient in the Z-axis direction of the satellite coordinate system (b).

4.2.6 Shock Analysis

In addition to random vibration analyses, mechanical shock response analyses should be considered for the design and validation of satellite integrity [1].The mechanical shock environment is defined by self-induced shocks and externally induced shocks [15].

The GSFC-STD-7000 standard predicts only shock environments (Shock Response Spectrum) for aerospace electronics and other hardware. However, when analyzing the shock envelope and the possibility of damage of the partition shelves to mechanical shock, it has been decided to use the Shock Response Spectrum (SRS) of the GSFC-STD-7000 standard [2], Figure 10, to assess the integrity of the structure with special attention to the secondary structure.

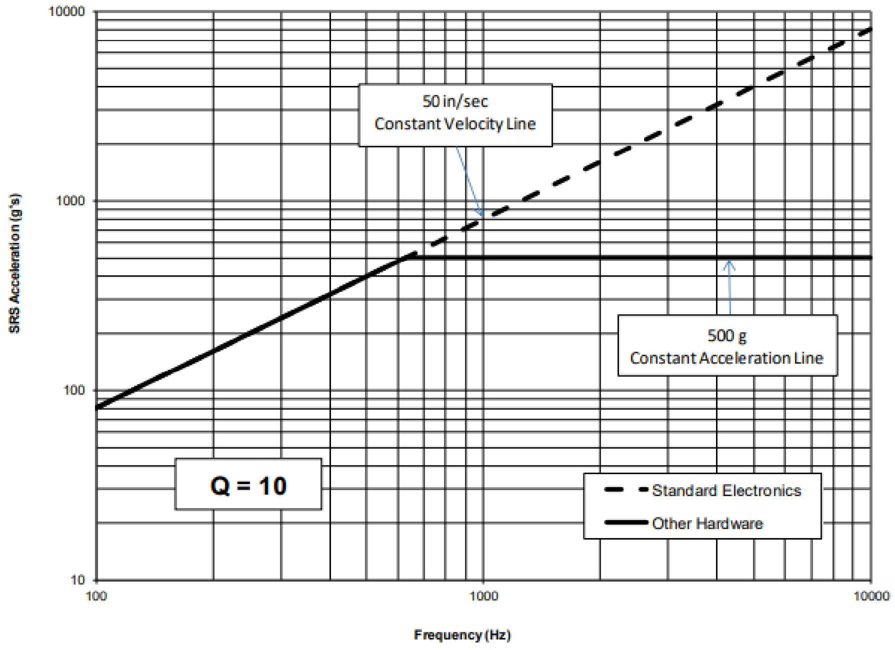
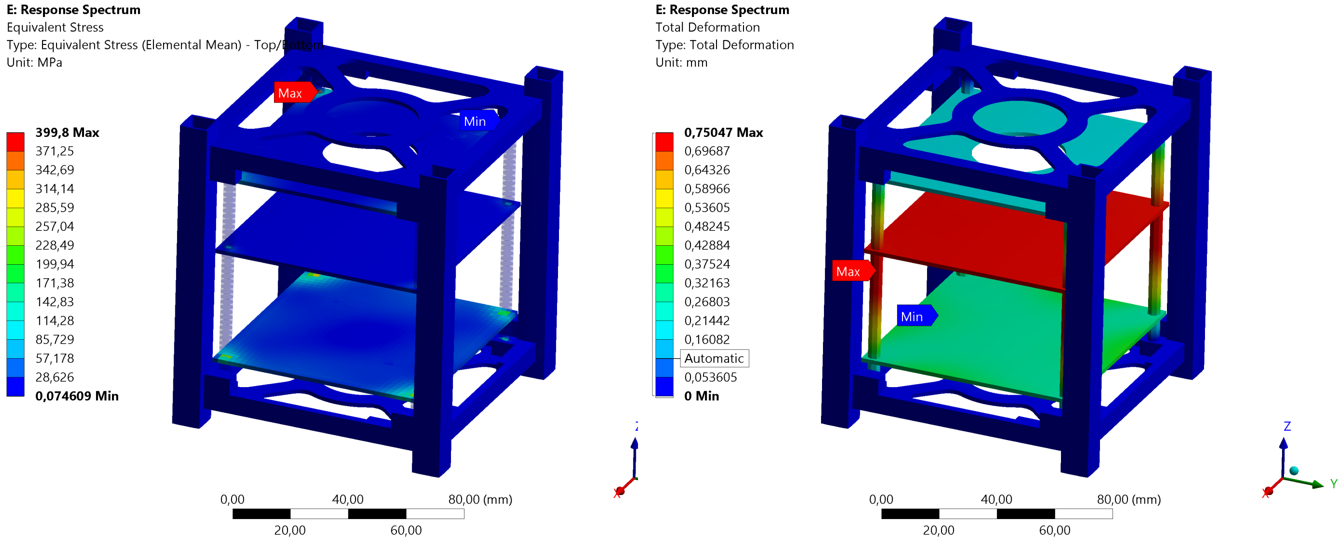


Figure 10 – Shock Response Spectrum (SRS) for assessing Component Test Requirements [2].

The signal has been applied to the base of the structure (-Z face of the main beams) in the Z direction of the satellite coordinate system. The equivalent von Mises stress gradient and the total deformation of the satellite are shown in Figures 11 (a) and 11 (b).



(a) (b)

Figure 11 – Von Mises equivalent stress gradient (a) and total displacement gradient of the GamaSat-01 satellite structure (b).

5. Conclusion

the structural design of the CubeSat is within the dimensional and geometric limits proposed by the standards. In addition, for manufacturing and integration, a final price of US$315.00 is estimated considering the pricing available in Brazil. Furthermore, by the finite element analyses, both the primary and secondary structures showed responses to the generalized dynamic loading of the GSFC-STD-7000 standard and the static loading (for the Minotaur 1 Launch Vehicle launch conditions) within the material design limit with considerable safety margin, therefore the satellite structure resists the launch environment which is the most critical phase of the entire mission.

6. Further

In further work, experimental testing of an engineering prototype will be conducted to verify the numerical results achieved by finite element methods. The experimental tests will be also required to qualify the GamaSat-01 CubeSat by the agency responsible for the launch vehicle yet to be selected.

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