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TFG TITLE: Design and construction of a picosatellite's primary structure by using 3D printing technologies

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Título: Diseño y construcción de la estructura primaria de un picosatélite usando tecnologías de impresión 3D

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Resumen

Se plantea el problema de la viabilidad de realizar el proceso de diseño y construcción de la estructura de un pequeño satélite tipo CubeSat en la Escuela de Ingeniería de Telecomunicaciones y Aeroespacial de Castelldefels (EETAC), en la Universidad Politécnica de Catalunya (UPC).
El diseño y las simulaciones detalladas de los tests más relevantes de comportamiento mecánico se realizan utilizando el software SolidWorks. Se propone el diseño de una estructura monocasco de nido de abeja -llamada *Hexagon*- como estructura primaria de una unidad CubeSat. Asímismo se realiza la comparación de su comportamiento mecánico frente al de la estructura de CubeSat *Pumpkin*, que ya ha sido testeada y utilizada previamente. Se realiza un estudio de viabilidad preliminar basado en los resultados de simulaciones estructurales y estudios teóricos. La estructura resultante cumple los requisitos tanto mecánicos como de ensayos exigidos por el documento de especificaciones de diseño de CubeSat, lo cual supone que es un diseño viable de estructura principal.
Tras un proceso de investigación de técnicas de manufactura de estructuras y de materiales susceptibles de ser utilizados para su construcción, se propone realizar la manufactura por impresión 3D de sinterizado láser, y se explica las ventajas que esta tecnología presenta frente a las técnicas de fabricación tradicionales. En cuanto al material, se propone utilizar un compuesto basado en poliamida PA11 reforzado con fibra de carbono (PA11CF), proporcionado por ADVANC3D Materials. Se describe el procedimiento a seguir para la manufactura y testeado, y se justifica que se puede completar por estudiantes de la EETAC, haciendo uso de equipamiento accesible para ellos, y se propone las líneas de trabajo futuras para testear el material propuesto y, eventualmente, construir y testear la estructura definitiva.

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Overview

The viability of developing the design and manufacture of the structure of a small satellite CubeSat, at the School of Telecommunications and Aerospace Engineering of Castelldefels (EETAC), at the Polytechnical University of Catalonia (UPC), is analyzed.
The design and detailed simulations of the most relevant mechanical tests have been performed by using the software SolidWorks. A honeycomb pattern monocoque structural design -called *Hexagon*- is proposed for a single unit CubeSat primary structure. Additionaly, *Hexagon*'s mechanical behaviour is compared to that of the operational CubeSat structure *Pumpkin*. A preliminary viability study is developed, based on the results of structure simulations and theoretical studies. The resulting structure meets the corresponding CubeSat design requirements, both at the Qualification and at the Acceptance testing levels. Therefore *Hexagon* can be considered a viable design of a CubeSat's primary structure.
After a process of research of manufacture techniques and appropriate materials, we propose to use laser sintering 3D-printing, and justify its convenience versus the use of traditional construction technologies. We suggest the material to use is a polyamide based (PA11) carbon fiber reinforced composite (PA11CF), provided by ADVANC3D Materials. We describe the construction and testing procedure and justify that the entire process can be completed by EETAC students, using equipment available to them. Finally, we propose the lines of future work to test PA11CF and, eventually, build and test the entire CubeSat structure.

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INTRODUCTION

Artificial satellite design and construction involve dealing with many aspects of physics and engineering. Therefore,working in a space mission project, even in an academic environment, provides with the opportunity of applying theoretical background in a more realistic and multidisciplinary context. This represents a huge enhancement in the learning experience which, until very recently, was hampered by high funding needs. This meant that only big organizations, usually non-academic, were able to engage in space-related enterprises. This scenario changed in the last years with the development and popularization of powerful and affordable technologies which could be applied to the design and assembly of small artificial satellites, and made space accessible to academic institutions. Along the present section we will briefly estate the aims of the present work, we will describe the different types of small satellites and the new technologies they use, and will focus on a special type, the *CubeSats*. We will briefly review the most relevant magnitudes in structural mechanics, and summarize the state-of-the art of the application of small satellites for educational purposes.

Space mission analysis and design begins with the establishment of broad (which is the key fact) objectives, requirements and constraints. The next step is to define a space system which will meet them at the lowest possible cost. To get the best performance for the money spent, it must require from the system only what it can reasonably achieve, no more. A space mission can focus on communication, navigation, or observation, among many other objectives, but it will always follow the same process of problem solving. Analysis and design are iterative, gradually refining both the requirements and methods to achieve them.

The difference between classic and low-cost space missions follows a very simple model. Launch costs usually have a linear dependence on mass. This implies that achieving low mass automatically minimizes launch costs. The main drawback is that achieving low mass requires minimizing payload requirements, redundancy and size. Therefore, even if a low-cost mission does not imply lower performance, it must minimize the requirements imposed on the spacecraft.

The main goal of this work is to set up the basis necessary to bring a space-related project to the academic world, particularly to the School of Telecommunications and Aerospace Engineering of Castelldefels (EETAC). We intend to learn from it and experience from within what makes space missions such unique and different from other engineering disciplines. Since the project proposed will be carried out in the EETAC, and is expected to be actually further developed and constructed and reproduced, keeping low costs will be crucial to make it feasible. Here it is where small satellites fit as demanded, giving the chance to create a small spacecraft with a simple structure, which eventually will be able to perform a modest but real space mission.

The term small spacecraft is used for those artificial satellites of low mass and size, usually under 500 kg, according to the application. For instance, in their Small Spacecraft Technology Program, NASA considers small spacecrafts to be those with a mass of less than 180 kg. Different classifications are used among small spacecraft based on their mass, as an example see Table 1.

Table 1: Satellite categorization based on their mass.

Minisatellites	**Microsatellites**	**Nanosatellites**	**Picosatellites**	**Femtosatellites**
100 - 500 kg	10 - 100 kg	1 - 10 kg	0.1 - 1 kg	0.01 - 0.1 kg

A CubeSat is a special category of large picosatellite or small nanosatellite. As they are the most relevant in relation to this project, they will be broadly explained in the following section.

CubeSat Standard

The CubeSat reference design (1) was conceived in 1999 for educational purposes by Jordi Puig-Sauri (Polytechnical University of California) and Bob Twigs (Stanford University). They intended to create a simple but realistic basic design for students to adapt, construct, test and, eventually, launch to Low-Energy Orbit and operate in space. Along the years the CubeSat has become a standard and used beyond the academy.

The standard CubeSat consists on 10x10x11.35 cm^3 unit which can be assembled forming several unit satellites. Each unit has a mass of up to 1.33 kg, and its design specifications seek to fulfil several goals. A simplified cubical structure allows the design and manufacturing of a fully functional low-cost satellite. Owing to the fact that all CubeSats from 1U to 3U are 10x10 cm^2 –no matter the length- they all can be launched and deployed by a common deployment system, as the Poly-Picosatellite Orbital Deployer (P-POD), which fits in almost every rocket as a secondary payload. This avoids expensive launching, bureaucracy and prohibition inconveniences, and makes the mating of the satellite with its launcher much easier. This payload-launcher encapsulation and unification enables quick payload exchanges and short-term launch opportunities.

Single unit CubeSats (1U CubeSats) correspond to large picosatellites, while several unit ones –such as 2U, 3U or 6U- already belong to the genre of nanosatellites. CubeSats equal or smaller than 3U are built stacking the cubic units one on top of the other along a single axis, while in the case of 6U a second axis will be needed (3Ux2U). Even larger CubeSats can be made, just by adding more units and axis. For instance, a 12U (3Ux2Ux2U) or 27U (3Ux3Ux3U) CubeSat would form a three axis satellite which would be categorized as a microsatellite.

CubeSats often use commercial off-the-shelf (COTS) components for their electronics and structure, which allows the use of many affordable and fully functional technologies which have been developed over the last years. For instance, Arduino open-source hardware, software and microcontrollers are reliable to be used in space missions and, in fact, an open source Arduino-based CubeSat, which contains a set of Arduino boards and sensors, has been designed. It was named *ArduSat* and was intended to allow the general public to use data gathered in space for their own creative purposes. Apart from Arduino, a myriad of affordable components can be purchased off-the-self in order to create a fully equipped Cubesat, such as solar panels, communication devices, power and attitude control systems among many others.

In this work we intend to perform the design and simulation tests of the structure of a 1U CubeSat, as well as a description of a realistic process of manufacturing to be carried out in the EETAC. The fact that CubeSats are small makes structure manufacture cheaper (less material is needed), and the choice of 3D-printing as the construction technique allows minimum waste of material. Furthermore, the reasons given above (mainly the use Arduino and COTS) will make its eventual complete construction affordable.

CubeSats in Education

The great potential of CubeSats as catalysts to attract, retain and provide high-level hands-on training to students and academics was exploited shortly after the CubeSat Standard was proposed in 1999. As soon as in 2001 students in Aalborg University (Denmark) started the design of the communication CubeSat (2) and later on many universities from all around the world joined in the design and construction of CubeSats. The number of these projects just kept growing: in 2015 more than one hundred CubeSats were actually launched, and the launches in the first 7 months of 2016 already outnumbered those in 2015. The development of CubeSats has not been restricted to the academy but, instead, many have been designed and manufactured for commercial use. Space agencies have also realised the importance of CubeSats in education and, in 2010, National AeroSpace Administration (NASA) started the CubeSat Launch Initiative (3) to actually launch CubeSats manufactured by educational and non-profit institutions, either as rocket's auxiliary payloads, or to be deployed from the International Space Station. In 2015 NASA started a more ambitious project, the Cube Quest Challenge (4), to encourage CubeSat missions beyond LEO and, eventually, near and beyond the Moon. The European Space Agency (ESA) also launched the Fly Your Satellite program (5), intended to provide students with assistance in the design, construction and launch of CubeSats as auxiliary payload of the rocket Vega.

Structural Analysis and Design Basics

Given that structural design and analysis are the main topics of the present project, in the present subsection we shall briefly define the main relevant magnitudes.

The structure and mechanism subsystem mechanically supports all other spacecraft subsystems, attaches the spacecraft to the launch vehicle and provides for ordnance-activated separation. The design must satisfy all strength and stiffness requirements of the spacecraft and of its interface to the booster. Primary structure, in which this project is going to focus on, carries the spacecraft's major loads. Secondary structure includes all essential appendages and support structures, such as solar arrays, antennas, fuel tanks, etc. The paramount difference between the primary and secondary structure is that when the primary structure fails it is almost always catastrophic, while despite a failure on the secondary structure can have a significant impact on the overall mission, it does not affect the integrity of the spacecraft. (6)

Structures must endure all environments from manufacture to the end of the mission. The launch vehicle is the main source of structural requirements, dictating the spacecraft's weight, geometry, rigidity and strength.

Random vibration from engines and other sources is a critical source of load. At lift-off, the main cause of random vibration is acoustic noise, which radiates from the engines (and is reflected on the ground) to engulf the vehicle. Acoustic stresses also develop from aerodynamic turbulence when the vehicle passes through the transonic portion of its flight. Structures with high surface area and low mass respond strongly to acoustic noise.

Another source of load, pyrotechnic shock, comes from explosive separation events involving the boosters, payload fairing and spacecraft, as well as release mechanisms for solar panels and other deployable devices. These processes are a source of high acceleration and high frequency shocks over a very short time. As shock loads attenuate quickly (between 5 and 15 milliseconds), they seldom damage structures, but they may seriously harm electronic components.

Design Criteria

In a structure design process many elements are taken into consideration, for instance optional materials, types of structure and methods of construction. In order to select from these options, several studies are traded to compare weight, cost and risk.

Materials are selected based on: strength, stiffness, density (weight), thermal conductivity, thermal expansion, corrosion resistance, ductility, fracture toughness, ease of fabrication, versatility of attachment options, availability and cost.

Types of structure include skin panel assemblies, trusses, ring frames, pressure vessels, fittings, brackets and equipment boxes. There are usually several options, but sometimes only one fulfills the requirements. When loads are spread out rather than concentrated, it is typical to use monocoque structures, which are panels and shells without attached stiffening members. Another example are skinstinger structures, which have longitudinal (stringers) and lateral (frames) members to accept concentrated loads and skin to spread them out.

There are many ways to attach structural elements. Adhesive bonds, welds or mechanical fasteners. But regardless of the selected structure type and attachment method, much of the structural subsystem's weight will be in the fittings used to transfer load from one member to another.

Structural Mechanics and Analysis

A solid material part will respond to a force exerted on it by changing its shape. The field that analyzes how materials respond to applied forces and other environments is mechanics of materials.

Stress, σ, is the most basic term in this field, which equals the load, P, applied on a member over its cross-sectional area, A:

$$\sigma = \frac{\text{Load}}{\text{Area}} = \frac{P}{A}$$

Typical units for stress are N/m^2 and lb/in^2 or psi.

Strain, ε, is a dimensionless measure of deformation for a given load, which will increase by ΔL the total length, L, of the piece:

$$\varepsilon = \frac{\Delta L}{L}$$

Poisson's ratio, υ, describes the thinning that solids experience when elongated under an axial load. It is the ratio of the lateral-to-axial strain:

$$\upsilon = \frac{\varepsilon_{\text{lateral}}}{\varepsilon_{\text{axial}}}$$

The **stiffness** of a material is the relationship of its stress to strain for a given load. In other words, it is the extent to which it resists deformation when a force is applied on it.

Young modulus or modulus of elasticity[1], E, is the ratio between stress and strain:

$$E = \frac{\sigma}{\varepsilon}$$

Some materials, mostly metals, start exhibiting a linear relationship between stress and strain. Strain in this region is termed elastic due to it will return to zero after the load is removed.

Beyond a value of stress called the proportional limit, a material's stress-strain curve is no longer linear. Owing to inelastic effects influence structural stability more than anything else, an important requirement for preliminary design is to keep the predicted maximum stress below the material's proportional limit.

Above the elastic limit, which can be higher but is often indistinguishable from the proportional limit, the material will undergo residual strain –or plastic strain-, which remains after the load is removed. By convention, yield stress is defined to be the stress that would cause the material to have a residual strain of 0.2%, due to although the material begins to yield at the elastic limit, this initial yielding is often not noticeable in a structural assembly.

Ductile is the term used to describe a material that can yield substantially before rupturing, for instance metals. This kind of materials can resist local concentrations of strain without failing, crack formation, and allow parts to be shaped through mechanical working processes. On the other hand, brittle materials, such as ceramics, do not deform plastically before rupturing.

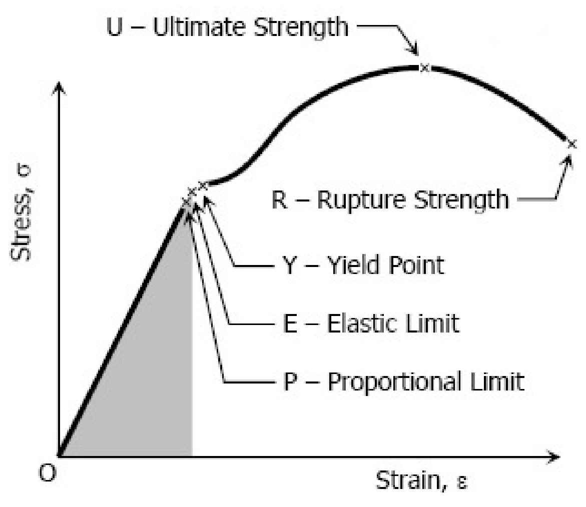

Figure 1: Stress-strain diagram. Shadowed area indicates the elastic region.

[1] Elasticity is the characteristic of a material to return to its original dimensions after an applied force is removed.

Small Spacecraft Structures and Materials State of the Art

This section will refer to small spacecraft structures and materials. Most of the information has been obtained from the NASA technical report (7), from 2015. We will focus on 1U-12U platforms and specially on the components whose role is to transmit the loads to the interface of the launch and deployment system, and to provide attachment points for payloads. These are usually classified as primary structures.

Most of them are machined from 6061-T6 and 7075 aluminum and designed with several mounting locations for the inner components in order to offer configuration flexibility. 1U to 3U are the most prevalent formats, but there are a few chassis designed for 6U and 12U spacecrafts. This is due to the fact that 1U to 3U standards are totally set and implemented. By contrast, 6U and 12U off-the-shelf frames can be considered on the horizon, in particular, the 12U format is still in development until an adequate dispenser is qualified. When that happens the standard for the dimensional constraints of the spacecraft will be set.

In terms of CubeSats' internal load disposition, different companies have chosen different approaches, which we shall briefly describe below.

i) Monocoque Construction

Pumpkin, Inc. CubeSat Kit has taken a monocoque approach for their 1U-3U spacecraft. In this type of constructions the loads are carried by the external skin trying to maximize internal volume. Pumpkin, Inc. provides several off-the-shelf CubeSat structures in 0.5U, 1U, 1.5U, 2U and 3U sizes.

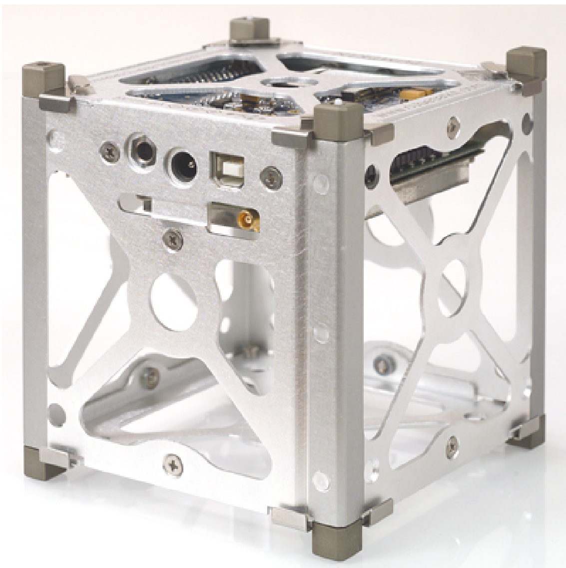

Figure 2: 1U Skeletonized CubeSat Kit. Image courtesy of Pumpkin, Inc. (2015).

ii) Modular Frame Designs

Radius Space has chosen a modular approach to develop a series of CubeSat structures from 1U to 12U sizes. In this frame, electronics integration is performed through a stacked configuration.

Figure 3: The Radius Space Modular Structures. Image courtesy of Radius Space (2015).

iii) Card Slot System

Complex Systems and Small Satellites (C3S) has developed a 3U CubeSat structure which uses a card slot system in order to enable access to individual cards during integration and testing. This configuration allows improved stack-up tolerance and better thermal management of individual cards, due to the fact that they are thermally independent.

Figure 4: C3S 3U CubeSat Structure. Image courtesy of Complex Systems and Small Satellites (2015).

A vital choice for a small spacecraft structure is the material of the structure itself. Typically, they are made up of metallic and non metallic materials (most of 6061-T6 and 7075 aluminum). Each material presents its own advantages and drawbacks and, most important, determines processes and manufacturing technologies that shall be used.

i) Additive Manufacturing Materials

For many years, addictive manufacturing has been quite common for small spacecraft secondary structural elements. But as primary structure concerns, it has been proposed but not adopted by flight missions until now. The benefits of additive manufacturing are to free the designer from traditional manufacturing constraints and to enable monolithic structural elements with complex geometry.

ii) Windform Materials

CRP Technology is using laser sintering technology in order to build parts with their carbon filled polyamide based material, Windform XT 2.0.

Montana State *Printsat* mission aims to demonstrate the effectiveness of additive manufacturing using Windform material with an spacecraft equipped with several sensors to determine the properties of the material during its mission.

Morehead State University's *Rapid Prototyped MEMS Propulsion and Radiation Test* (*RAMPART*) spacecraft will also be demonstrating the rapidly prototyped Windform material during its mission. Benefits of the *RAMPART* propulsion system are the lightweight and specialized cell structures of the propellant tank made from Windform XT. The spacecraft was scheduled for launch in June 2013, but was delayed.

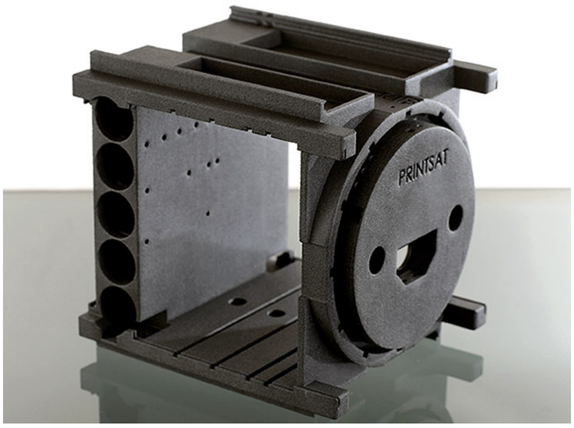

Figure 5: Windform PrintSat Structure. Image courtesy of CRP Technology (2015).

Project Structure

This work is structured as follows. The first chapter summarizes how the software tools and the experimental setup –such as Solidworks, the test machines, and the 3D printers-work and which outputs they can provide in order to achieve the goals of this project.

Once the theoretical background and the behaviour of a reliable CubeSat structure are understood, we start in Chapter 2 the design process using the 3D design and simulation software SolidWorks. This software allows performing a high number of trial and error tests prior to the actual construction process, which ideally becomes more efficient in terms of time and use of material. This chapter describes which criteria have been followed in order to get the final design.

A spacecraft structure must fulfill a number of standard requirements if it is to be launched. In Chapter 3, three simulation analyses are performed: frequency analysis, random vibration analysis and shock response analysis. The conditions characteristic of a typical launching environment have been implemented in Solidworks and the corresponding simulation tests have been performed in order to assess whether the satellite is able to survive the launching process while keeping its integrity.

Chapter 4 describes the process of choice of an adequate material for the manufacture of the CubeSat, as well as the most convenient manufacture technology available to EETAC students. We also introduce the equipment required to test the material proposed and, eventually, the entire structure.

To sum up, the report will end with the summary, conclusions and future lines of work section.

Figure 6 represents (in dark blue and orange) a schematic view of the iterative work done in this project. In the present document Chapter 2 corresponds to the preliminary design, Chapter 3 corresponds to the detailed SolidWorks simulations and Chapter 4 deals with the choice of material to manufacture the CubeSat structure.

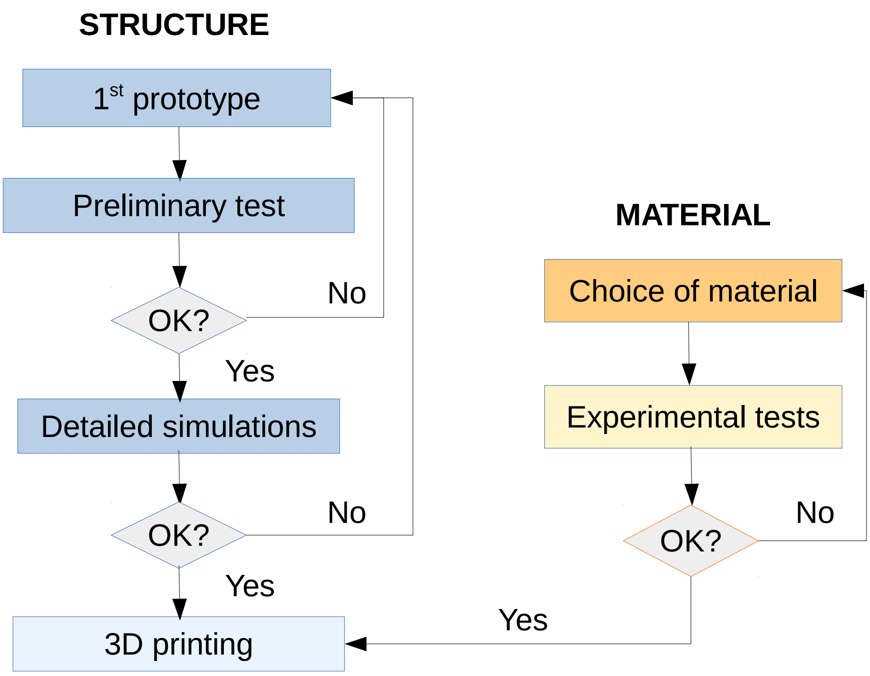

Figure 6: Summary of the work done in the present project.

CHAPTER 1. SOFTWARE TOOLS AND EXPERIMENTAL SETUP

In this chapter we briefly describe SolidWorks, which is the software program we have used to perform our simulation tests, 3D printing, which is the technique we propose to manufacture our CubeSat structure, and the Universal Testing Machine, which we would use to test the mechanical properties of the structure materials.

1.1. SolidWorks: Design and Simulation Software

Solid modeling is based on a consistent set of principles for analytical and numerical modelling of three-dimensional solids. The paramount difference from related areas such as geometric modeling and computer graphics is the emphasis solid modeling puts on physical fidelity.

The use of solid modeling techniques allows to perform complex engineering calculations automatically during the design process. Simulation, planning and verification of the processes such as machining and assembly are some of the multiple advantages this technology presents. Moreover, solid modeling covers a wide range of manufacturing applications such as sheet metal manufacturing, injection molding, welding and, more recently, additive manufacturing or 3D printing.

Apart from manufacturing, solid modeling techniques allow rapid prototyping, digital data archival, reverse engineering and mechanical analysis using finite elements, motion planning and kinematic and dynamic analysis of structures and mechanisms.

SolidWorks is a solid modeling software which uses a parametric feature-based approach to create models and assemblies. Building a model in SolidWorks usually starts with a 2D sketch, which is composed by points, lines, arcs, conics, splines, etc. Size and location of the geometry are defined by adding dimensions to the sketch. These dimensions can be controlled independently, or by setting relationships to other parameters, within or outside the sketch. Then, relations are used to define attributes such as tangency, parallelism, perpendicularity, and concentrity. Dimensions and relations drive the geometry, not the other way around.

From a defined 2D sketch, features are used to build the part by extruding (adding material) or cutting (removing material) the shape the sketch indicates. Besides, non-sketch based features can be performed, such as fillets, chamfers, shells, etc.

In an assembly, relations concerning individual 3D parts and components are defined by mates, allowing an easy assembly construction.

Once the 3D model is obtained, SolidWorks Simulation allows to perform several structural analysis by previously defining the material properties and the fixed parts of the structure. As this project concerns, frequency and dynamic analysis will be performed. They will return the different resonant frequencies and the structure behavior under the applied random vibration and shock circumstances. We will develop the structural analysis simulation test along the next few chapters.

1.2. Universal Testing Machine (UTM)

A Universal Testing Machine (UTM) is named after it can perform several standard tests on materials, components, and structures by changing the clamps for the appropriate tooling for the corresponding test, such as tensile, compression or bend tests. (8)

i) Tensile Test

The UTM clamps a single test specimen on each of it ends and pulls it apart until it breaks. Tensile strength, yield strength, and tensile modulus of the material can be obtained with this test, as well as its stress-strain curve.

ii) Compressive Test

It is the opposite of a tensile test. The machine compresses an object between two level plates until it reaches a certain load or distance or the product breaks. The typical outputs obtained are the maximum force the specimen resists before rupture (compressive force), load at a certain displacement, and displacement at a certain load.

iii) Bend Test

It is a compressive test where a length of material is supported on each end. Then, the machine loads from above in the middle of the span material until it breaks or reaches an specific distance. This test measures how strong the material is in flexure (flexural strength) and how stiff it is (flexural modulus).

1.3. 3D Printing

Highly evolved traditional manufacturing dominates the process of construction of artificial satellites, regardless their size. It involves the use of new automatized processes such as machining, casting, forming and moulding [1]. Nevertheless, these manufacturing processes present several drawbacks, among others, that not all geometries can be generated as solid single units and relatively high amounts of material are wasted. Besides traditional design and production requires the use of expensive tools, fixtures and the need for assembly of complex parts.

By contrast, 3D printing –or additive manufacturing- covers a wide variety of technologies and different processes which offer many possibilities for production of parts and products in different materials. It converts a three-dimensional digital model (CAD representation) into a physical object by adding successive thin layers of a certain material. There are many different techniques and processes of 3D printing, according to the chosen material and the desired geometry. For instance, laser sintering process is used for powder materials (plastic or metal), plastic filaments are handled by the fused deposition modelling

[1] **Machining:** Process in which a piece of raw material is cut, drilled and/or abraded into a desired final shape by a controlled material-removal process.**Casting:** Consists on pouring or injecting molten material (normally metal) into a mold's hollow cavity of the desired shape and then allowed to cool and solidify.**Forming:** It gives a piece of material a desired shape without adding or removing material, its mass remains the same. It is based on the principle of plastic deformation. **Moulding:** It consists on shaping liquid or pliable raw materials using a mold or matrix.

(FDM) process and liquid or molten state materials are used in material jetting technology, among many others.

The two main innovations 3D printing presents are the manipulation of models in digital format, enabling free designs, and the manufacturing of new shapes by addition of material. This makes 3D printing a ”tool-less process”, which reduces costs and time. Moreover, it allows components to be designed in order to avoid assembly requirements and to create complex shapes and geometry at no extra cost. Apart from reducing costs and time it may improve the performance and the operational life of the product through a lighter and stronger design.

In the recent years, 3D printing is becoming more accessible to small companies, academic organizations or even individuals. This accessibility, together with the above mentioned advantages and the high costs which involve traditional manufacturing make 3D printing the best candidate process for the construction of small satellites, specially in an academic context.

CHAPTER 2. DESIGN OF THE PRIMARY STRUCTURE OF A CUBESAT

As we explained in the Introduction, the goal of this project is to design the primary structure of a 1U CubeSat, and to perform the corresponding numerical tests of structural analysis. The present section describes the process of design, which was performed using SolidWorks, and involved an iterative process of preliminary design and numerical testing. It must also be emphasized at this point that the design was made according to the requirements stated in the CubeSat Design Specification document (1).

These requirements are classified as follows:

- **General requirements:** involve minimization of pollution (no space debris, low outgassing criteria), and hazards (all components must remain attached during the mission, maximum thresholds on vessel pressures and stored chemical energy, no pyrotechnics,...)
- **Mechanical requirements:** related to weight (maximum 1.33 kg for a 1U CubeSat) and dimensions (100.0 $\pm$ 0.1 mm base -XY coordinates, 113.5 $\pm$ 0.1 tall -Z coordinate), centre of mass location, characteristics of the rails in relation to displacements along the P-POD, and materials.
- **Electrical requirements:** related to safety issues, for instance to assure that no electronics is active during the launch, and subsystem diagnosis.
- **Operational requirements:** to meet legal and, again, safety issues. As an example, capability to receive a shutdown command in case of emergency, and limitations in relation to the frequency range and time of operation of certain transmitters, time of component deployment, and of orbital decay ($<$ 25 yr).

The most relevant CubeSat specifications in relation to the present work are those corresponding to the mechanical requirements, which we present in Appendix 4.3.2..

The preliminary design and simulation tests will be performed assuming Aluminum 7075-T6 for the SolidWorks computations. The main reason for this choice is that the initial objective is to get a reliable geometry, without paying much attention to the material. This choice is also supported by the fact that it is quite a realistic option, as Aluminum 7075-T6 has a good strength behavior and is actually a material suggested by the CubeSat Design Specification. (1)

Our proposed structure has a honeycomb pattern, whose geometry allows minimizing the amount of used material and consequently its density, total mass and material cost. Furthermore, such pattern endows structures with good mechanical properties, specially relative high out-of-plane compression and shear properties. Honeycomb structures have been used in the aerospace industry since the 1950s, specially because of its high specific strength[1], and have been manufactured in different materials, from aluminum to new composites.

[1] The specific strength is a material's strength (force per unit area at failure) divided by its density.

2.1. First Prototype

The purpose of our first model was to make a preliminary exploration of the order of magnitudes of the characteristic frequencies of resonance and mode shapes of a CubeSat structure with honeycomb pattern.

Let us first briefly describe the main theoretical concepts which shall be used in the present section. Every structure can vibrate at certain frequencies called natural frequencies. The lowest frequency of vibration is commonly called the fundamental frequency, and higher multiples of that are called harmonics. Also, each natural frequency is associated with a certain shape of the structure called mode shape, which the structure tends to assume when vibrating at that frequency. If dynamic loads coincide with one of the structure's natural frequencies it can undergo large displacements; this phenomenon is known as resonance. For undamped systems, resonance theoretically causes infinite motion, however some damping always exists in real systems, and it helps to limit the response of the structure.

Figure 2.1 shows the results of the frequency simulation, where the green arrows correspond to the fixed parts. In this case, the rails of the CubeSat are fixed geometry because they are the only surfaces which make contact with the P-POD. As it can be seen, according to the several mode shapes analyzed, the structure suffers the highest resonance in amplitude at the center of each face. Thus, this is where the main source of displacement will take place in this kind of geometry.

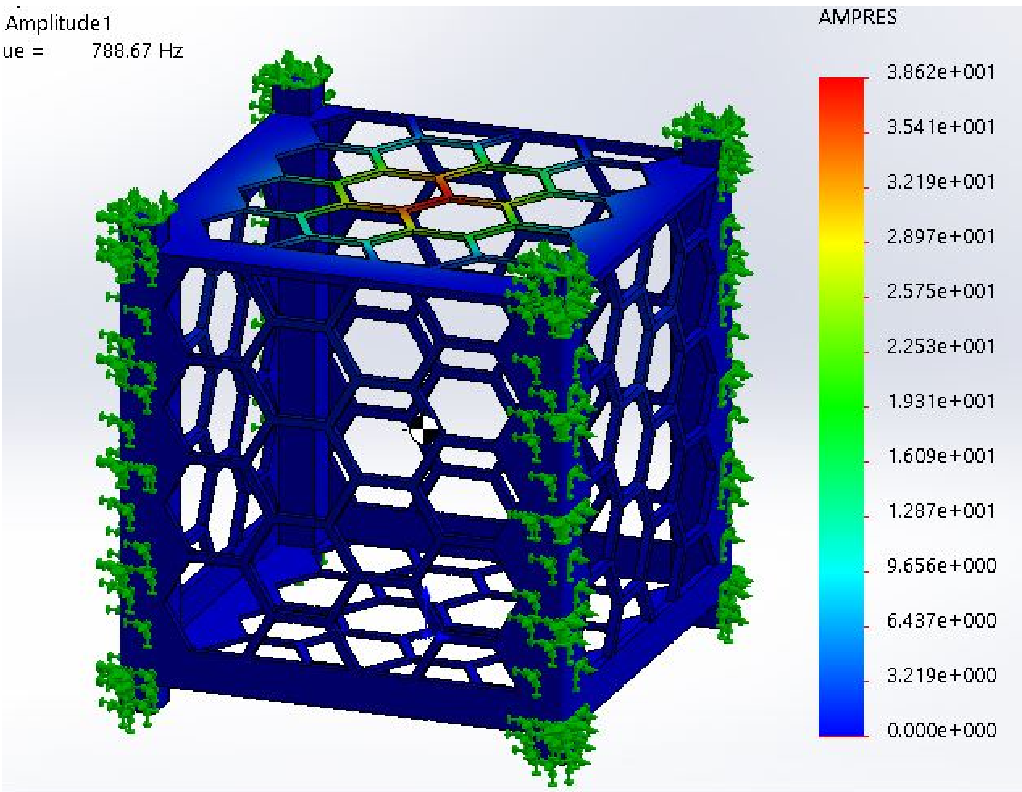

Figure 2.1: First prototype behavior. The legend shows the displacement results as a function of the resultant amplitude (AMPRES), which has no units. Warmer colors represent wider displacements.

Since Figure 2.1 represents a free vibration problem, there are no loads applied and so no real displacement results can be given. Therefore, resultant amplitude is a factor that should be taken into account when a load is applied. Under the present conditions, it gives a general idea about the performance of the structure, which may be used for further analysis. For instance, red coloured areas on the structure will move twice as far as the green coloured areas and blue coloured areas will barely move or stay static.

2.2. Hexagon I

According to the design specification, the CubeSat's center of mass must be within 2 cm of the geometric center. Then, in order to avoid any trouble with the electronic component balance, the structure will be as symmetric as possible, trying to place the center of mass as close to the geometric center as possible. Actually, the center of mass of Hexagon I is located at the same position as the geometric center.

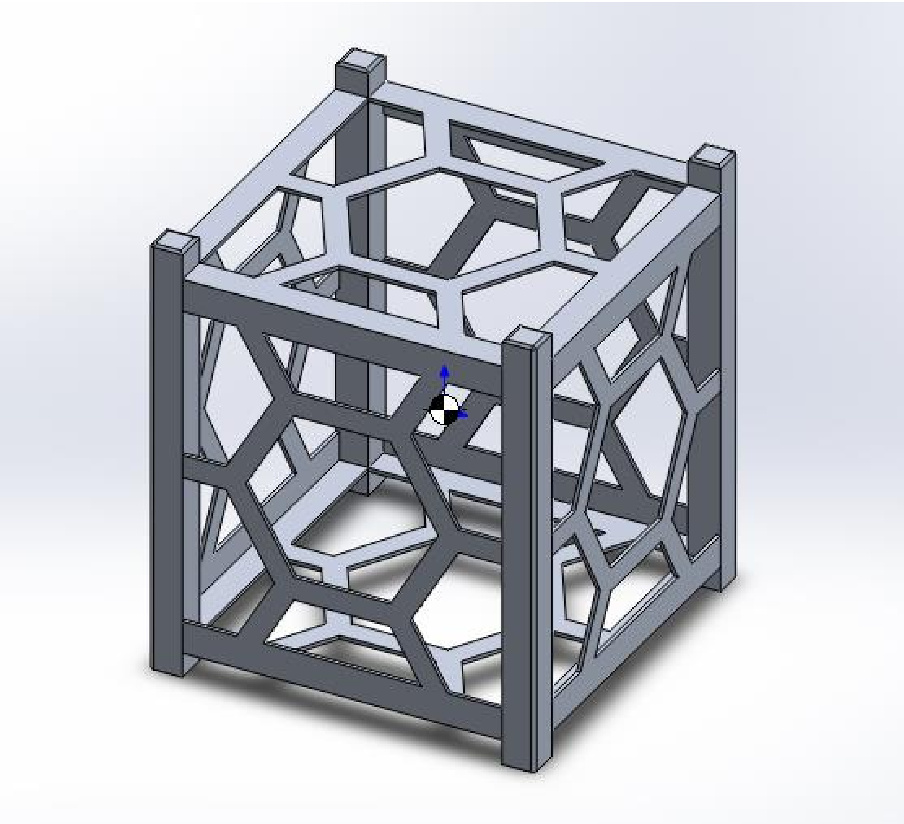

Figure 2.2: Hexagon I SolidWorks model

2.2.1. Frequency Analysis

The preliminary frequency test of the first prototype showed that the parts of the structure which suffered the widest displacements were the centers of each face of the CubeSat. This suggested that, if we intended to improve the behaviour of our structure by avoiding the maximum amplitude areas, we should be able to get rid of the material in the center of the faces. Keeping this in mind we considered another honeycomb structure but, in this case, the hexagons were larger and thus we got cube faces with empty centers (see Figure 2.2)

Figures 2.3 and 2.4 show how the maximum resultant amplitude has been reduced in more than a half by the improvements of the new model.

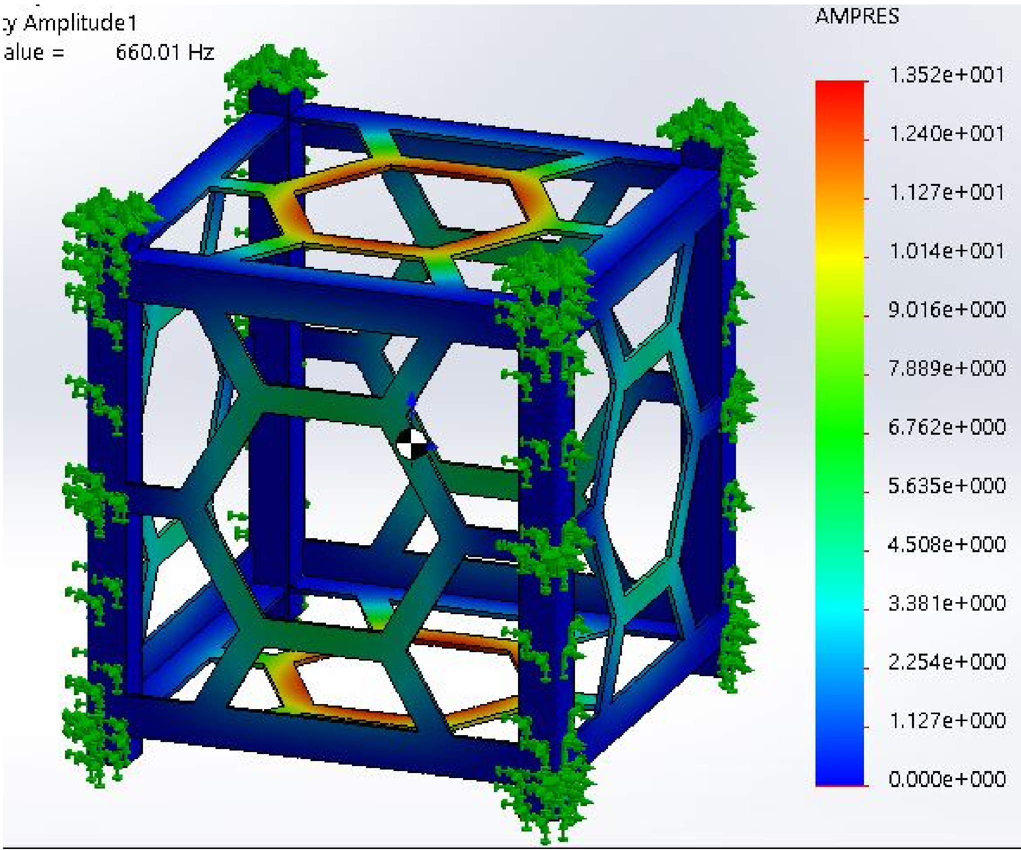

Figure 2.3: Hexagon I frequency analysis. The legend values represent the same as in Figure 2.1.

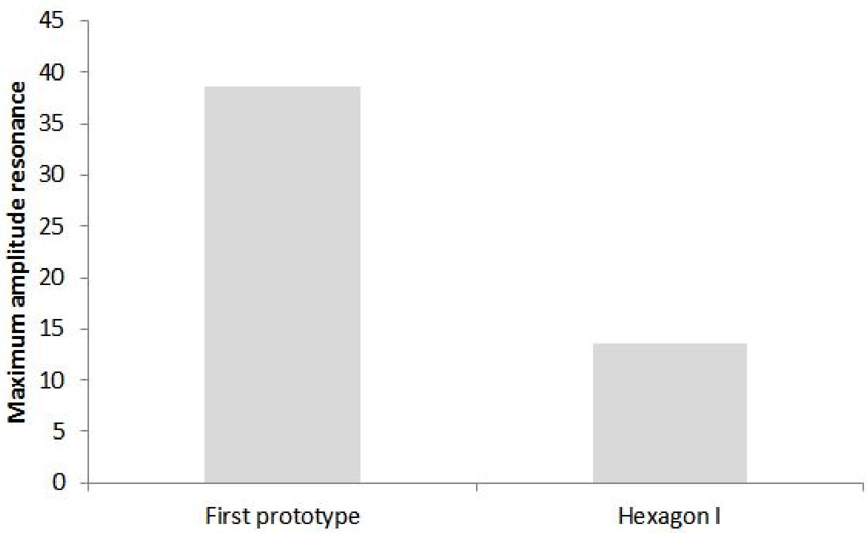

Figure 2.4: Resulting maximum amplitude comparison between First prototype and Hexagon I

2.2.2. Stress analysis

Once we got a model with notably enhanced resonance behavior, we performed further vibration analysis. In particular, we modeled a minimum random vibration spectrum, defined in Ariane 5 User's Manual document (9), plus an external load corresponding to a downwards acceleration in the vertical axis, in order to simulate the conditions characteristic of a real launch. Section 3.2. provides broader information about random vibration environments.

We can see in Figure 2.5 how the maximum stress takes place in the corners of the connection between the central hexagon and the sides of the face. Nevertheless, this value -2.480E+06 N/m^2- is far below the yield strength -5.050E+08 N/m^2-, meaning that the deformation of the structure will be elastic and consequently reversible.

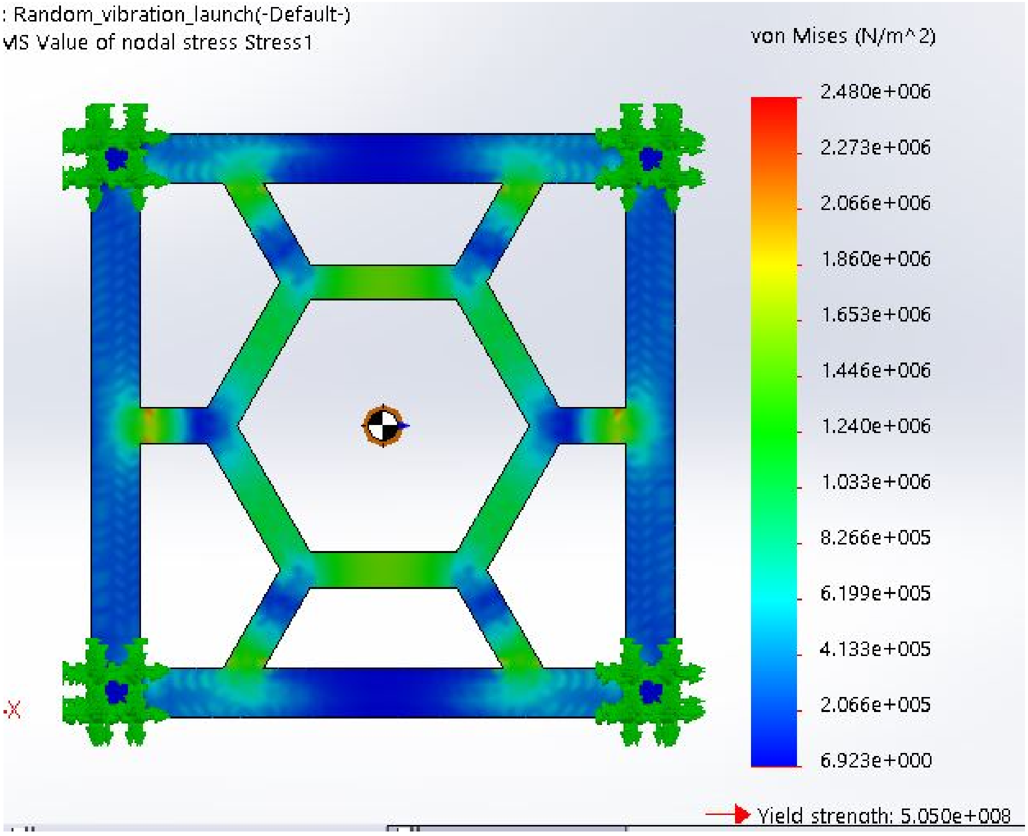

Figure 2.5: Hexagon I stress analysis (under minimum random vibration spectrum).The legend values represent the amount of stress in N/m^2 that the corresponding coloured part experiences. For instance, red coloured part will experience around 2.480E+06 N/m^2, while blue coloured ones will the least stress.

2.3. Hexagon II

Even if the structure fulfills by far the mechanical requirements, we can still introduce a final improvement in order to reduce the maximum stress by removing the right angle that connects the hexagon and the sides of the face, see Figure 2.6. Again, the center of mass is placed exactly in the geometric center.

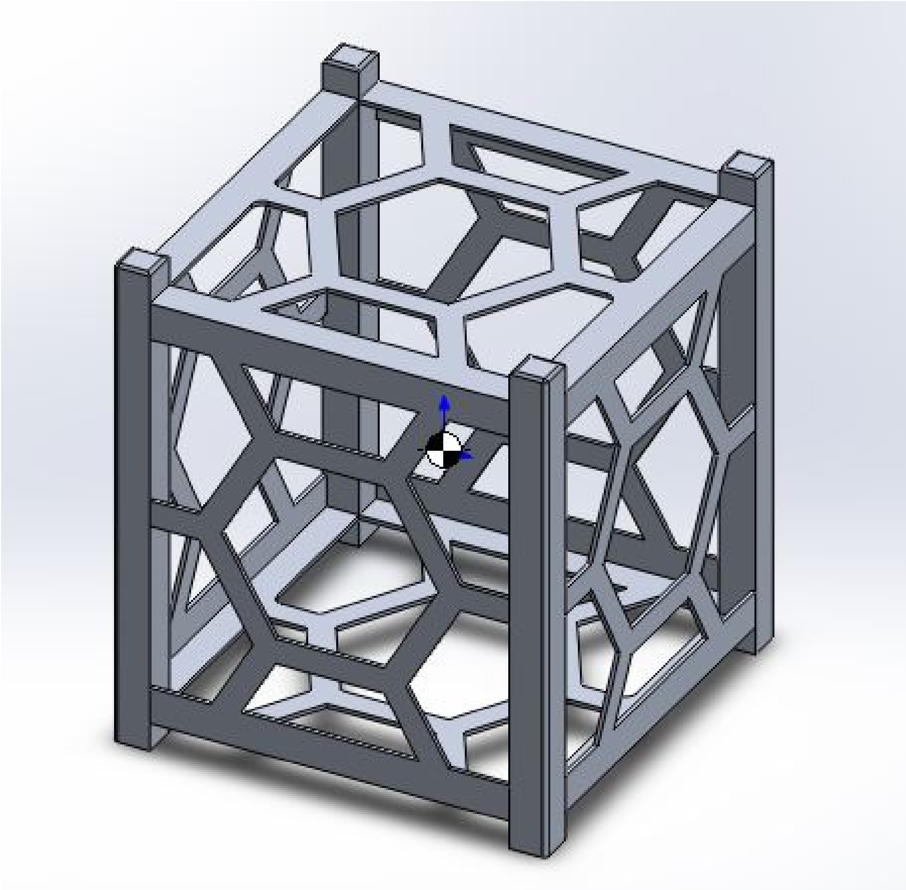

Figure 2.6: Hexagon II model

2.3.1. Stress Analysis

Figures 2.7 and 2.8 show how due to the change in the angle, the yield strength percentage has been reduced in more than 1%.

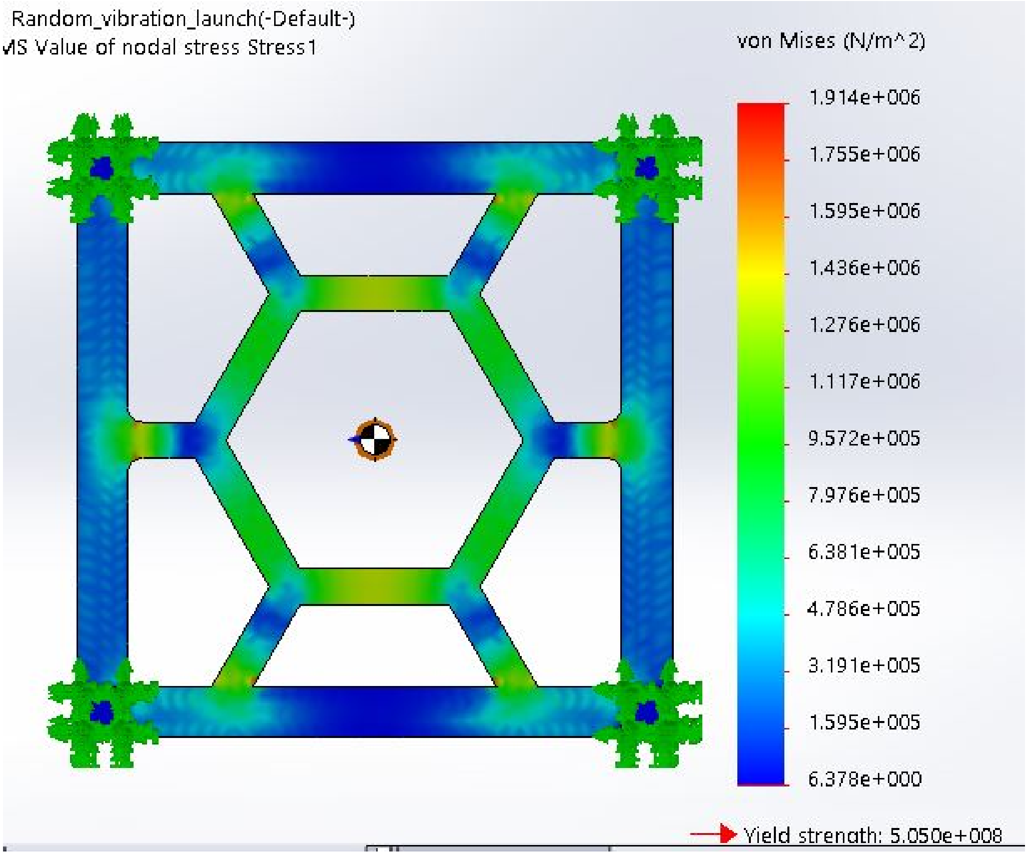

Figure 2.7: Hexagon II stress analysis (under minimum random vibration spectrum).The legend values represent the same as in Figure 2.5.

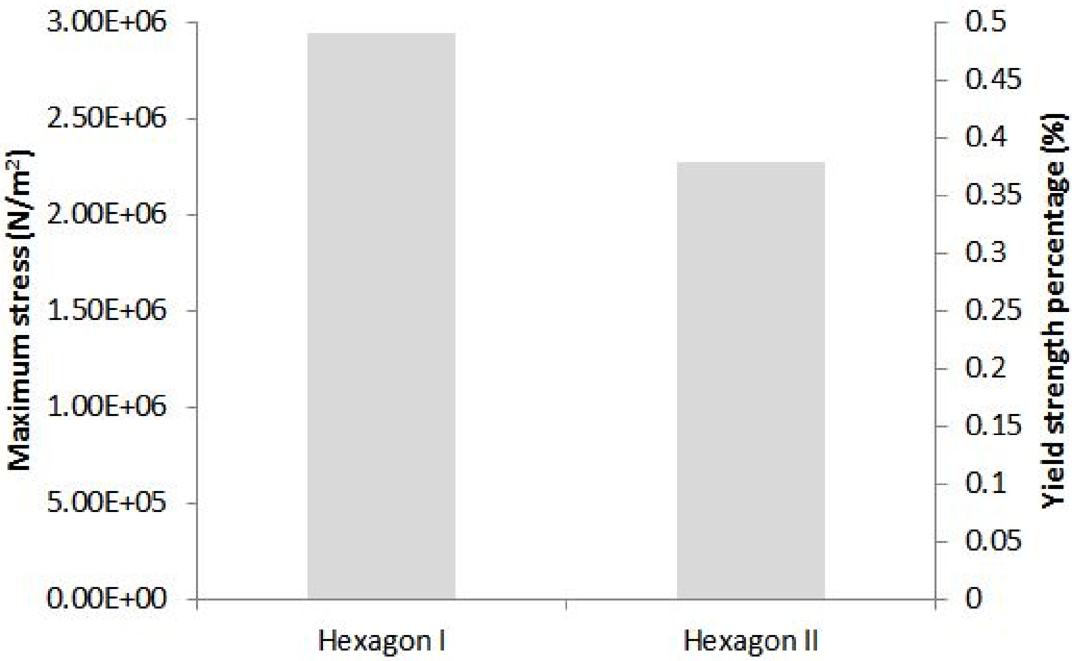

Figure 2.8: Stress (N/m^2) performance comparison between Hexagon I and Hexagon II (under minimum random vibration spectrum)

2.4. Hexagon Bolts

Finally, the structure needs to have removable parts in order to allow a proper access to the inner electronic components. In particular, it is convenient to introduce a removable cube's face in order to allocate the CubeSat's subsystems and, if it happens to be convenient in terms of improving the overall performance of the satellite and its response to vibration environments, to reallocate those components as required by successive compliance tests. Thus, despite the drawback which represents a certain loss of mechanical performance; a side face will be joined to the rest of the body by six bolts.

Due to geometry constraints, the only type of bolt that fits in the structure is a M1.6 countersunk flat screw as shown in Figure 2.9. A flat head screw has been chosen not to protrude above the structure and compromise the mechanic requirements. Figure 2.10 shows the hole made in the structure's removable face in order to fit the M1.6 bolts.

Figure 2.9: M1.6 countersunk flat screws

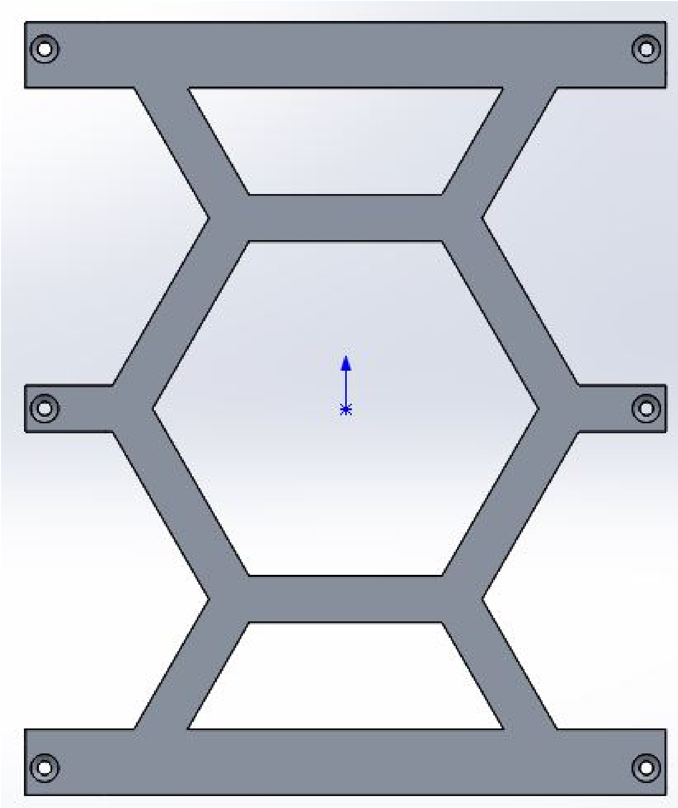

Figure 2.10: Structure's removable face with M1.6 holes

In order to join the removable face to the main body of the structure, some parts have to be added in order to hold the bolts. Figure 2.11 shows the corrections performed in the main body in order to achieve this objective.

Finally, Figure 2.12 shows the assembly between the removable face and the main body, joined with the described bolts.

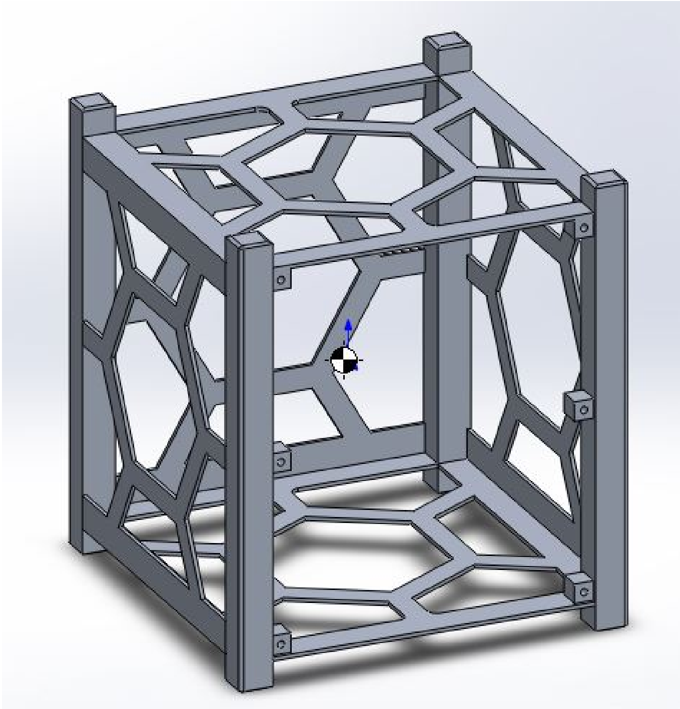

Figure 2.11: Structure's main body

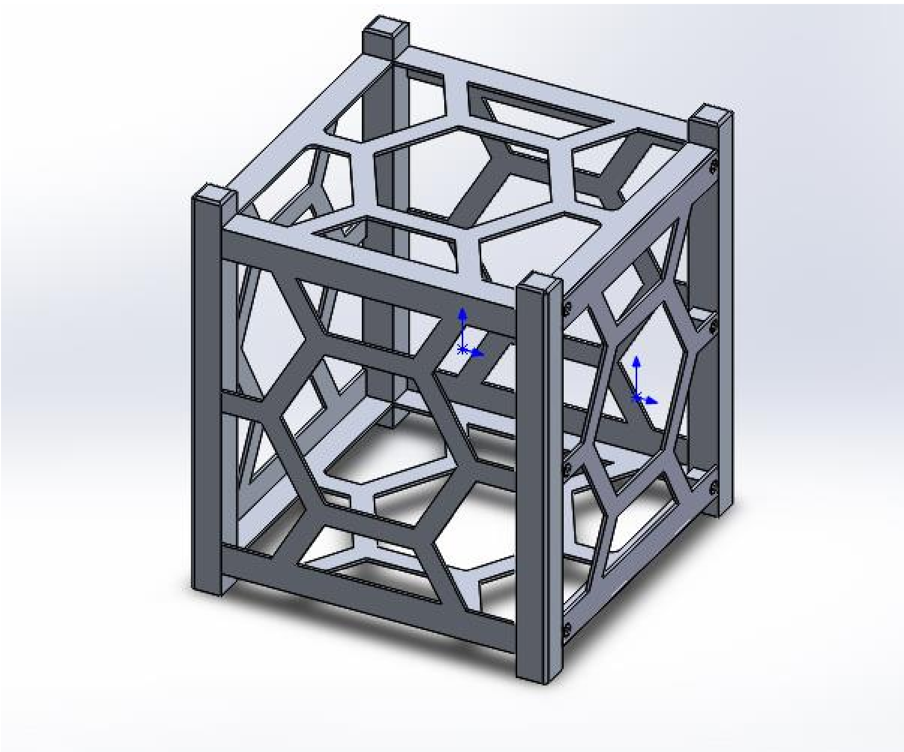

Figure 2.12: Hexagon Bolts model

The effect of the bolts make the center of mass to move slightly from the geometric center. Making its position coordinates: (-1.49 mm, -0.08 mm, 0.00 mm)

2.4.1. Stress analysis

Figures 2.13 and 2.14 show how due to the introduction of a removable face in the structure, its maximum predicted stress has increased by 65% compared to Hexagon II structure. Nevertheless, it remains in the elastic zone (below the yield strength of 5.050E+08 N/m^2), so the Hexagon Bolts structure still has a reliable performance.

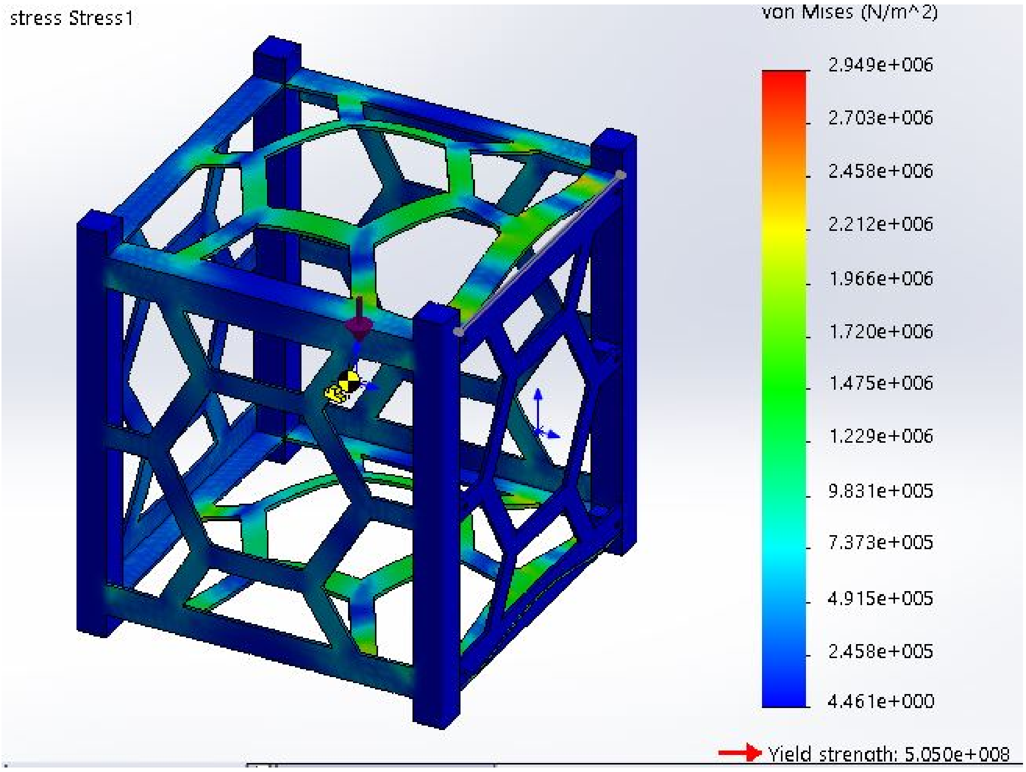

Figure 2.13: Hexagon Bolts stress analysis (under minimum random vibration spectrum).The legend values represent the same as in Figure 2.5.

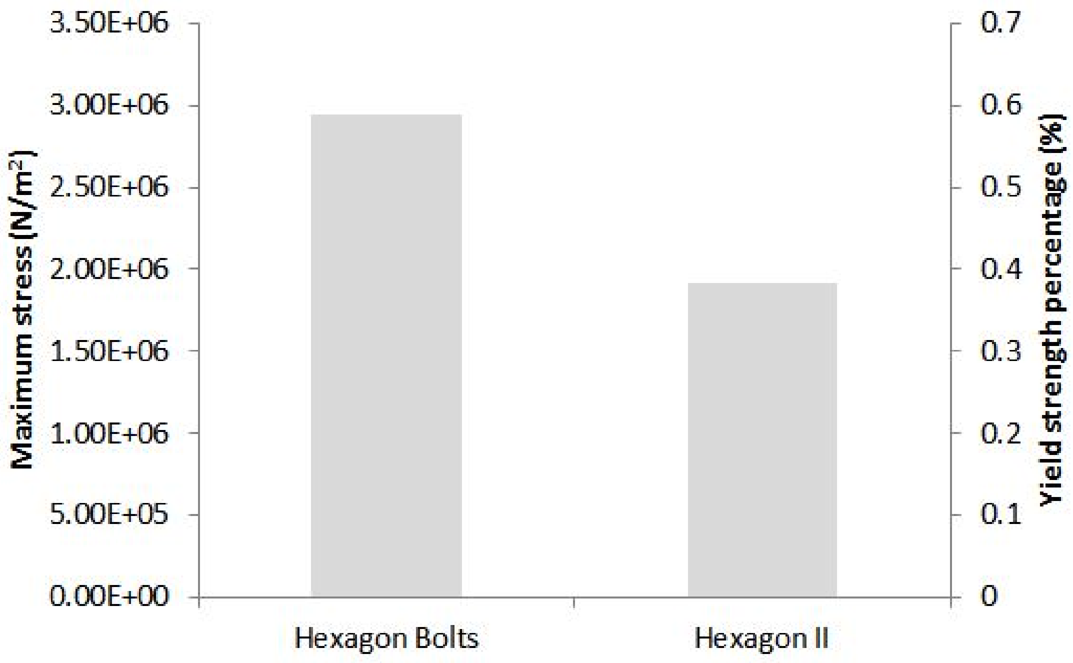

Figure 2.14: Stress (N/m^2) performance comparison between Hexagon II and Hexagon Bolts (under minimum random vibration spectrum)

CHAPTER 3. DETAILED SIMULATION TESTS

This chapter intends to show the main performance differences between Hexagon II, Hexagon Bolts and Pumpkin model, built in 7075 Aluminum. We also intend to check whether they fulfil the requirements of the qualification and acceptance tests in the random vibration environment and the shock spectrum.

The Pumpkin model -see Figure 3.1- has been reproduced in the same conditions as the Hexagon II one. It is important to point out that both are fixed geometry models, without floating parts, and thus the comparison results can be considered relevant.

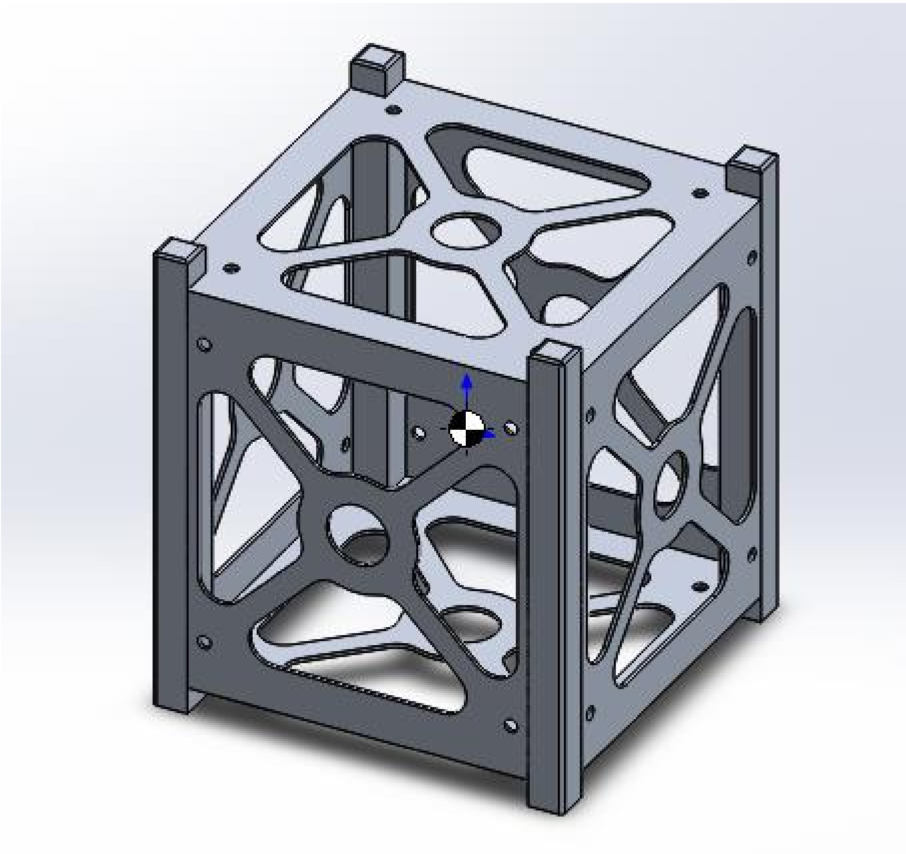

Figure 3.1: Pumpkin model

The following sections will show the behavior of the Hexagon II, Hexagon Bolts and Pumpkin structures in resonance, random vibration qualification and acceptance testing environments and shock spectrum response. An analysis of the resultant fundamental parameters such as stress and displacement will be carried out.

The first is paramount in order to keep the structural response in the elastic zone. As it has been mentioned in the Introduction section: Structural Mechanics and Analysis, it is crucial to keep the maximum predicted stress under the yield limit (5.050E+08 N/m^2 in this project case), meaning that the structure will not experience permanent (plastic) deformation or even rupture.

Displacement is very important as surrounding components concern. If the structure experience large displacements (a displacement of more than 1 mm will be considered un-acceptable) may harm close components such as solar arrays, electronic sensors, etc.

As a first check, we must keep in mind that weight is a paramount parameter in structure design, so Table 3.1 and Figure 3.2 show the mass differences between the three structures that are going to be compared.

Table 3.1: Mass (g) assessment of the different structures

Hexagon II	Hexagon Bolts	Pumpkin
148.22 g	150.7 g	182.67 g

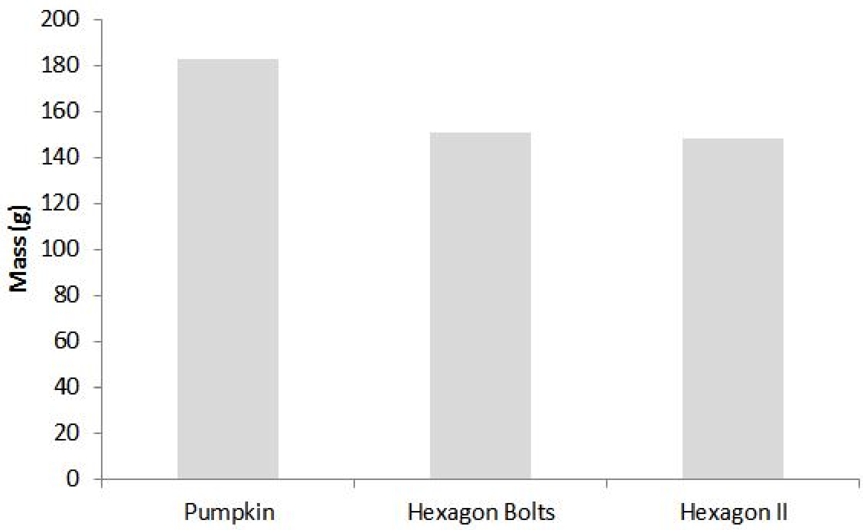

Figure 3.2: Mass (g) assessment of the different structures

As it is shown, Hexagon II structure is 34.45 grams lighter than the Pumpkin one, which represents almost a 19% saving in mass.

3.1. Frequency Analysis

Frequency analysis is the starting point for dynamic analysis (such as random vibration and shock response). It gives mode shapes and their corresponding resonant frequencies. The description of the process necessary to perform a frequency analysis with SolidWorks is given in Appendix 2 4.3.2.. Table 3.2 shows the natural frequencies for each of the five mode shapes studied.

Table 3.2: Resonant frequencies (Hz)

Mode	Hexagon II	Hexagon Bolts	Pumpkin
1	662.42	621.70	578.44
2	682.70	632.11	581.40
3	828.15	708.68	632.07
4	842.16	772.83	632.28
5	855.73	828.13	632.90

3.2. Random Vibration Analysis

The random vibration environment is due to the direct or indirect action of the acoustic and aerodynamic excitation, to roughness in combustion or burning processes and to machinery induced random disturbances. It is expressed as a power spectral density (PSD) or acceleration spectral density in g^2/Hz over a minimum frequency range from 20 to 2000 Hz.(10).

Power Spectral Density (PSD) measures the power intensity of a signal in the frequency domain. It is a characterization of the amplitude versus frequency context in a random signal, that is, it is a way to determine which frequencies contribute more to the signal's amplitude (and ultimately to its power). The PSD can be computed as the FFT spectrum of a signal. The accelerations associated to vibrations can also be expressed in an analogous way and then we consider the acceleration spectral density.

Random vibration environment analysis is critical during the launching, in which resonances can generate and amplify loads at certain locations of the CubeSat of up to a few tens of g.

According to the testing requirements demanded in the CubeSat Design Specification (1) the structures will be tested under the qualification and acceptance testing level environment defined in MIL-STD-1540C document (10; 11). MIL-STD-1540C corresponds to a military standard approved by the US Department of Defense in 1994. It is a set of requirements and compliance tests for all the participants of an on-orbit space mission (launch, upper stage, space vehicles and their components, computer software, ground stations, people...). It aims to assure the success of the mission. The specific information from the MIL-STD-1540C document which we have used for this work corresponds to the specifications related to the random vibration environment (frequency range, PSD values and overall acceleration level).

In this chapter we will consider both the *Qualification Testing Level* and the *Acceptance Testing Level*. They correspond to the list of tests that the equipment must undergo in order to make sure that it performs according to its specifications, when placed in the environment of the mission. To summarize, Qualification Testing Level refers to the design, construction and testing program, whereas Acceptance Testing level refers to the validity of each deliverable item. [1]

[1] From MIL-STD-1540C document (11): "Qualification tests shall be conducted to demonstrate that the design, manufacturing process, and acceptance program produce mission items that meet specification requirements. In addition, the qualification tests shall validate the planned acceptance program including test techniques, procedures, equipment, instrumentation, and software. The qualification test baseline shall be tailored for each program. Each type of flight item that is to be acceptance tested shall undergo a corresponding qualification test, except for certain structural items as identified herein.
Acceptance tests shall be conducted as required to demonstrate the acceptability of each deliverable item. The tests shall demonstrate conformance to specification requirements and provide quality-control assurance against workmanship or material deficiencies. Acceptance testing is intended to stress screen items to precipitate incipient failures due to latent defects in parts, materials, and workmanship. However, the testing shall not create conditions that exceed appropriate design safety margins or cause unrealistic modes of failure. If the equipment Is to be used by more than one program or in different vehicle locations, the acceptance test conditions should envelope those of the various programs or vehicle locations involved."

3.2.1. Qualification Testing Level

Table 3.3 and Figure 3.3 show the qualification random vibration environment at which the structure will be tested.

Table 3.3: Generalized random vibration environment at qualification test level

Frequency(Hz)	Minimum PSD (g^2/Hz)	Overall acceleration level
20	0.026	
20 - 50	+6dB/oct	
50 - 800	0.16	14.1 Grms
800 - 2000	-6dB/oct	
2000	0.026	

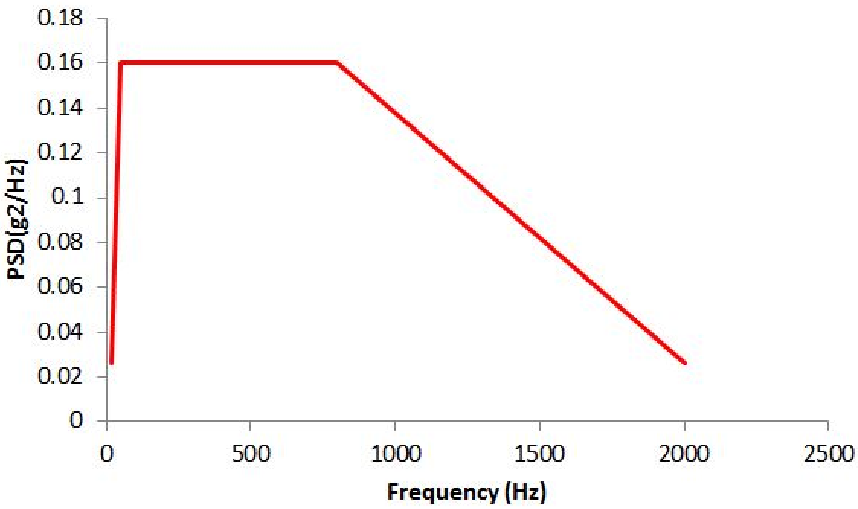

Figure 3.3: Random vibration environment at qualification testing level. The vertical axis corresponds to the power spectral density (g^2/Hz) as a function of the frequency (Hz) in the horizontal axis.

Tables 3.4 and 3.5 and Figures 3.4 and 3.5 show an analytic and graphical stress and displacement behavior comparison of the tested structures under the random vibration qualification testing level environment.

Table 3.4: Maximum stress (N/m^2) at random vibration qualification testing level

Hexagon II	Hexagon Bolts	Pumpkin
4.322E+06	5.898E+06	4.350E+06

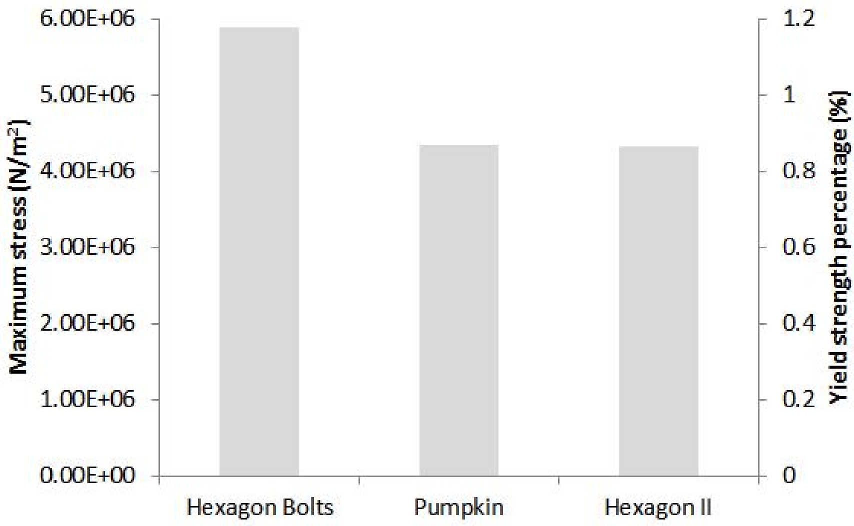

Figure 3.4: Maximum stress (N/m^2) comparison at qualification testing level

Pumpkin and Hexagon II structure show almost the same stress behavior, both around 4.3E+06 N/m^2 of maximum predicted stress, being Hexagon II the one which presents the best behavior. This represents a very reliable performance, as it does not reach the 0.9% of the yield strength (5.050E+08 N/m^2). Besides, Hexagon Bolts, with a removable face, experiences a 27% higher stress than Pumpkin and Hexagon II. However, it slightly overcomes the 1% of yield strength, which still makes it a very reliable structure.

Table 3.5: Maximum displacement (mm) at random vibration qualification testing level

Hexagon II	**Hexagon bolts**	**Pumpkin**
4.962E-02	6.561E-02	6.265E-02

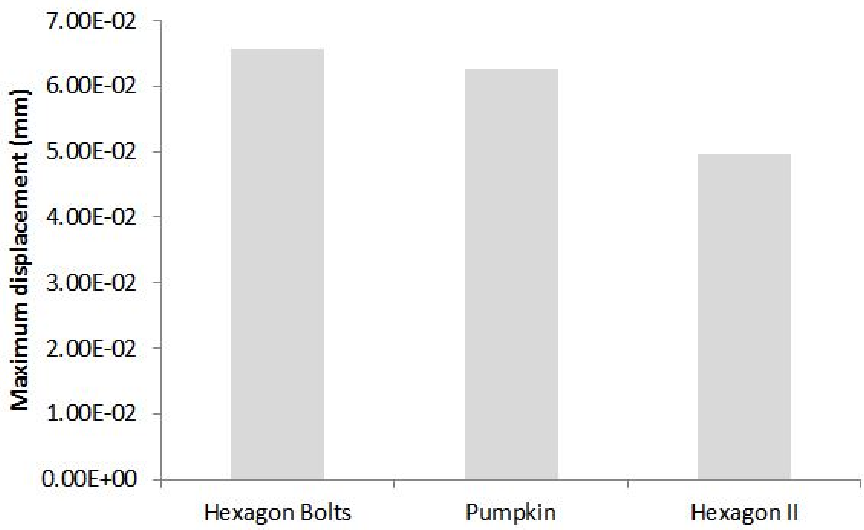

Figure 3.5: Maximum displacement (mm) comparison at qualification testing level

In terms of displacement, Hexagon II presents 0.013 mm less displacement than Pumpkin, which represents a 20% improvement for the Hexagon II model. Hexagon Bolts presents almost the same displacement performance than Pumpkin. Its maximum displacement is 6.561E-02 mm, that is, only 3.86E-03 mm further than Pumpkin, which makes it another reliable design.

3.2.2. Acceptance Testing Level

Table 3.6 and Figure 3.6 show the acceptance random vibration environment at which the structure will be tested.

Table 3.6: Generalized random vibration environment at acceptance test level

Frequency(Hz)	**Minimum PSD (g^2/Hz)**	**Overall acceleration level**
20	0.013	
20 - 50	+6dB/oct	
50 - 800	0.08	10.0 Grms
800 - 2000	-6dB/oct	
2000	0.013	

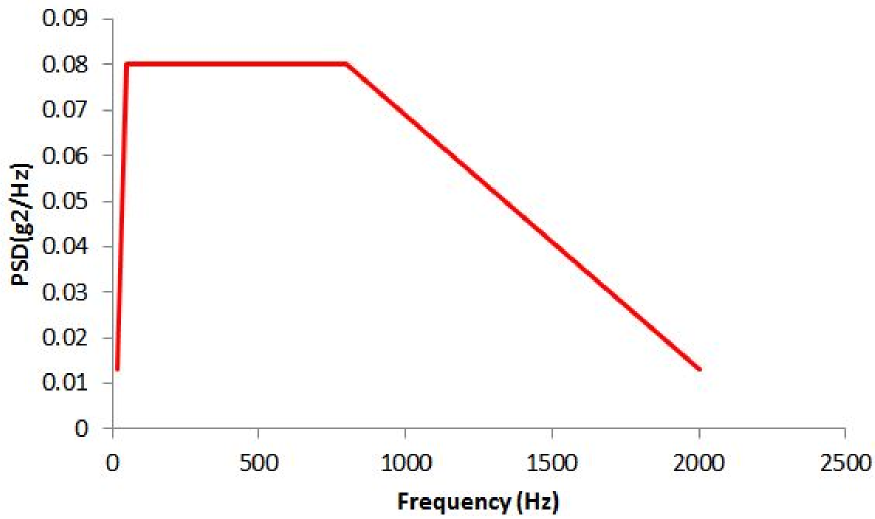

Figure 3.6: Random vibration environment at acceptance testing level. The vertical axis corresponds to the power spectral density (g^2/Hz) as a function of the frequency (Hz) in the horizontal axis.

Tables 3.7 and 3.8 and Figures 3.7 and 3.8 show an analytic and graphical stress and displacement behavior comparison of the tested structures under the random vibration acceptance testing level environment.

Table 3.7: Maximum stress (N/m^2) at random vibration acceptance testing level

Hexagon II	**Hexagon bolts**	**Pumpkin**
3.056E+06	4.170E+06	3.076E+06

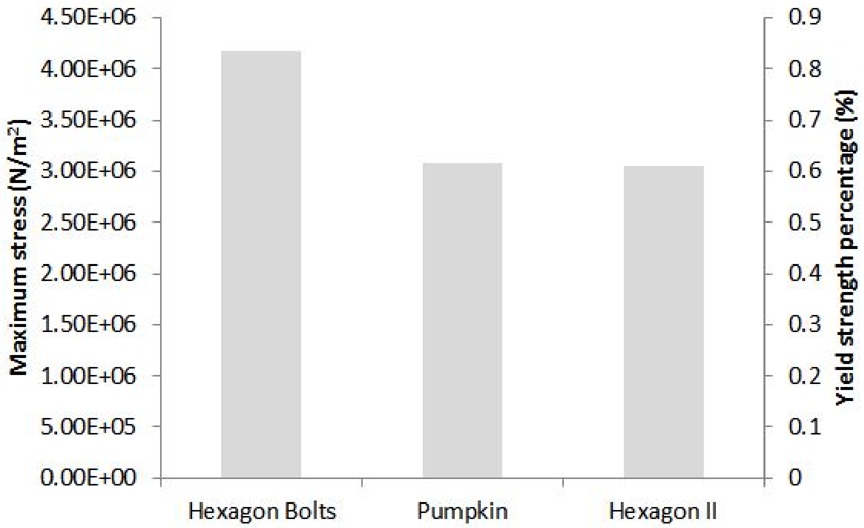

Figure 3.7: Maximum stress (N/m^2) comparison at acceptance testing level

Table 3.8: Maximum displacement (mm) at random vibration acceptance testing level

Hexagon II	**Hexagon bolts**	**Pumpkin**
3.509E-02	4.639E-02	4.430E-02

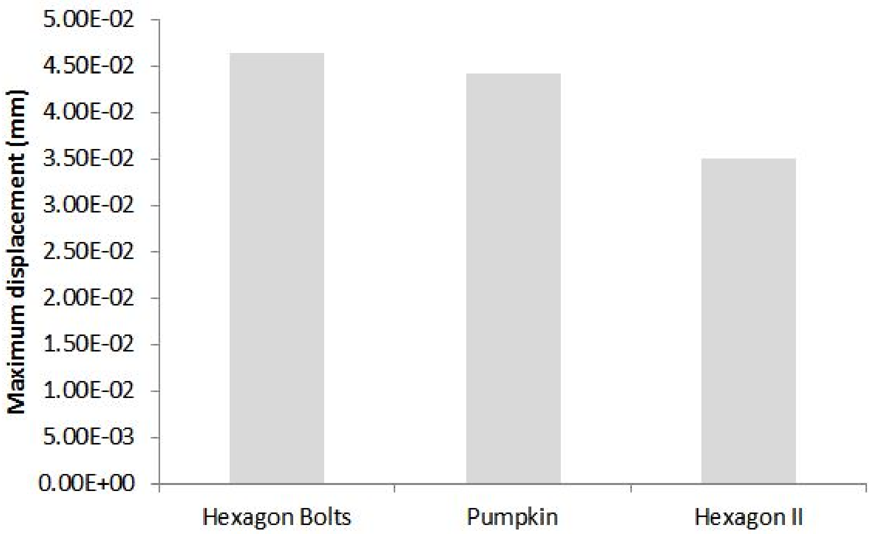

Figure 3.8: Maximum displacement (mm) comparison at acceptance testing level

Due to random vibration acceptance testing level presents the same environment as qualification level but half the loads. The results percentage relating the three structures will be the same. As numeric values concern, Hexagon Bolts is the one which presents the larger ones, without reaching the 1% of yield strength (5.050E+08 N/m^2) and with a maximum displacement of 4.639E-02 mm, making all the structures reliable.

3.3. Shock Response Analysis

Release devices such as aerodynamic fairing separation or spacecraft separation bolts, often use pyrotechnics that, when activated, generate a shock load that transmits through the structure of the payload. The shock pulse is a complex wave which induces mechanical response over a wide band of frequencies which decays typically within 5 to 15 milliseconds.

Because shock loads attenuate very quickly, they seldom damage structures, but they present far higher accelerations and frequencies, so the structural response will be more dramatic than in random vibration environment.

Table 3.9 and Figure 3.9 show the shock spectrum environment at which the structure will be tested under the acceptable shock spectrum environment based on the MIL-STD-1540C document (10) and more specifically defined in Ariane 5 User's Manual document (9) according to the testing requirements demanded in the CubeSat Design Specification document (1).

Table 3.9: Acceptable shock spectrum

Frequency (Hz)	Acceleration (g)
100	20
1500	600
3100	10000
10000	10000

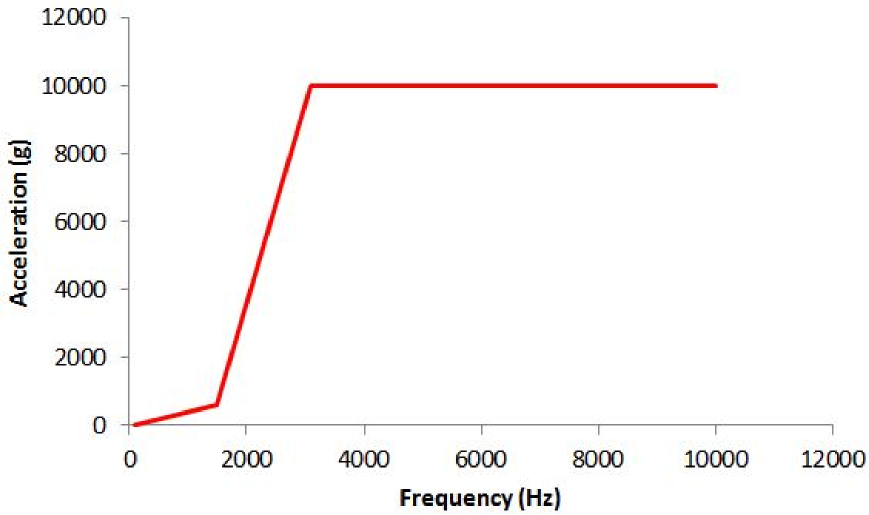

Figure 3.9: Acceptable shock spectrum. The vertical axis corresponds to the instant acceleration (g) as a function of the frequency (Hz) in the horizontal axis.

Tables 3.10 and 3.11 and Figures 3.10 and 3.11 show an analytic and graphical stress and displacement performance comparison of the tested structures under the shock spectrum environment.

Table 3.10: Maximum stress (N/m^2) at acceptable shock spectrum

Hexagon II	Hexagon bolts	Pumpkin
1.940E+07	2.498E+07	1.638E+07

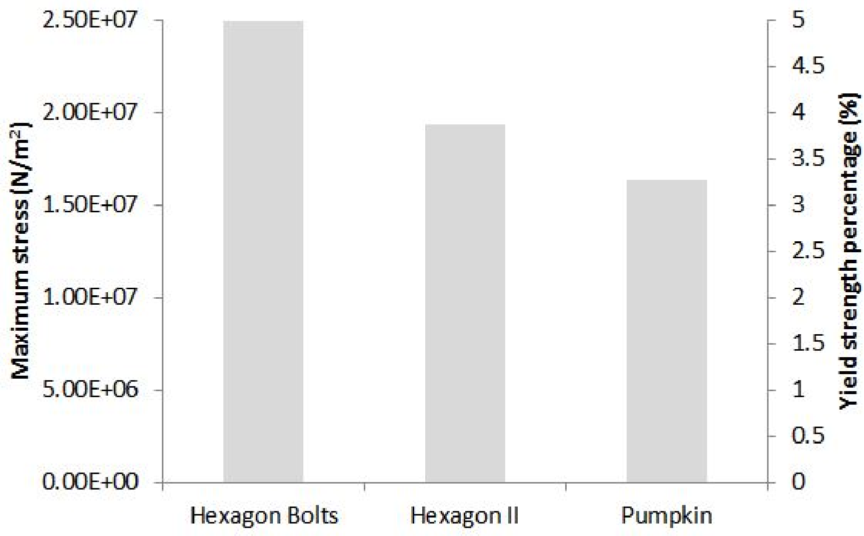

Figure 3.10: Maximum stress (N/m^2) comparison at shock response

Pumpkin structure is the one which presents the best shock performance, as it experiences 15% less of maximum predicted stress than Hexagon II. Again, because Hexagon Bolts has a removable face, it presents the largest stress, reaching almost 5% of the yield strength (5.050E+08 N/m^2). Even if the maximum stress that shock response implies is around 423% larger than in qualification testing level random vibration environment, it keeps being in the elastic zone by far, which makes the three structures very reliable. They would have to suffer a 2024% larger stress than in shock spectrum in order to start experiencing permanent deformation.

Table 3.11: Maximum displacement (mm) at acceptable shock spectrum

Hexagon II	Hexagon bolts	Pumpkin
1.725E-01	2.643E-01	1.949E-01

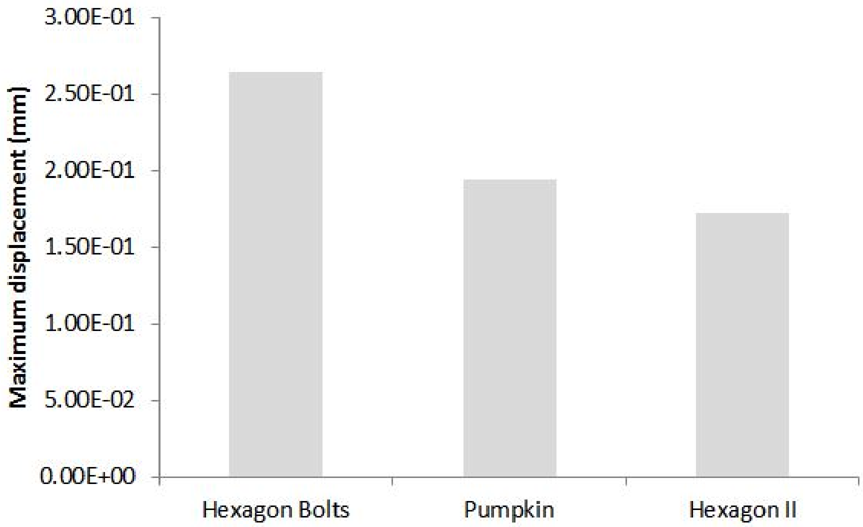

Figure 3.11: Maximum displacement (mm) comparison at shock response

As in the stress analysis, the structure which presents the largest displacement (Hexagon Bolts) overcomes by a 402% the maximum displacement presented in the qualification testing random vibration environment. However, this value (1.725E-01 mm) barely reaches two tenths of millimeter, making the structures a food candidate to pass the shock response test. The one that presents the best behavior in terms of displacement is Hexagon II which presents 0.02 mm of less displacement (11.5%) than Pumpkin.

CHAPTER 4. PRACTICAL IMPLEMENTATION PLAN

Once a reliable CubeSat design has been obtained, the next step is manufacturing. The CubeSat Design Specification document (1) states that the materials to build a standard CubeSat are Aluminium 7075 (with which we have performed our simulation tests) or 6061. Nevertheless alternative materials may be used, provided that they comply with the requirements of a specific approval request process [1].

As we have explained in the Introduction we intend to propose a CubeSat design which can be manufactured in the EETAC, using laboratory equipment from the School, or which can be easily accessed to. This forced us to discard aluminum, because the manufacturing process which it requires implies the need of rather sophisticated equipment, presently unavailable to us. Instead, we propose the use of alternative materials which could be used in 3D printers in TinkerersLab (12). TinkerersLab is a workshop specialized in digital manufacturing. It has 3D-printers (DSL/FFF), laser cutting and engraving machines, milling machines, CNC router, cutting plotter, etc. TinkerersLab offers the use of its equipment to students, and it is located at the Parc Mediterrani de la Tecnologia, at the same campus as the EETAC, which makes collaboration with them very convenient.

In this Chapter we discuss the choice of possible materials for the manufacture of the CubeSat and outline the process of printing specimens and testing of such materials, printing the entire CubeSat and finally testing the entire structure.

4.1. Choice of the material

The choice of the material is a critical part in this process. We need to find a material which meets the following requisites: it must be able to eventually pass the Qualification and Acceptance Tests, it must be available to us (and not prohibitively expensive), and it must be fit for the 3D-printing process.

Part of the research and search of a suitable material has been done during the development of the present project. As aluminum 7075 and 6061 are the materials indicated in the CubeSat Specification Design document (1), their mechanical properties will be our zeroth order reference for comparison with our alternative materials. These mechanical properties can be determined using the UTM at the EETAC.

Windform XT2.0 (13) is the high-tech polyamide-based carbon filled composite whose performance outranked all selective laser sintering materials (a description of laser sintering, which is a type of 3D-printing technology, is presented in the next subsection.) [2]. It is produced and commercialized by CRP Technology and has been successfully used to manufacture a CubeSat, see for instance (14). Figure 4.1 represents an example of a CubeSat structure built by CRP in 2011. Our first option was to try and purchase this material to build our own CubeSat, but CRP Technologies only sells quantities from about 120 kg, which made the purchase unaffordable in the academic context. The good news, nev-

[1] From (1): ”Aluminum 7075 or 6061 shall be used for both the main CubeSat structure and the rails. If other materials are used the developer will submit a DAR (Deviation Wavier Approval Request) and adhere to the waiver process.”

[2] http://www.windform.com/

ertheless, was that these types of materials were adequate for space and could eventually be used for our purposes.

3D printers in TinkerersLab may use different types of polyamide (PA6, PA11, PA12) and PA-based composites. PA by itself is not adequate for manufacturing rigid structures, but when mixed with other materials, such as carbon fiber, aluminium, or glass, its mechanical properties may improve dramatically, as in the case of Windform XT2.0. The German company ADVANC3D Materials developed PA11CF, their own PA11-based carbon fiber-reinforced material with enhanced resistance and thermal conductivity behaviour. ADVANC3D kindly made 2 kg of PA11CF available to TinkerersLab and to our group. Unfortunately the material arrived too late and some unexpected problems with the 3D-printers made it impossible to print the specimens for the mechanical tests and a first prototype of the CubeSat structure.

A natural continuation of the present work will consist on printing and characterizing PA11CF by performing tests with this new material. Furthermore there is the exciting chance of doping PA with graphene and test its behaviour. The mechanical and thermal characteristics of this material, either on its own or included in composites, even at very low percentages, are most promising.

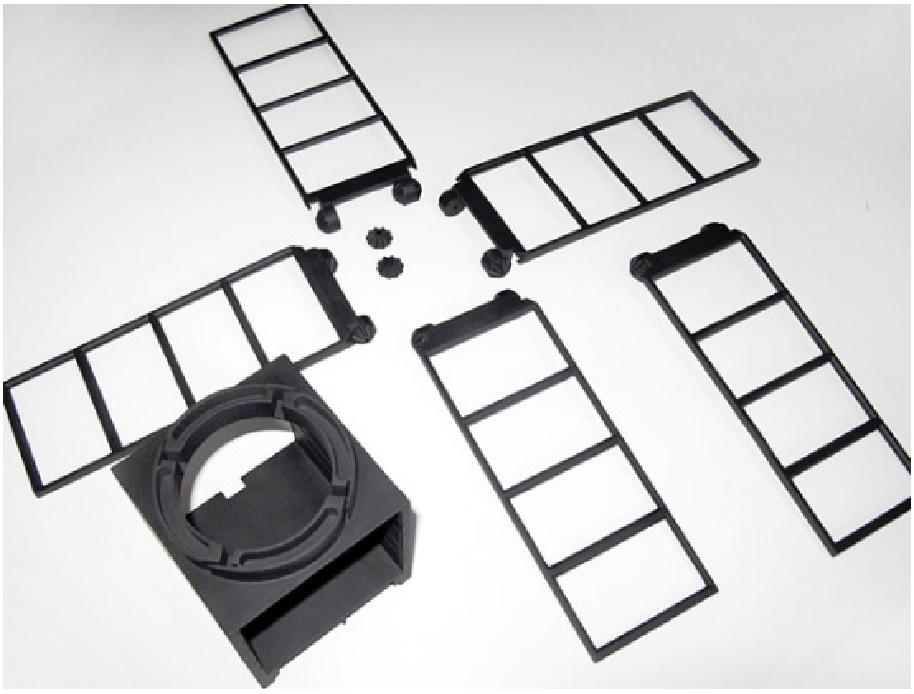

Figure 4.1: Primary and solar panel structure of a CubeSat (Image credit: CRP / the building of a CubeSat with Additive Manufacturing with the WINDFORM XT.)

4.2. 3D Printing Process

Generic 3D printing was described in Section 1.3.. In the present section we focus on the process of additive manufacturing by laser sintering, which is relevant in our case. Among all the 3D printing technologies existing, this process is the one which will be used to print both the test specimens and eventually the CubeSat structure.

Laser sintering or laser melting are synonym terms that refer to a laser based 3D printing process which works with powder materials: plastic and metal. The basic performance is a laser trace across a building plate of tightly compacted powder material according to the data file uploaded to the machine. As the laser interacts with the material, it sinters the particles forming a solid. As every 3D printing process, the piece is build layer by layer. Each layer is sintered to the previous one as the laser fuses the material of the powder bed. (15)

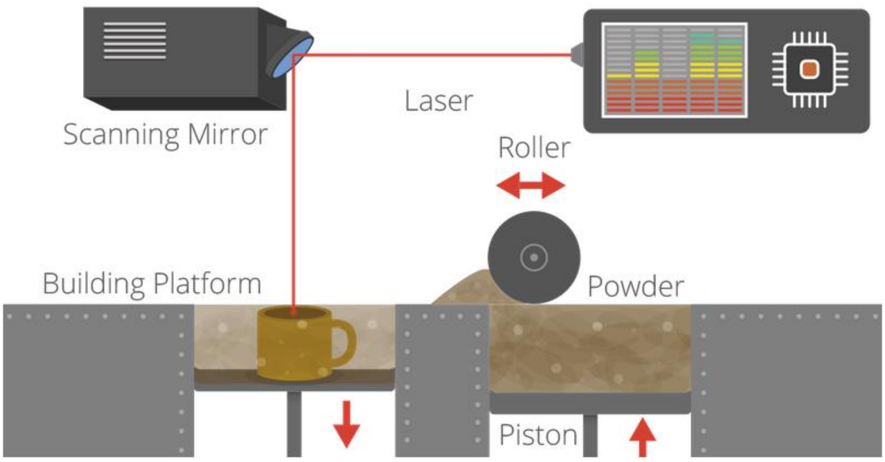

Figure 4.2: Laser sintering printing process

The first step consists on setting the printer according to the piece that is going to be built and the material which is going to be used. Different geometries and materials will require different printing parameters.

The next step consists on filling of the tanks of material. The amount of material needed for a certain 3D model is called offset. It is a critical process due to the fact that the tanks are filled with powder and there must not be any air bubbles left among the material once the laser begins sintering. Once the tanks are filled and free of air, they will move upwards and lay a certain amount of material on the building plate. Then, the recoater –or roller-will spread this material over the building plate twice. Again, it has to be assured that the layer of material the recoater has spread over the plate is completely homogeneous, flat and free of air bubbles. If there is any evidence of some imperfections in the layer, the process will have to be repeated as many times as needed.

Once there is a completely homogeneous and flat layer of powder on the building plate, the 3D file with the digital data of the piece is loaded.

Now, the laser will begin sintering as the 3D file demands. As each layer is sintered and completed, the powder bed will move downwards and the recoater will level the material over the building plate prior to the next pass of the laser, which will sinter the corresponding particles again fusing with the previous layer. The process will repeat layer by layer until the piece is completed.

The temperature inside the building chamber has to be very precise because it has to be specifically related with the melting point of the working material. This means that the printing volume must be completely sealed during the whole process of sintering in order to maintain this precise temperature.

Once the process is finished, the building plate can be taken out from the machine and the excess powder can be easily removed, leaving the printed components ready. One of the advantages of the laser sintering is that it makes feasible the creation of complex shapes which would be impossible to make by means of any other manufacturing process. The main reason is that the powder bed serves as a support structure for overhangs and undercuts. The highest resolution attainable is 0.1 mm, which is compatible with the requirements laid in CubeSat Specifications Document. (1)

Besides the fact that cooling times can be considerably long due to the high temperatures required for laser sintering, the main drawback this printing technology presents is the porosity that some of the resultant pieces use to present. In order to improve their mechanical properties some applications need infiltration with another material.

4.3. Experimental Test Plan

4.3.1. UTM

The first step of the experimental plan is to print the tests specimens in order to perform Universal Testing Machine (UTM) test analysis to determine the PA11CF mechanical properties and then compare it to other commercial materials such as aluminum 7075. At this point, if the specimens fail to pass the UTM tests, we must go back to the *Choice of Materials* step. The UTM and the tests it can perform were briefly described in Section 1.2..

The test specimens have been designed with SolidWorks as Figure 4.3 shows, according to UNE-EN ISO 6892-1 document (16), which determines the geometry and dimensions of the specimens necessary to perform approved traction tests. Being the minimum length of the calibrated part 57 mm.

Test specimens were already printed with an aeronautical approved material, but just visual inspection determined that it was not a proper structural material due to its poor mechanical properties such as excessive ductility.

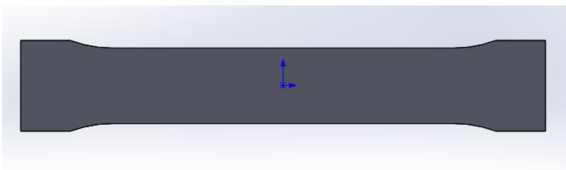

Figure 4.3: Test specimen for UTM analysis

4.3.2. Shaker

Finally, once the CubeSat structure is built a shaker test will be performed, with conditions similar to the ones we proposed in our simulations. This way we can assess whether the simulation tests were close to reality an so the structure is reliable, and thus that we have some reassurance that it will perform reasonably well during the launch.

The Polytechnical University of Catalonia has a shaker which would be appropriate for our purposes, as it has been used to perform tests on small satellites -see (17) and references therein, and thus we expect to be allowed to use it.

CONCLUSIONS

A honeycomb pattern monocoque structural design -called Hexagon- is proposed for a single unit CubeSat primary structure, which is going to be constructed in a polyamide based (PA11) carbon fiber reinforced composite (PA11CF), provided by ADVANC3D Materials, by using 3D printing technologies or additive manufacturing. A preliminary feasibility assessment is made, based on structural simulation outputs and theoretical research. The main conclusions are:

- A reliable design has been obtained. It fulfills the mechanical design specifications and requirements of the CubeSat Design Specification. (1)
- According to simulation results, the structure will have no problem to withstand the launch environments such as random vibration and shock loads, as determined in the CubeSat Design Specification document (1). The predicted maximum stress remains in the elastic zone of the material and barely exceeds the 1% of the yield strength.
- Taking as a reference the 1U Skeletonized CubeSat Kit structure from Pumpkin, Inc. and taking into consideration that weight is a paramount parameter to keep in mind in structural design, the Hexagon structure is 34.45 grams lighter than the Pumpkin one, which represents almost a 19% saving in mass.
- As geometry concerns, considering both structures as a unique block, Hexagon II and Pumpkin, the first presents a better stress behavior in both random vibration analysis (qualification and acceptance level). In terms of displacement, when subjected to random vibration and shock spectrum environments, Hexagon II presented a 20% and 11.5% less displacement than Pumpkin, respectively.
- Compared to traditional manufacturing, 3D printing or additive manufacturing presents several advantages such as the manipulation of models in digital format, enabling free designs, the creation of complex shapes and geometries, reduction of cost and time, and the avoidance of assembly requirements.
- The use of carbon fiber reinforced composite materials may provide some advantages like lighter, cheaper and more resistant designs.
- We have become familiar with material specification and characterization research, as well as with the use of laser sintering techniques. Unfortunately technical problems beyond our control did not allow us to obtain actual material specimens and perform UTM tests.
- Nevertheless we have outlined a work plan as a natural continuation of the present project, the alternative materials and manufacturing techniques to use have been proposed and, what is more important, the material provider and the appropriate 3D-printers have been located.
- The ideas being considered for future work are: (1) to perform UTM tests with the PA11CF specimens in order to characterize the material; (2) to assess the reliability of the printed structure by performing shaker tests and checking whether the experimental results agree with the simulations. Figure 4.4 summarizes the work done in

this project and the general context of the entire design, manufacturing and testing process. We should also test whether the PA11CF is able to cope with the space environment. This should be the case given its similarity to other materials that are already space qualified.

- Finally, we may suggest that it is actually possible to design and manufacture the structure of a CubeSat in the EETAC, with currently available technology.

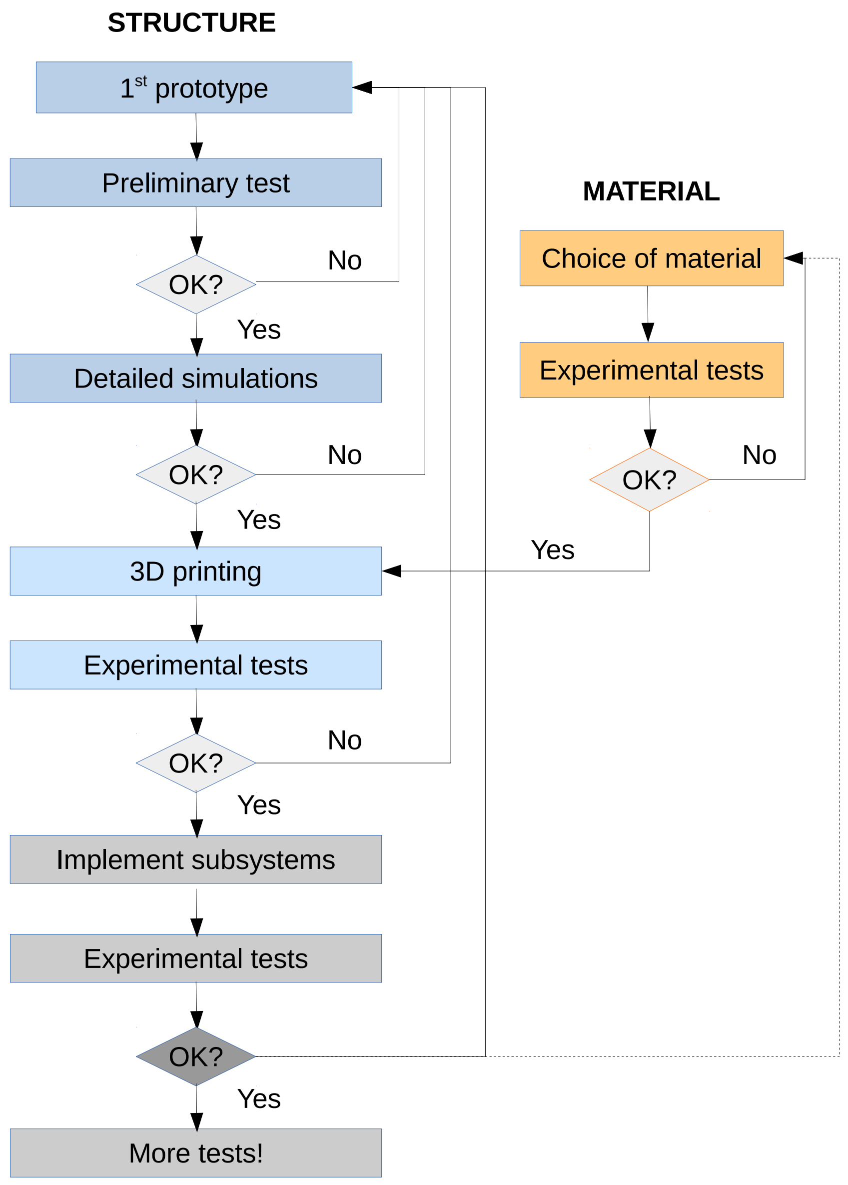

Figure 4.4: Summary of the work done in the present project and its context and future work.

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APPENDIX 1: MECHANICAL REQUIREMENTS OF THE CUBESAT

The present Appendix is an excerpt from the CubeSat Design Specifications (1).

CubeSat Mechanical Requirements (for single CubeSats)

CubeSats are cube shaped picosatellites with a nominal length of 100 mm per side. Dimensions and features are outlined in the CubeSat Specification Drawing. General features of all CubeSats include:

i) **Exterior dimensions**

- The CubeSat shall use the coordinate system as defined in 4.5 for the appropriate size. The -Z face of the CubeSat will be inserted first into the P-POD.
- The CubeSat configuration and physical dimensions shall be per Figure 4.5.
- The CubeSat shall be 100.0 $\pm$ 0.1 mm wide (X and Y dimensions per Figure 4.5).
- A single CubeSat shall be 113.5 $\pm$ 0.1 mm tall (Z dimension per Figure 4.5).
- All components shall not exceed 6.5 mm normal to the surface of the 100.0 mm cube (the green and yellow shaded sides in Figure 4.5).
- Exterior CubeSat components shall not contact the interior surface of the P-POD, other than the designated CubeSat rails.
- Deployables shall be constrained by the CubeSat. The P-POD rails and walls shall not be used to constrain deployables.
- Rails shall have a minimum width of 8.5 mm.
- The rails shall not have a surface roughness greater than 1.6 μm.
- The edges of the rails will be rounded to a radius of at least 1 mm
- The ends of the rails on the +/- Z face shall have a minimum surface area of 6.5 mm x 6.5 mm contact area for neighboring CubeSat rails (as per Figure 4.5).
- At least 75% of the rail will be in contact with the P-POD rails. 25% of the rails may be recessed and no part of the rails will exceed the specification. For single CubeSats this means at least 85.1 mm of rail contact.

ii) **Mass**

- Each single CubeSat shall not exceed 1.33 kg mass.
- The CubeSat center of gravity shall be located within a sphere 2 cm from its geometric center.

iii) **Materials**

- Aluminum 7075 or 6061 shall be used for both the main CubeSat structure and the rails. If other materials are used the developer will submit a DAR [3] and adhere to the waiver process.
- The CubeSat rails and standoff, which contact the P-POD rails and adjacent CubeSat standoffs, shall be hard anodized aluminum to prevent any cold welding within the P-POD
- The 1U, 1.5U, and 2U CubeSats shall use separation springs with characteristics defined in 4.1 on the designated rail standoff. Separation springs with characteristics can be used using McMaster Carr P/N 84985A76. The separation springs provide relative separation between CubeSats after deployment from the P-POD.
- The compressed separation springs shall be at or below the level of the standoff.
- The throw length of the separation spring shall be a minimum of 0.05 inches above the standoff surface.

Table 4.1: CubeSat Separation Spring Characteristics

Characteristics	**Value**
Plunger material	Stainless Steel
End Force Initial/Final	0.5 lbs / 1.5 lbs
Throw Length	0.05 inches minimum above the standoff surface

[3] Deviation Wavier Approval Request

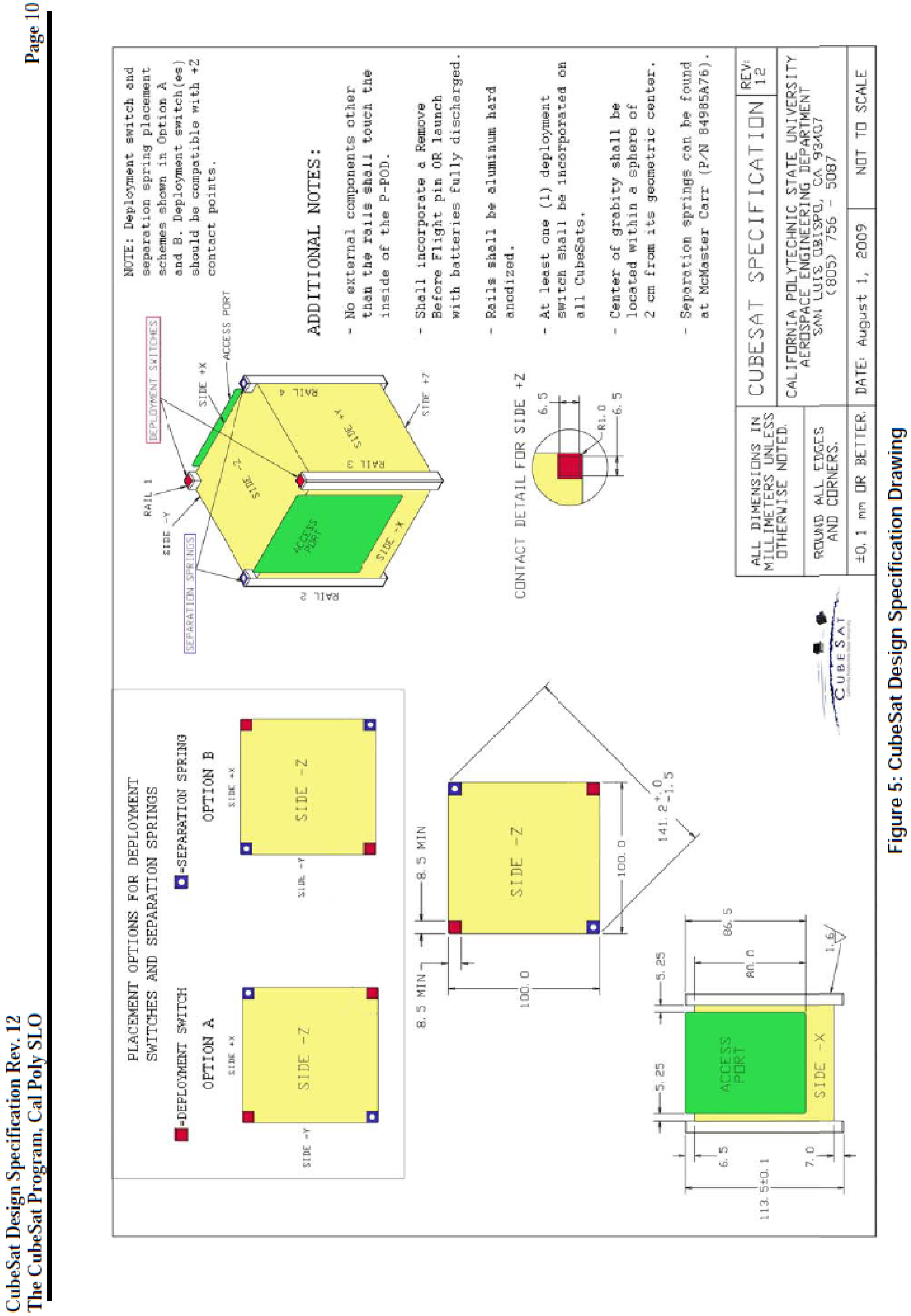

Figure 4.5: From CubeSat Design Specifications Rev. 12.

APPENDIX 2: SOLIDWORKS SIMULATION

The present Appendix shows step by step how the simulations in SolidWorks have been performed.

SolidWorks Simulation allows to perform several studies. Frequency will be chosen for modal or frequency analysis.

Frequency Analysis

- Firstly, it is necessary to set the material of the model. The simulator requires the material properties in order to carry out the structural computations. SolidWorks provides a large library with the most common materials properties. However, if the required material is not present, the user can introduce its properties.

- Once the model is fully defined, the first step for every simulation test is to set the parts of the structure that will be fixed with SolidWorks Fixtures Advisor tool. Figure 4.6 shows the fixed geometry for Hexagon II structure.

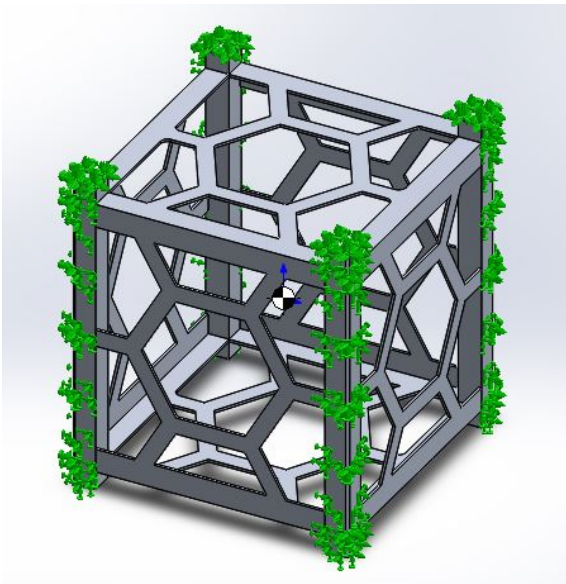

Figure 4.6: Hexagon II fixed geometry

- Now, the creation of the mesh is required. SolidWorks offer some setting configurations in order to adapt the mesh to the user's preference as Figure 4.7 shows. The finer the density of the mesh is, the more accurate the simulation will be, although the time of the test will be longer. Figure 4.8 shows Hexagon II structure already meshed.

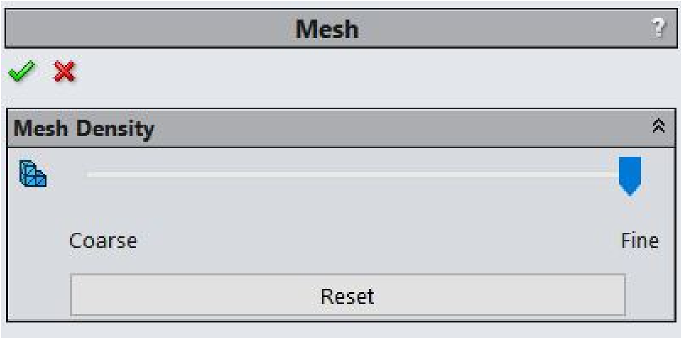

Figure 4.7: SolidWorks mesh density settings

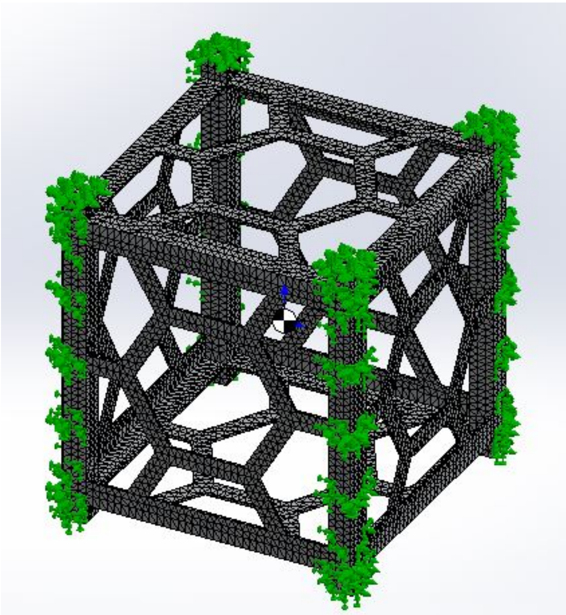

Figure 4.8: Hexagon II mesh

- Before running, the software allows to set the properties of the test (see Figure 4.9), such as the number of frequencies or mode shapes required, an upper bound frequency, etc.

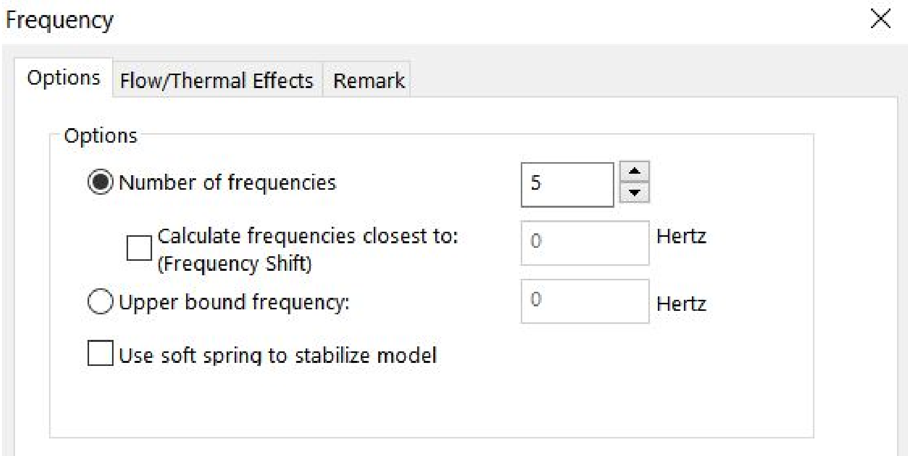

Figure 4.9: SolidWorks frequency test properties

- Once all the data is set as the user demands, the study is ready to run.

Dynamic Analysis

Random vibration and shock response analysis are among linear dynamic tests. Shock response is a particular case of response spectrum analysis.

- For random vibration or shock response analysis, the same steps are going to be followed, but with some additional settings.
- Once the mesh is defined. It is important to set the operating frequency limits in the properties menu. For instance, random vibration tests are usually performed between 20 and 2000 Hz. Figure 4.10 shows the random vibration properties window with the test range settings between 20 and 2000 Hz.

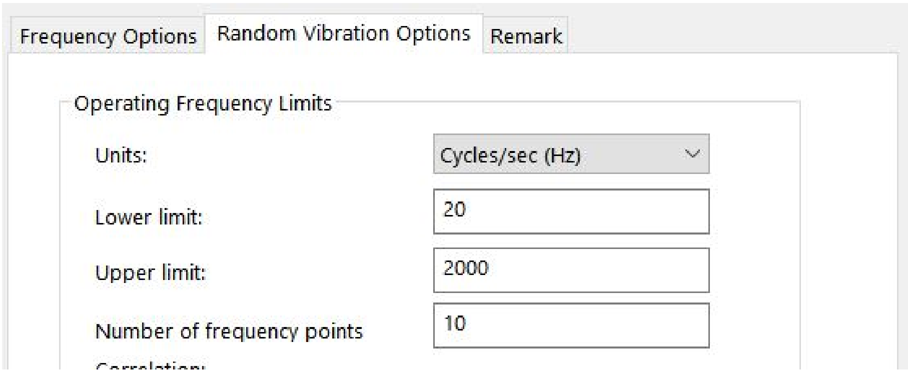

Figure 4.10: SolidWorks random vibration properties

- Besides the general properties of the material, vibration analysis require the material's damping ratio, which has to be set by the user if it is not already defined by the software.
- Finally, dynamic analysis need an external load to be able to perform the test. In the present project, a downwards acceleration has been chosen in order to recreate

the launch conditions as possible as Figure 4.11 shows. Then, a variation of the power spectral density (PSD) with frequency (test environment) is required. SolidWorks offer the possibility to make it linear or customized. As this project concerns, the environment has been set as the qualification and acceptance tests require, besides the preliminary design tests which were performed under a minimum random vibration spectrum. Figure 4.12 shows a customized random vibration environment.

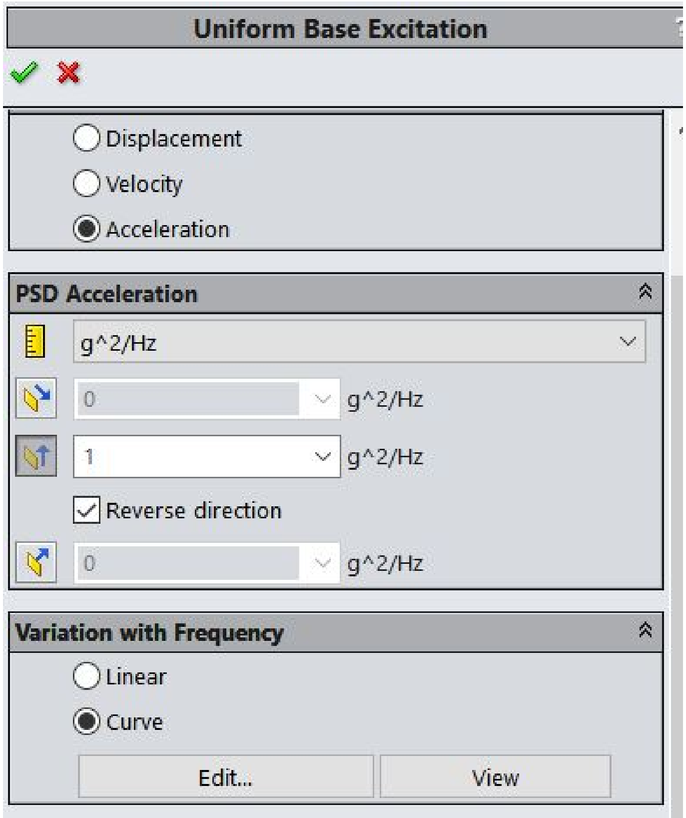

Figure 4.11: SolidWorks random vibration settings

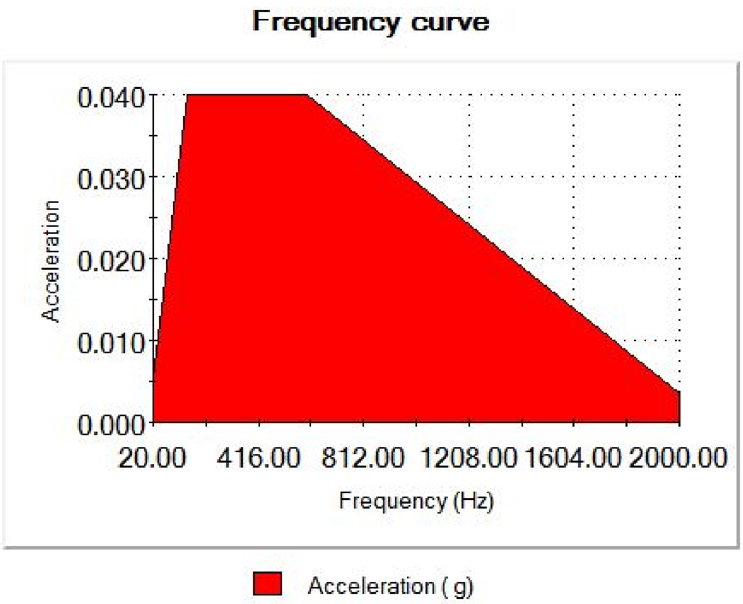

Figure 4.12: SolidWorks minimum random vibration spectrum

- Once all the properties are properly set and the environment well characterized, the test is ready to be performed.