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LETECKÝ ÚSTAV

DESIGN PROPOSAL OF THE 12U CUBESAT STRUCTURE

NÁVRH NOSNÉ KONSTRUKCE CUBESAT-U VELIKOSTI 12U

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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Assignment Master's Thesis

Institut: Institute of Aerospace Engineering
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Design proposal of the 12U CubeSat structure

Brief Description:

CubeSats are small satellites with standardized dimensions and mass suitable for space research and demonstration of new technologies. Each satellite consists of one or more cubic modules (so–called "units" – U) with a size of about 10x10x10 cm. There are currently several companies in the world that provide support structures for these types of satellites. One of them is the company VZLÚ, a.s., which during the design of the supporting structure is focused primarily on weight, modularity, and inside accessibility within the entire structure. This approach after the creation of 1U to 6U support structures continues the path of developing sophisticated CubeSats of larger dimensions, specifically to a 12U–sized structure.

Master's Thesis goals:

– Review of the commercial Cubesat structures.
– Design of 12U CubeSat structure.
– Analysis and check of the proposed structure.
– Evaluation of the proposed structure in the context of competing solutions.

Recommended bibliography:

PUIG-SUARI, J., TWIGGS, B. CubeSat Design Specification. Rev. 13. USA: California Polytechnic State University, 2014.

CAPPELLETTI, Ch., BATTISTINI, S., MALPHRUS, B. ed. CubeSat Handbook: From Mission Design to Operations. USA: Academic Press, 2020, 498 s. ISBN 978-0128178843.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2021/22

In Brno,

L. S.

doc. Ing. Jaroslav Juračka, Ph.D.
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Abstrakt

CubeSat-y jsou v dnešní době velmi populární téma díky své ceně a jednoduchosti. Jejich použití se v poslední době ubírá spíše směrem ke komerční sféře trhu, kde vzniká velké množství společností poskytující široké spektrum služeb pro mise CubeSat-ů. Jednou z těchto společností je i Výzkumný a zkušební letecký ústav (VZLÚ), který nedávno zahájil vývoj série struktur CubeSat-ů o velikosti 1U – 3U.

Tato závěrečná práce je zpracována ve spolupráci s VZLÚ. Práce je zaměřena na vytvoření informační platformy, zahrnující průzkum trhu a následující konstrukci včetně její pevnostní kontroly, struktury CubeSat-u o velikosti 12U jakožto pokračování v rámci dalšího vývoje série struktur o velikosti 6U – 12U.

Klíčová slova

CubeSat, návrh, pevnostní kontrola, PCB stack, nosný rám, 12U CubeSat, dispenser, MKP analýza, CubeSat průmysl, kill-switch mechanismus, optimalizace

Abstract

CubeSats are nowadays highly popular topic, due to their price and simplicity. Lately, their use is mainly concentrated in commercial sphere of market, where number of companies providing wide spectrum of services for CubeSat missions, are being founded. One of these companies is also Czech Aerospace Research Centre (VZLÚ), which recently began development of series of 1U – 3U CubeSat structures.

This master´s thesis is written in collaboration with VZLÚ. It is focused upon creation of information platform, including market research and following design with its analysis and check of 12U CubeSat structure as a continuation in the scope of further development of series of 6U – 12U structures.

Keywords

CubeSat, design, analysis and check, PCB stack, structural frame, 12U CubeSat, dispenser, FEM analysis, CubeSat industry, kill-switch mechanism, optimalization

Prohlášení o spolupráci

Tato diplomová práce *„Návrh nosné konstrukce CubeSat-u velikosti 12U“* byla zpracována s použitím důvěrných informací a se souhlasem společnosti VZLÚ, a.s.

Declaration of cooperation

This master´s thesis *"Design proposal of the 12U CubeSat structure"* was written with use of confidential information and agreement of company VZLÚ, a.s.

Rozšířený abstrakt

Lidstvo vždy vzhlíželo ke hvězdám a pokoušelo se o jejich průzkum a kolonizaci. Z tohoto důvodu získal vesmírný průmysl tolik popularity. Avšak, veškeré mise a zařízení, vypouštěné do vesmíru, měly v minulosti jednu společnou vlastnost. Byly příliš nákladné a pouze velké instituce (NASA/ESA) si je mohly dovolit.

Toto se změnilo, když se na konci 20. století objevil koncept malých satelitů. Tyto satelity byly nazvány jako CubeSat-y a jsou dostupné ve velkém množství verzí a tvarů.

Brzy poté vznikl CubeSat průmysl a jeho většina byla rychle přesunuta do soukromého sektoru vesmírného průmyslu. Velké množství společností začalo vytvářet komponenty pro tyto satelity (struktury, anténové systémy, solární články, …), aby poskytly podporu potenciálním zákazníkům s jejich misemi.

Jedna z těchto společností je také VZLÚ, které nedávno začalo s vývojem jejich vlastních CubeSat struktur, určených ke komerčnímu využití.

Tato závěrečná práce byla zpracována ve spolupráci s VZLÚ. Soustředí se na vytvoření průzkumu trhu, týkajícího se CubeSat struktur velikosti 12U a potenciálních dispenserů, které by mohly být použity pro 12U CubeSat-y.

V návaznosti na průzkum trhu byl vytvořen seznam požadavků a konstrukčních předpokladů, sloužících jako vstupní data pro následující návrh. Díky tomuto seznamu byl vytvořen návrh tzv. PCB stack jednotky (nejzákladnější typ užitečného zatížení v CubeSat průmyslu) a jeho uchycovacího systému.

Se znalostí možností poskytovaných konkurencí a navrženým uchycovacím systémem, byly navrženy 3 verze struktury o velikosti 12U. Každá verze byla zanalyzována kvůli následujícímu zhodnocení jejich vlastností. Následně byla pro každou verzi spočítána modální analýza, aby bylo možné jednoznačně určit, která z navržených struktur poskytuje vyšší tuhost.

Toho bylo docíleno „standardizací“ všech 3 představených návrhů tak, že jednotlivým dílům, plnícím stejnou funkci, byly přiděleny totožné nominální tloušťky stěn. Po provedení zmíněného výpočtu však vyvstala otázka ohledně chování integrované PCB stack jednotky. Z toho důvodu byla provedena 2. série výpočtů, aby se zjistilo, která struktura poskytuje pro integrované užitečné zatížení nejvyšší tuhost.

Po provedení výpočtů, byly výsledky spolu s parametry jednotlivých struktur zhodnoceny. Na základně hodnocených parametrů vyšla 1. verze navrhované struktura jako nejoptimálnější přistup a byla zvolena jako finální koncept.

Tato struktura byla následně detailněji namodelována a do jejího návrhu byl již zahrnut i kill-switch mechanismus a komponenty uchycované na vnější část rámu. Dále návrh prošel procesem optimalizace, v tomto případě redukcí hmoty při zachování jeho vlastností a funkce.

Tento detailní návrh byl pak zkontrolován, aby byla ověřena jeho schopnost přenášet zatížení a plnit svou funkci. Do zahrnutých výpočtu byly zahrnuty detailnější modální analýza a analýza kvazistatického zatížení, ve kterých struktura úspěšně splnila veškeré požadavky.

V poslední kapitole byla navržená struktura srovnána s konkurencí, avšak pouze na základě dostupných parametrů. Z tohoto porovnání struktura navržená v této práci vyšla jako nejlepší možnost.

Na základě zpracovaného úkolu a zvoleného postupy byla pak vytvořena kritická diskuse, zahrnující potenciální nedostatky návrhu a provedených výpočtů a navržena doporučení pro další vývoj představené struktury.

Bibliography

KOPECKÝ, Matěj. *Design proposal of the 12U CubeSat structure* [online]. Brno, 2022 [cit. 2022-05-19]. Available at: https://www.vutbr.cz/studenti/zav-prace/detail/140098. Master´s thesis. Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering. Supervisor: Milan Junas.

Declaration of authenticity

I declare that I have written my master´s degree thesis on the topic of *"Design proposal of the 12U CubeSat structure"* independently, with usage of information provided by contractor, literature, and other sources, which are all quoted at the end of the thesis, at section *list of bibliography*.

In Brno on May 19, 2022 …………………………...

Matěj Kopecký

Acknowledgement

With this acknowledgement I would like to thank my parents and family for their support during my studies, as I would not be able to get here without them. I would also like to express my gratitude to VZLÚ for the opportunity to collaborate with them on their project.

A special thanks belongs to my supervisor Ing. Milan Junas, for his guidance, patience and highly valuable information, and Ing. Václav Lazar, as a guarantor for Institute of Aerospace Engineering, for his assistance.

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Introduction

Humanity has always looked up into the stars and tried to colonize and explore them. That is why whole space industry gained so much popularity. However, all missions or even devices, deployed into the space, had one thing in common in the past. They were way too expensive and only big institutions (NASA/ESA) could afford them.

This changed when the concept of miniaturized satellites (nano – microsatellites) appeared at the end of 20^{th} century. These satellites were called CubeSats, because of their cube-like shape, and came in various versions and sizes. Because of their shape, dimensions and mass, they have gained immediately high popularity, as they are significantly cheaper and easier to develop, compared to conventional big satellites.

Soon after, CubeSat industry was launched, its majority was quickly transferred into the private sector of space industry. Variety of different companies were being founded, because of the commercial potential of CubeSats. They started with development of wide spectrum of CubeSat components (bearing structural frames, antenna´s systems, solar panels, …), to help potential customers with their mission design.

One of these companies is also **VZLÚ**, which has recently begun development of their own CubeSat structures intended for commercial purposes. Their current development is mainly focused upon smaller CubeSat structures (1U – 3U) intended for commercial purposes.

This thesis is written in collaboration with VZLÚ, as a part of their upcoming development. This project is following their basic design philosophy and applying it to larger CubeSat structures (6U – 12U).

It is this thesis´s ultimate goal to propose 12U CubeSat structural design, based on market research, CubeSat standards, requirements of launch and deployer providers, and requirements requested by the contractor (VZLÚ).

Following design, analysis and check of proposed structure are required to determine behaviour and structural properties of performed design. Based on acquired results, proposed structure will be compared with competition and thesis´s results will be discussed. After the discussion, relevant recommendations for following development will be proposed, if necessary.

1. CubeSat industry

Whether we are talking about research or colonizing other planets space industry is constantly evolving field of interest. That offers many possibilities and motivates people into creating new technologies.

However there always has been one issue, when talking about space, affordability. This issue led to creation of "CubeSat industry". [1]

1.1 CubeSat movement

The CubeSat project started at California Polytechnic State University at San Luis Obispo (Cal Poly) and Stanford university´s Space Systems Development Laboratory (SSDL) during a year 1999. As fathers of this movement are considered Jordi Puig-Suari (Cal Poly) and Bob Twiggs (SSDL). [1]

By this time, Cal Poly came up with basic standards to follow, when designing CubeSat. These standards are affecting dimensions, electronics and even weight of the satellite. [1]

The most basic type of the CubeSat is so called "**1U** (1 unit)", which is roughly cube with dimensions *100x100x113.5 mm* with total mass about *1 – 1.3 kg*. This type is however not that popular nowadays. 2U,3U,6U or higher, are much more popular (Figure 1.1). [1]

Originally developers intended to include universities, high schools and private companies into space industry. That however, escalated into a lot more practical usage of these miniature satellites. [1] [2]

Figure 1.1 – CubeSat units [1]

CubeSats are today commonly used as new technology demonstrators, whether we are talking about monitoring devices or even planetary probes for missions, where conventional satellite would be unnecessarily expensive choice. [1] [2]

Class	Wet Mass (kg)
Minisatellite	100 - 500
Microsatellite	10 - 100
Nanosatellite	1 - 10
Picosatellite	0.1 - 1

Figure 1.2 – Satellites divided in respect to their mass [3]

1.2 Dispenser/CubeSat deployer

Whole affordability, however, comes with variety of disadvantages. One of them is that CubeSat structures are not that strong and stiff. Due to that, these small satellites cannot be deployed in any conventional way. [1] [4] [5]

Therefore, when transported to the orbit, CubeSat requires some kind of protection and deployment system. It also needs to be connected to the rocket, in order to be deployed in convenient time. All of these tasks are performed by **CubeSat dispenser system**, better known as “CubeSat deployer” or “CubeSat deployment system” (Figure 1.3). [1] [4] [5]

Figure 1.3 – CubeSat dispenser [1]

Dispensers represent basic and standard deployment system for CubeSats. They are developed to satisfy CubeSat´s dimension and mass standards. All of them are designed to hold up 1 or more CubeSat units (most common is use of 3U CubeSat dispensers). [1] [4] [5]

The **deployment mechanism** is based on rocket sending signal to dispenser´s door and opening it. CubeSat is then launched, by the force generated by spring (attached to the pusher plate) or any other compressible component, along flat rails inside the dispenser. [1] [4] [5]

There have been some rare cases of CubeSats being deployed without using dispenser. For example, CubeSat Peruvian Chasqui 1 was released by cosmonaut during his spacewalk in International Space Station (ISS). However, that is an exception. [1]

1.3 Launch Vehicles

In order to deploy CubeSats (or any other type of payload as a matter of fact), they need to be transported out of Earth´s atmosphere. As a means of transportation rockets are used in space industry. However, they are more often referred to as **Launch Vehicles** (or **LVs**). [1]

There are a lot of options and variety of launch providers. Each of them has their own specifications regarding transported payload. However, properties required by them are more or less uniform (stiffness, strength, …). [1]

1.3.1 Falcon 9

First one is **Falcon 9** (Figure 1.4), which is a rocket developed and manufactured by company SpaceX. It is one of the new generation rockets, which are partially reusable (most expensive parts are gathered and then repaired). [6] [7]

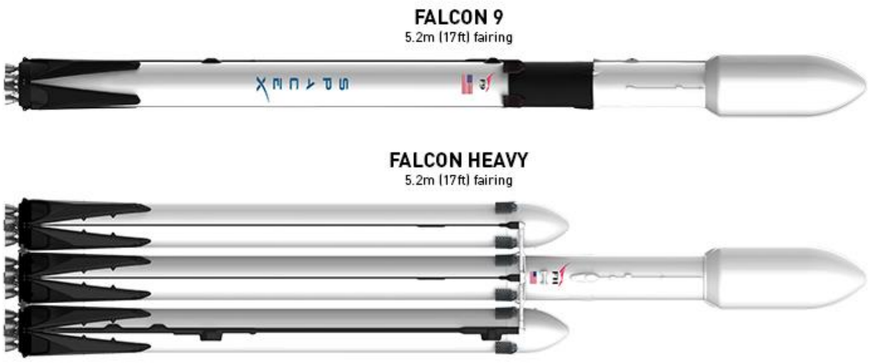


Figure 1.4 – Falcon 9 [6]

From the very start, Falcon 9 program was focused upon transportation of wide variety of payloads, from medium and heavy-weight cargo to small satellites (where CubeSats belong as-well). [6] [7]

Parameters of Falcon 9 LV can be found in Table 1.1. [6] [7]

Table 1.1 – Falcon 9 properties [6] [7]:

Height	Diameter	Total mass	Payload mass	Stages
[m]	*[m]*	*[kg]*	*[kg]*	*[-]*
70	3.7	549 054	8 300 *(1)* 22 800 *(2)*	2
(1) Payload mass that can be transported to GTO *(2) Payload mass that can be transported to LEO*				

1.3.2 Electron

Electron (Figure 1.5) is another representative of partially reusable LV, developed by company Rocket Lab. However, compared to Falcon 9, Electron is designed particularly to transport small satellites (CubeSat payload). [8] [9]

Figure 1.5 – Electron [8]

Electron´s properties are shown in Table 1.2. [8] [9]

Table 1.2 – Electron´s properties [8] [9]:

Height	Diameter	Total mass	Payload mass	Stages
[m]	*[m]*	*[kg]*	*[kg]*	*[-]*
18	1.2	13 000	300	2

1.3.3 Vega

Last LV is **Vega** (Figure 1.6), which is a small rocket used by ESA in Europe´s spaceport (French Guiana). It has first flown in 2012 and later on was used on commercial mission´s payloads. [10]

Figure 1.6 – Vega [10]

Since it is classified as a "small rocket", its utilization is mostly limit upon small payload´s transportation (CubeSats, dispensers, …). [10]

Table 1.3 – Vega´s properties [10]:

Height	Diameter	Mass	Payload mass
[m]	*[m]*	*[kg]*	*[kg]*
30	3	137 000	1500

1.4 Standards and requirements

Every launch provider has its own manual including necessary requirements regarding transported payload. However, these include mostly mass, environmental conditions and only very generally dimensions of transported payload.

In case of CubeSats, general requirements and recommendations are formulated separately. These are provided mostly by mentioned Cal Poly (CubeSat design specification or simply **CDS**) and are related to CubeSat´s size, shape, structural materials, mass properties, electronics and so on.

1.4.1 General requirements

Although CDS prescribes a lot of parameters, that CubeSat has to follow in order to be deployed, it is highly important to consider requirements prescribed by dispenser and launch providers as-well.

So, when designing CubeSat, CDS requirements serve more as a list of recommendations, since final design is highly dependent upon used deployer and LV. The issue regarding combination of all mentioned requirements will be discussed later on, so within this chapter only general requirements regarding design (from CDS document) will be addressed.

General requirements regarding design of the CubeSat are: [11]

- Any hazardous material has to be in accordance with **AFSPCMAN 91-710**.

- Extra protruding mass can be used at CubeSat (so-called **Tuna can**)(Figure 1.7). Dimensions of this additional mass are limited by used dispenser.

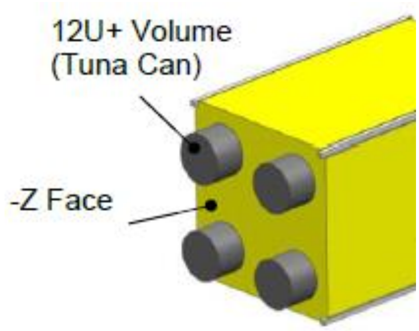


Figure 1.7 – Tuna can [11]

- No components are allowed to protrude further than *6.5mm* from the rail´s surface, which is in contact with deployer. This applies for all rails and both of the contact surfaces (this restriction is dependent upon used deployer and can vary).
- Rails will have surface roughness less than *1.6μm*.
- Rails will have minimum width of *8.5mm*.
- Edges of the rails should be rounded to radius (or tapered) of at least *1mm* (*1mm x 45°*).
- The end of the rails will have minimum of *6.5mm x 6.5mm* surface area.
- Maximum mass will not exceed prescribed values (Table 1.4). CubeSat with total mass higher than standardised limit, shall be discussed with launch or dispenser provider.

Table 1.4 – Standard maximum mass table [11]:

CubeSat configuration	Total mass
["U"]	*[kg]*
1	2
1.5	3
2	4
3	6
6	12
12	24

- Minimum of *75%* rail´s surface will be in contact with the deployer.
- CubeSat´s **Centre of Gravity** (**CoG**) has to be located within ranges prescribed by CubeSat standards (Table 1.5).

Table 1.5 – Position of CG [11]:

CubeSat configuration	x axis	y axis	z axis
["U"]	*[mm]*	*[mm]*	*[mm]*
1	± 20	± 20	± 20
1.5	± 20	± 20	± 30
2	± 20	± 20	± 45
3	± 20	± 20	± 70
6	± 45	± 20	± 70
12	± 45	± 45	± 70

- As a structural material, **Aluminium alloys** shall be used (recommended are Aluminium alloys type 7075, 6061 and 6082).
- Any aluminium surfaces that are in contact with dispenser will be hard anodized.
- If there are more separate CubeSats, sharing the same dispenser, each of them will have its own mechanism to support other CubeSat´s separation.
- To prevent CubeSat to activate any of its powered functions, CubeSat has to be powered off until its deployment.

1.5 Qualification/Acceptance process

After CubeSat is designed in accordance with all necessary standards, it has to go through a procedure called **qualification/acceptance process** (Figure 1.8). [4]

The procedure itself is very simple. First developers need to come up with their own mission (CubeSat design), which can then be analysed by variety of software to verify their work and conclusions before any manufacturing process (of the final product). This is shown at column **hardware** in Figure 1.8. [4]

Verification and manufacture are then followed by **qualification** tests. This type of testing intentionally puts designed structure under higher level of loading than the actual loading during the launch. That is to proof its capability to function even under harder conditions then predicted. [1] [4]

Developers can also perform as many of these tests as they desire, and simplified versions of tested object can be used (recommended for dispenser). [1] [4]

Unfortunately for **protoflight** testing, prototype of developer´s designed structure needs to be used. Conditions during this kind of test is again higher that predicted mission environment, but unlike qualification testing, it is not that harsh. [4]

Final chapter of testing procedure is called **acceptance test**. This test is not performed by CubeSat/dispenser developer. It is done by “mission provider”, who is responsible for integration of the structure and the **flight** itself. [1] [4]

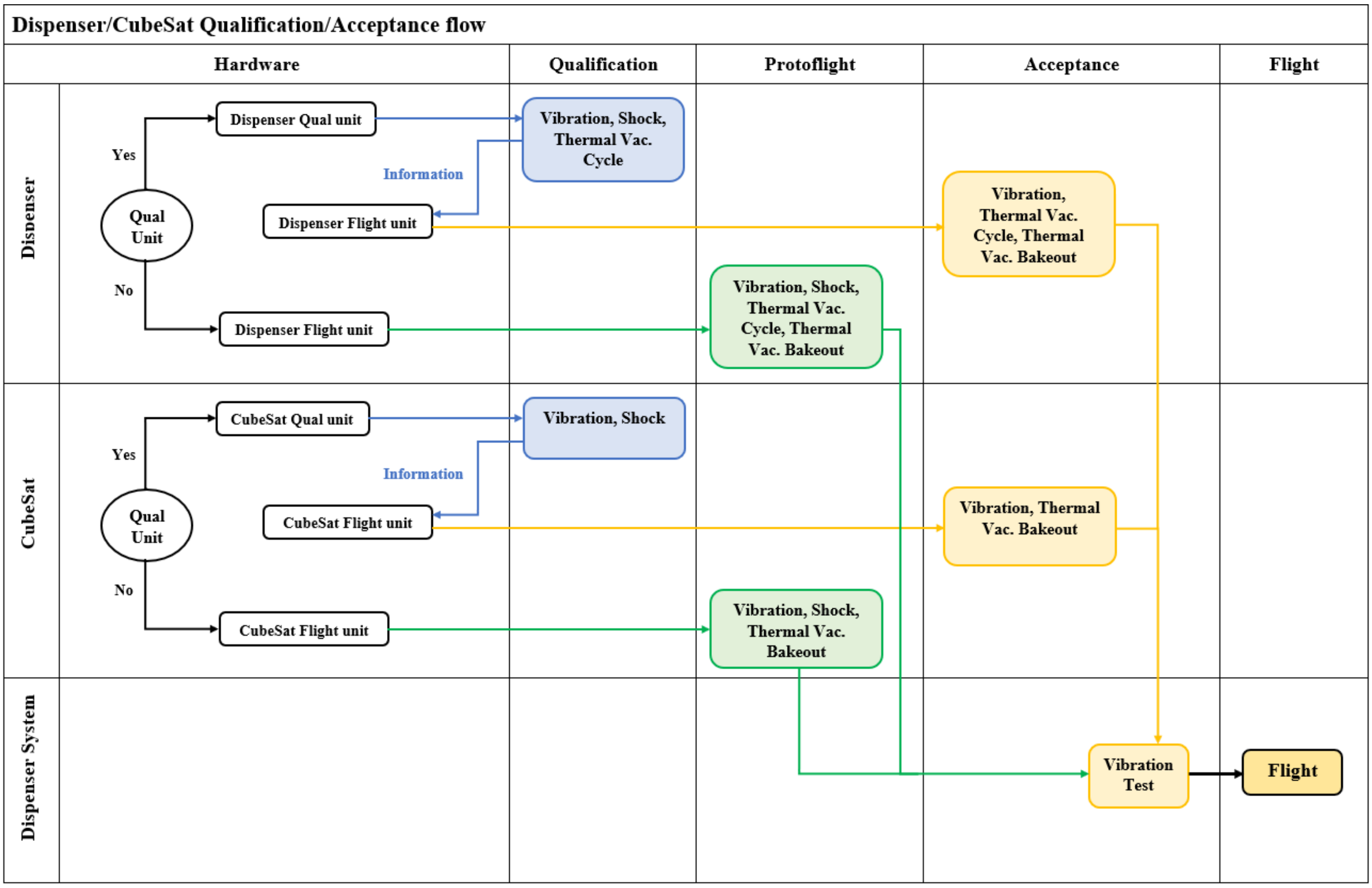


Figure 1.8 – Qualification/Acceptance process [4]

2. 12U CubeSat structures

Since the goal of this thesis is to design structure of 12U CubeSat for commercial purposes, it is of course necessary to perform market research of options provided by competition (regarding 12U CubeSat structures as well as deployers available for them).

Creating this sort of information platform and analysing market demands (structural features) will set initial data for following design.

2.1 Increasing importance of 12U CubeSats

Ever since whole CubeSat movement started it has gone through a lot of development. From the initial specified missions to more commercial sphere.

Whole point of companies developing accessory, deployers or, as more recently, structural frames for CubeSats is to provide customers with as much help as possible.

Following above mentioned development, the popularity of larger CubeSats has been increasing lately. Which is quite natural, since they can fulfil more tasks at once, compared to smaller units.

2.2 12U CubeSat structure analysis

It is exactly because of their size, that structural composition of larger CubeSats is a bit different from smaller units (1U, 2U and 3U). It is mostly to ensure structural stiffness and comfortable accessibility.

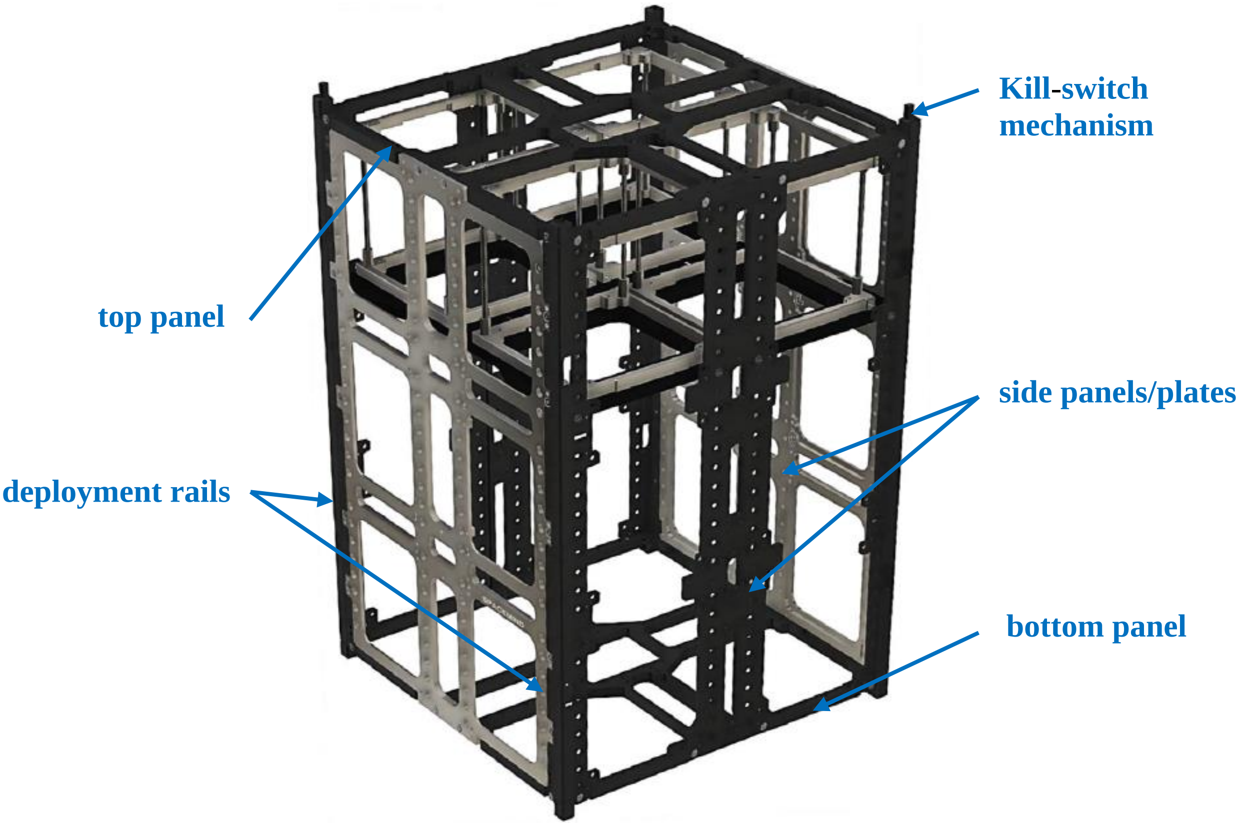


Figure 2.1 – Typical 12U CubeSat structural frame [12]

Parts that are identical to smaller satellites are **deployment rails** (Figure 2.1). This component is designed to perform 2 simple tasks. Firstly, it has to secure CubeSat´s safe deployment out of the deployer and second, it provides attachment support for payload´s integration.

Another feature that is common for smaller and bigger CubeSats is **kill-switch mechanism**. This sub-assembly is often realized by utilization of multiple small components (pin housing, pin and a spring)(Figure 2.2) and is used in pair of two, at opposite sides (corners), per one CubeSat.

Whole mechanism is design to simply press down the kill-switch itself, into position where it powers down all systems inside the satellite, so that they are not affected by possible electrical (or magnetic) spikes during launch. [13]

CubeSat is then integrated into the dispenser so that both kill-switch mechanisms are pressed against the pusher plate, which ensures full compression of mechanism and kill-switch at the same time.

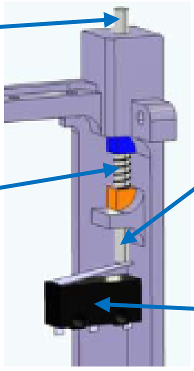


Figure 2.2 – Kill-switch mechanism [13]

Next up are components which are not used for design of smaller CubeSats, because they are simply not needed.

First are **side panels/plates** (Figure 2.1), which are designed to provide stiffness, attachment support for payload´s integration and support for integration of solar panels or any other additional components.

And lastly, **top** and **bottom panels** (Figure 2.1), which are designed as the same component. These have similar function to side panels, since their main purpose is stiffening whole structure and attachment of antennas or solar panels (possibly they can serve as additional support for payload´s integration.

2.2.1 PCB stacks (PC/104)

Even though structural components of CubeSat structures are not particularly limited by standards (besides external CubeSat dimensions) and lunch provider requirements, they need to form a space, to implement payload.

Since most of the time payload comes in a form of on-board electronics, this space is reserved for them. These electronics have to be of course modified, as they are meant to work in space environment (**PCB board**/**PC/104**). When combined with structural elements, they form so-called **PCB stacks**. [12]

Most recent trend is to design PCB stacks as a completely separate units, so that their integrity is independent upon structural frame. These units consist of **inner structural rings**, **stack rods**, **PCB boards** (Figure 2.3 and Figure 2.4) and some sort of **attachment element** for stack rod´s integration into inner rings. [12] [15]

Attachment element can be designed in form of capsule with internal thread or simply by matrixes.

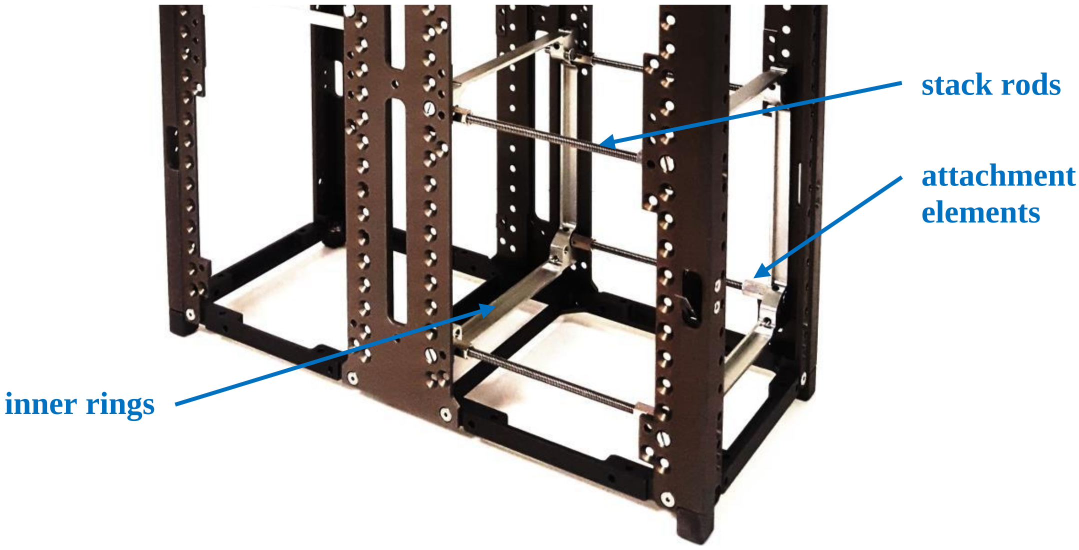


Figure 2.3 – PCB stack integrated inside of the CubeSat structure [12]

This separate PCB unit is then easy to manipulate with (access, adjustments, …) and can be easily integrated into the CubeSat structural frame. Thanks to that, payload (PCB board)(Figure 2.4) used for PCB stacks is protected from contact with structural frames components and can be set in desirable direction. [15]

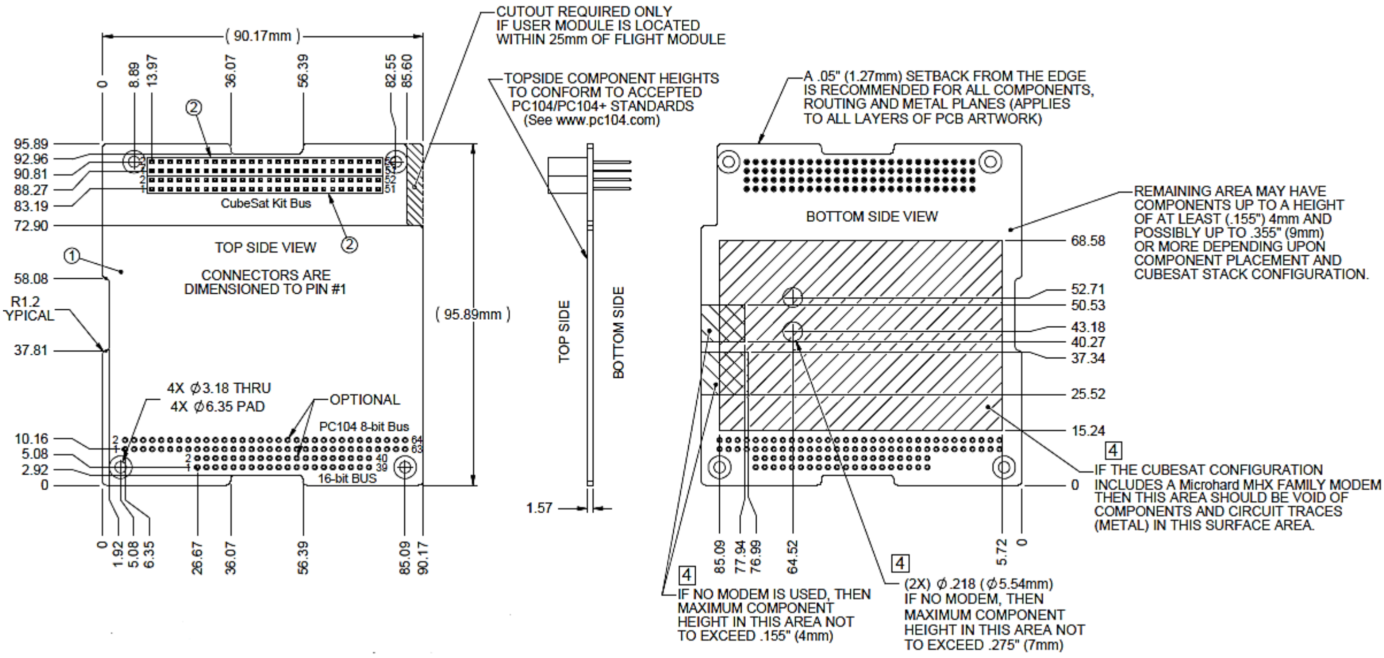


Figure 2.4 – PC/104 standard [14]

2.3 Particular 12U Structures

Even though CubeSat industry is becoming more and more accessible, versatile and shifting itself into more commercial sphere, when it comes to bigger CubeSat units, it is quite different.

Most of the 12U CubeSat structure´s developers are providing structures only after a customer applies a specific request with requirements regarding his own mission. Developers than design a structure based on these requirements. That is of course theoretically the best approach, however in reality it carries a lot of disadvantages.

The structure itself is made particularly for customer, so it is naturally a lot more expensive, and it takes more time to design it, since each structure is developed separately.

There are only a couple of companies that provide customer with pre-prepared structures, with set parameters. These structures are already capable to include basic payloads in CubeSat industry (PCB stacks, telescopes, …), however they can also be easily modified based on customer´s requirements. Thanks to that, only one structure has to be developed, which saves money, time and since it has to be officially certified, it assures quality of the product.

2.3.1 ISISPACE structure

The first mentioned structure definitely (Figure 2.5) should be 12U CubeSat structure developed by Dutch company Innovative Solutions In Space (**ISISPACE**). When it comes to CubeSat structures ISISPACE is the leading developer in the industry.

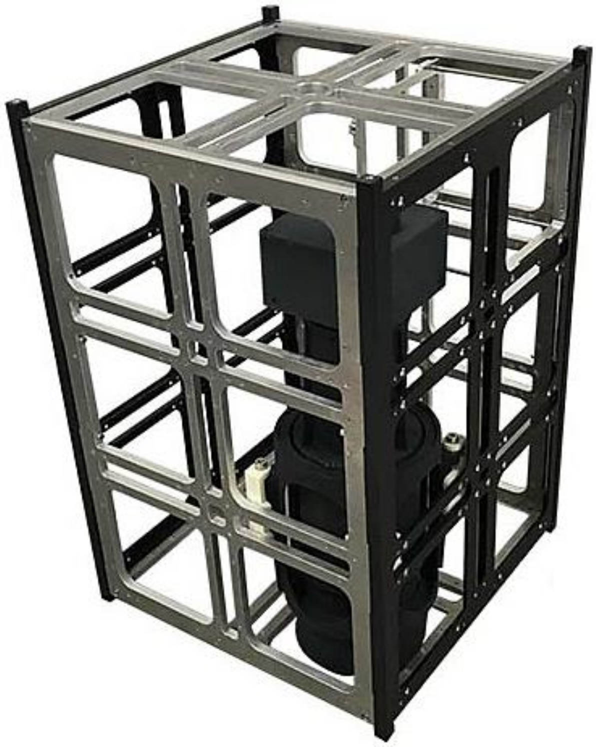


Figure 2.5 – ISISPACE 12U structural frame [16]

This structure is compatible with different PCB stacks, offers high level of modularity and accessibility in a form of different orientations of PCB stacks. Stack can be either integrated **vertically** (default option) or **horizontally** in all axis (this option is only featured for modified 1U PCB stacks). Stacks can also be modified into smaller 0.5U dimensions. [16]

Table 2.1 – ISISPACE 12U structural frame parameters [16] [17]:

Primary mass (1)	Total mass (secondary mass included) (2)	External dimensions	Price
[g]	*[g]*	*[mm]*	*[EUR]*
1500	2000	226.3x226x3x340.5	12,000

(1) Primary mass consists of Side Frames, Ribs and 2 kill-switch mechanisms
(2) Secondary mass includes the Stack Rods (Side Shear Panels not included)

External frame then consists of 3 pairs of plates (deployment rails plate, side plate and top panel). Thanks to that, structure is visibly provided with high stiffness, and it is easy to manufacture and assemble. [16]

In its basic constellation, it provides internal dimension envelope for 4 independent 3U payload units (not only PCB stacks). [16]

2.3.2 SM12 structure

Next up is **SM12** (Figure 2.6), which is a 12U CubeSat structure, designed by aerospace division **Spacemind** of the company N.PC. New Production Concept S.r.l.

Their solution of 12U bearing frame brings a lot of structural options for the payload´s integration and sizing. [18]

Whole frame is completely compatible with standard PCB stacks and their orientations. It is possible to mount PCB stacks either **vertically** (default) or **horizontally** (without the need of using modified PCB stacks) in all axis. There is also an option of modifying stacks length (other than 1U). [18]

Figure 2.6 - SM112 structural frame [12]

Unlike ISISPACE´s structure, SM12 is utilizing more standard structural components. Structure is assembled of deployment rails, side panels, side plates and top panels. Because of this approach, structure is lighter than previous option. [18]

Table 2.2 – SM12 structural frame parameters [12][18]:

Primary mass (1)	Total mass (secondary mass included)	External dimensions	Price
[g]	*[g]*	*[mm]*	*[EUR]*
1430	1750	226.3x226x3x340x5	9,980
(1) PCB mounting elements are not included in primary mass			

Despite its significant advantages when it comes to total mass and price, from the Figure 2.6, it is clear that the structure is **a lot more complicated** than previous option.

The frame itself is composed from more different components, which makes it more challenging to manufacture and assemble. And due to that, structure´s stiffness is reduced as-well.

2.4 Optional deployers

Another important part of market research are dispenser (CubeSat deployer) options, since it is the choice of particular deployer that limits additional mass of CubeSat.

As right now, there are many options at the market and most of them are utilizing pretty much the same features. However, only a handful of deployer providers are offering highly modular and adjustable options for 12U CubeSats.

Another factor that comes into play is location of CubeSat developers and therefore their launch providers.

Since this thesis is created in cooperation with European company (**VZLÚ**), and European "home" space industry is highly supported within ESA´s jurisdiction, only deployers developed by European companies will be mentioned.

2.4.1 QuadPack

First deployer at created list is **QuadPack**. QuadPack is a 12U CubeSat deployer developed by Dutch company ISISPACE (Figure 2.7). It has rich flight heritage since 2014 on multiple LVs. [19]

It utilizes standard dispenser features, such as deployment rails, enclosed internal environment for CubeSat and compressed spring with wire-based door release mechanism. [19]

Figure 2.7 – QuadPack deployer [19]

This deployer is also adjustable to multiple CubeSat standard sizes. Standard internal dimension envelope for this deployer is 12U sized space (other combinations, giving 12U envelope at total, are possible)(Figure 2.8). However, it is possible to modify it to "12UXL (226.3x226.3x366mm)" and 16U (226.3x226.3x454mm) envelopes (again other combinations are possible)(Figure 2.9). [19]

It offers an extra space for CubeSat´s additional mass in transversal (solar panels, …) as well as in lateral direction (tuna can). In case of 12U/12UXL/16U CubeSat, it provides additional space for 5th tuna can. [19]

QuadPack´s properties are visualized in following Table 2.3.

Table 2.3 – QuadPack´s parameters [19]:

Mass	**Deployment velocity**	**Maximum payload mass**	**Additional CubeSat mass** *(1)*
[kg]	*[m/s]*	*[kg]*	*[-]*
6 - 7.5 (7.5 - 9) *(2)*	0.8 - 1.8	24	YES
(1) Additional mass in longitudinal (so-called "tuna can") and in transversal direction to increase hardware volume or to provide additional space for photovoltaic panels *(2) Data for QuadPack modified for 16U payload envelope*			

Figure 2.8 – QuadPack 12U payload envelope [19]

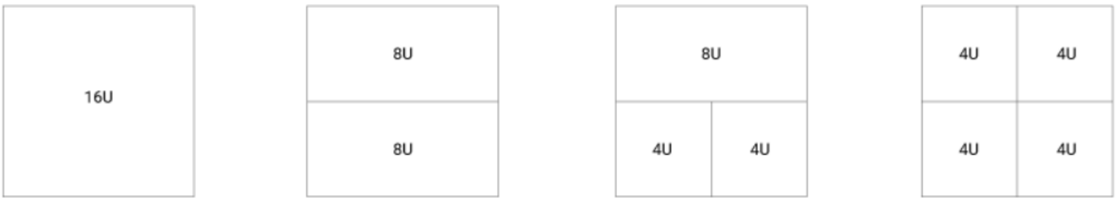


Figure 2.9 – QuadPack 16U payload envelope [19]

2.4.2 EXOPOD

Next up is EXOPOD (Figure 2.10), which is one of the most advanced CubeSat deployers, developed by company EXOLUNCH. It is compatible with multiple LVs. [20] [21]

Figure 2.10 – EXOPOD deployer [20]

EXOPOD is using the same deployer features as previously mentioned QuadPack does (deployment rails, enclosed internal environment and combination of compressed spring and door release mechanism). [20] [21]

As for the payload (CubeSat) envelopes, it is possible to adjust deployer either to 12U payload envelope (Figure 2.11) or 16U payload envelope (Figure 2.12). [20]

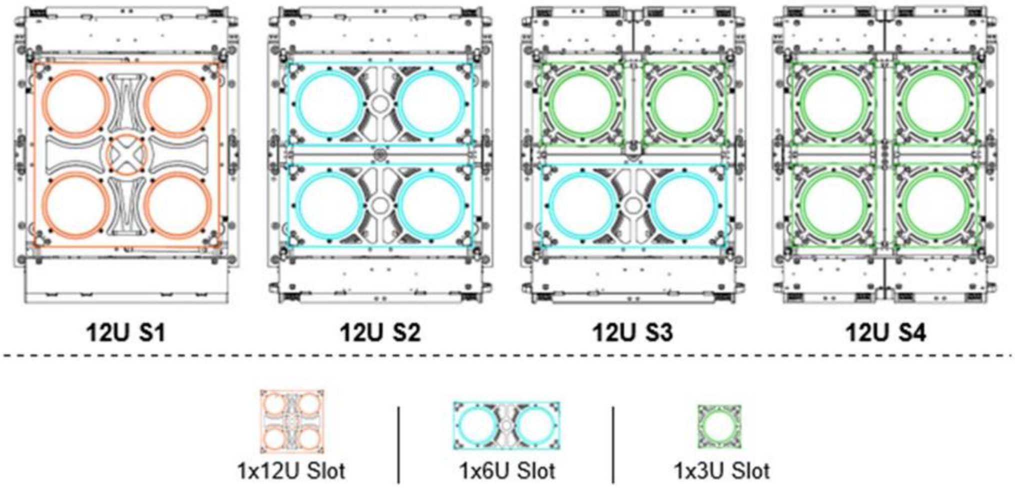


Figure 2.11 – EXOPOD 12U payload envelope [20]

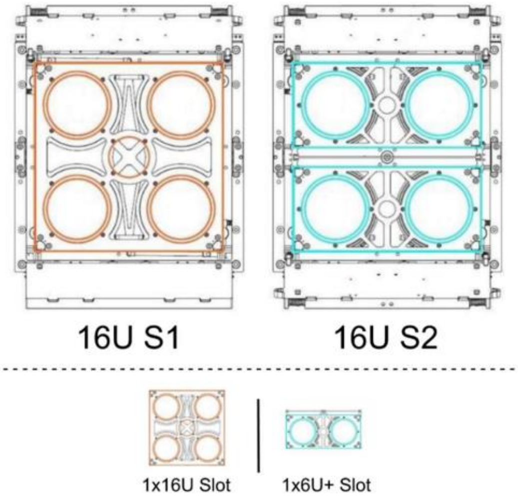


Figure 2.12 – EXOPOD 16U payload envelope [20]

All variants of EXOPOD provide customers with an option to utilize additional mass in transversal and lateral dimensions. In case of 12U/16U CubeSats it is possible to use 5th tuna can. [20]

EXOPOD´s properties are mentioned in following Table 2.4.

Table 2.4 – EXOPOD´s properties [20]:

Deployment velocity	Maximum payload mass	Additional CubeSat mass (1)
[m/s]	*[kg]*	*[-]*
1.16 - 1.64	22 (24) *(2)*	YES
(1) Additional mass in longitudinal (so-called "tuna can") and in transversal direction to increase hardware volume or to provide additional space for photovoltaic panels *(2) Data for modified version of 16U EXOPOD*		

2.4.3 ASTROFEIN PSL12U

Last deployer is **ASTROFEIN PSL12U** (picosatellite launcher for 12U CubeSats)(Figure 2.13), which is a dispenser system developed by germen company ASTROFEIN.

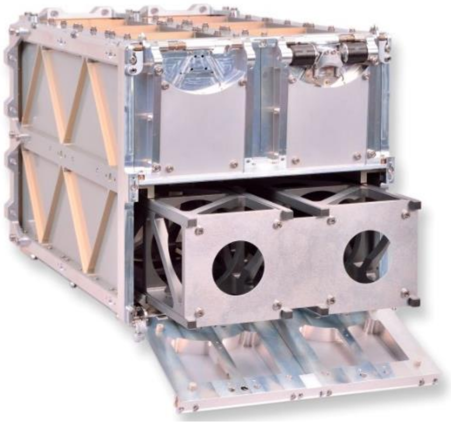


Figure 2.13 – PSL12U [22]

PSL12U provides enclosed environment for variety of CubeSat sizes, from 1U up to 12U (12UXL). It is incorporating non-explosive lock and door release mechanism, which are both resettable and reusable. [22]

Just like both of the previous options, PSL12U offers a usage of additional mass in transversal and lateral direction, as well as optional 5th tuna can. [22] [23]

Its parameters are shown at the Table 2.5.

Table 2.5 – PSL12U´s properties [22] [23]:

Maximum payload mass	Additional CubeSat mass (1)
[kg]	*[-]*
24	YES
(1) Additional mass in longitudinal (so-called "tuna can") and in transversal direction to increase hardware volume or to provide additional space for photovoltaic panels	

2.5 Summary

Since all CubeSat structures and all relevant deployers were mentioned, it's only fair to compare market options (Table 2.6). This comparison provides an intel regarding assumptions and limitations for further design.

Table 2.6 – 12U CubeSat structures options [16] [18]:

Structure	ISISPACE	SM12
Primary mass *[g]*	1500	1430
Total mass *[g]*	2000	1750
External dimensions *[mm]*	226.3x226x3x340.5 226.3x226x3x366	226.3x226x3x340.5
Thermal range *[°]*	(-40) - (+80)	N/A
Price *[EUR]*	12,000	9,980
QT	YES	YES
Kill-switch mechanism	YES	YES
PCB stack orientation – Vertical (default)	YES	YES
PCB stack orientation – Horizontal	YES [(1)]	YES
Deployer options	QuadPack; EXOPOD; PSL12U	QuadPack; EXOPOD; PSL12U
Simplicity	High	Low

(1) only for modified PCB stacks only

From mentioned Table 2.6 its quite clear, that both structures offer **optional integration of PCB stacks** in vertical and horizontal directions, which will definitely be considered as one of the criterions during design.

Another evident property to consider is **total mass**. Table 2.6 sets a range of total mass from *1750g* to *2000g*. These values will be set as boundaries for target range of maximum total mass for designed structure.

And lastly, the **price** and **simplicity** (manufacturing and assembling) of whole structure. Price range is set from *9,980 euros* to *12,000 euros*, while the target simplicity of whole structure will be kept to the maximum.

3. Design assumptions

First step to approach structural design, was creation of a list of assumptions and questions, which would provide initial data for following design. This list includes basic design engineering tasks, such as essential requirements based on purpose of the structure, shape and restricted dimensions (by standards or particular parts), materials of the structure, surface treatment and so on.

Since CubeSats are limited by variety of factors, most of previously mentioned assumptions are not optional and have to comply with CubeSat standards. Thus the design is narrowed mainly on internal design of the structure.

3.1 Primary requirements

When talking about essential or **primary requirements** of the structure, CubeSats are quite simple frames filled with payload. Because of that, there are only couple of primary requirements regarding their purpose.

First is **modularity**, which is a feature typical for CubeSat industry. Modularity itself means, that the parts used at 1 type of structure (for example 6U CubeSat) can be utilized at other type of structure (such as 12U CubeSat) and can be easily modified, if needed. This ability is iconic for smaller CubeSat units with the same cross-sectional area (1U, 2U and 3U). However in the case of bigger structures (6U and 12U), the absolute modularity is not expected.

Second feature is common for all of the technology in space industry. And that is a **total mass**. The ultimate goal of space engineers is to make the structure as light as possible, while the function and payload storage space are preserved. This make sense, since CubeSats are restricted by standards to comply with prescribed maximum mass. So the lighter the structure is, the more payload can be carried and less of the structural material has to be used. That results in lower production price and higher profits.

However, even total mass has to be kept within reasonable intervals. That is due to the fact, that mass is also related to structural **stiffness**. Stiffness is another requirement of high important throughout space engineering, as it has a direct influence upon structure´s behaviour under loading. So, higher stiffness means higher protection of integrated payload.

Last of primary requirements is **accessibility**. This means that developers of CubeSat structures have to assure their payload is as accessible as possible and can be safely worked with, even after some parts of the structural frame are removed.

3.2 External dimension envelope

As for dimensions, they are another highly important feature of CubeSat structures, because they are defining special layout and shape of the structure.

In this case however, most of the basic dimensions are prescribed by standards (or deployer providers) either specifically or by particular range of numbers. That is iconic for maximum external dimensions and some of the design nodes (Figure 3.1). [11]

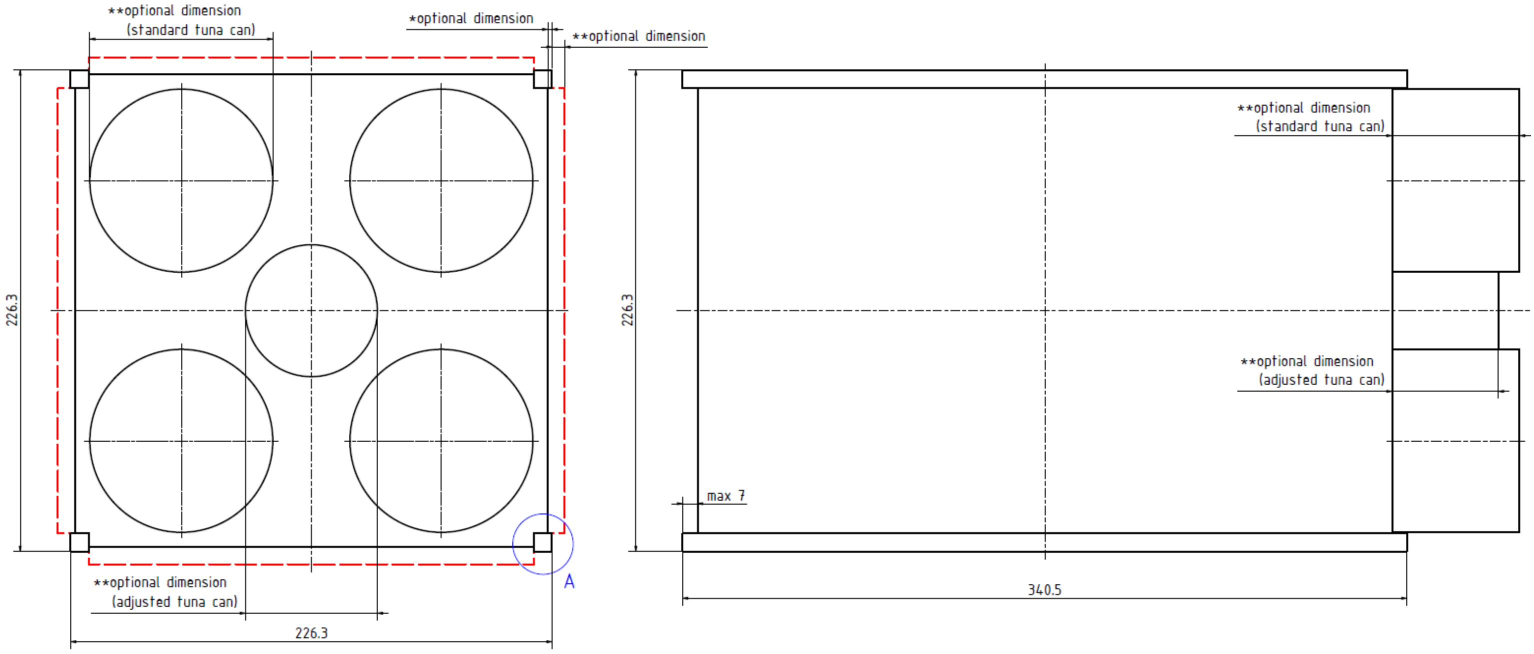


Figure 3.1 – Maximum external dimensions of 12U CubeSat unit [11]

The “**rail to rail dimension**” is constant along the cross-sectional area and is equal to *226.3x226.3mm* of nominal dimensions. **Longitudinal dimension**, which is equal to the total length of the rail, is *340.5mm* (this value is set as a default length by dimension envelope of optional deployers, but it can be changed up to *366mm*). [11]

Another important dimension is the **maximum protrusion of the rail**. This length is measured from frontal area of the rail to the face of top panel and is equal to maximum of *7mm*. [11]

At Figure 3.2, can be seen the detail A from previous picture, which displays frontal area of the CubeSat rail (*6.5x6.5mm*). [11]

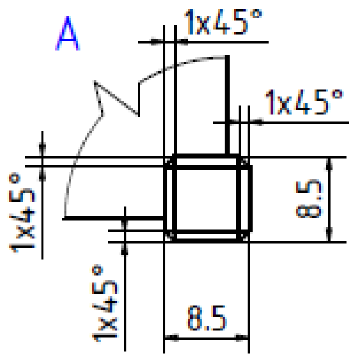


Figure 3.2 – Detailed view of frontal area of the CubeSat rail [11]

Last of the important dimensions are “**optional dimensions**” in transversal and longitudinal axis of the CubeSat. These are marked at the Figure 3.1 as “*/** optional dimension”. They are not specified by standards, however, are dependent upon particular deployer.

Most of the deployer developers are offering the possibility to add extra mass in transversal and longitudinal direction, therefore the “****optional dimension**” is prescribed strictly by used deployer (examples are shown at Table 3.1).

Table 3.1 – Additional space provided by deployer [16] [20] [22]:

Deployer	QuadPack	EXOPOD	PSL12U
Additional space *(1)* **[mm]**	10	11.2	N/A
Tuna can diameter[mm]	80 45 *(2)*	78 62 *(2)*	N/A 62 *(2)*
Tuna can protrusion [mm]	40 38 *(2)*	86 67 *(2)*	N/A 67*(2)*

(1) Additional space in transversal directions of CubeSat/dispenser
(2) Dimensions are valid for 5th (adjusted) tuna can which is located in the middle of 12U/16U CubeSat structures

The ”***optional dimension**” is more standard feature and is prescribed by CubeSat developers. This particular dimension serves as sort of insurance, so the only components that are in contact with deployer, are CubeSat´s rails.

3.3 Internal dimension envelope

Internal dimensions are directly dependent upon external dimension envelope, due restricted internal space, which is caused by maximum external dimensions and thickness of used components.

These internal envelopes are not restricted by any standard, which means that CubeSat developers can modify them as they seem fit.

In this case, the internal space was divided into 4 separate “**3U payload units**”, which are represented by **PCB stacks**, as they are basic representation of CubeSat´s payload.

With this being said, maximum dimensions of PCB stacks were proposed. That was achieved by combination of 2 previously mentioned parameters. These included an optional integration of PCB stacks in different directions (see chapter *2.5 Summary*) and prevention of contact between PCB boards and structural frame (see chapter *2.2.1 PCB stacks (PC/104)*).

The important note to be mentioned here, is the fact that PCB stacks are not only payload units that can be utilized. Since there is room for 4 3U payload units within the structural frame, wide variety of other payloads can be used (telescopes, capsules with cargo, …). However, further design will be modified for integration of PCB stacks as its default option.

3.4 Structural materials

Another important design feature is of course the choice of structural material. Structural material sets structure´s basic properties (stiffness, strength, …) and has direct influence upon its behaviour.

Generally speaking, in space industry one of the biggest obstacles and requirements is to guarantee lowest total mass possible, while preserving function, stiffness and other useful properties. Therefore, the price of most materials, technologies and structural features is significantly increased and even requirements for manufacturing processes are way more challenging.

So, used materials have to have most beneficial combination of price, mass and strength.

All of these requirements are met by usage of Aluminium alloys, that are light, strong, though and have naturally high resistance against corrosion. [24] [25]

The official CubeSat standards are referring to an **aluminium alloy type 7075** as a core structural material. Other options are of course available, users can even use their own materials, but all of them have to have similar properties as a type 7075 aluminium. [25] [26]

This type of aluminium alloy is usually treated to achieve even more favourable characteristics. [25] [26]

The most common treatment is a heat-treatment called **tempering** (Figure 3.3, which is strictly illustrational), during which is alloy heated up bellow melting point and then cooled (most of the time in air). Following that, alloy is **artificially aged**. Artificial ageing is decomposition of the supersaturated solid solution at increased temperature, so that the whole process is faster. Basically, this process creates homogeneous material structure. [26] [27] [28]

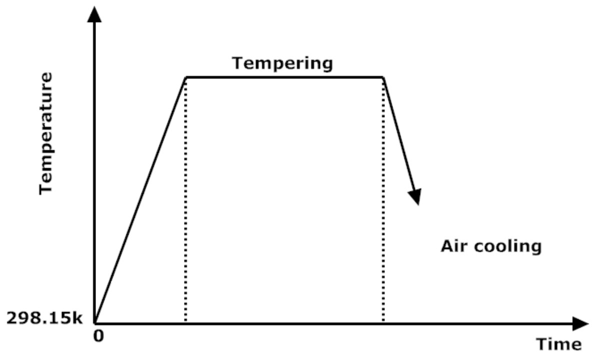


Figure 3.3 – Illustration of tempering process [27]

These processes increase material´s properties (toughness) and stress-corrosion resistance. The alloy after treating, is called an **aluminium alloy 7075-T73**. [26] [27]

The second option is **aluminium alloy type 6061**. In general, it does have quite similar properties to previous option, however it is lighter, and its strength, toughness and hardness are visibly lower (Table 3.2). [29]

As for the heat-treatment, the same procedure is used. Tempering and artificial ageing enhances alloy´s characteristics and its designation is changed to **aluminium alloy 6061-T6**. [29]

Last option is **aluminium alloy type 6082-T651**, which is just another option of class 6000 aluminium alloys. This alloy is tempered, **stress relieved** (elimination of internal forces by stretching material) and lastly artificially aged. [30]

It has rich flight heritage in CubeSat Industry, higher mechanical properties and lower thermal conductivity than aluminium alloy 6061-T651. [30]

Table 3.2 – Materials used in "CubeSat industry" [26] [29] [30]:

Material properties (composition)	units	Aluminium alloy 6061-T6	Aluminium alloy 7075-T73	Aluminium alloy 6082-T651
Chemical composition	[-]	Al - 95.9-98.6 % Mg - 0.8-1.2 % Si - 0.4-0.8 % Fe - 0-0-7 % Cu - 0.15-0.4 %	Al - 86.9-91.4 % Zn - 5.1-6.1 % Mg - 2.1-2-9 % Cu - 1.2-2.0 % Fe - 0-0.5 %	Al - 95.2-98.3% Si - 0.7-1.3% Mg - 0.6-1.2% Mn - 0.4-1.0% Fe - 0-0.5%
Density	[g/cm^3]	2.70	3.00	2.70
Ultimate Tensile strength	[MPa]	310.00	500.00	320.00
Tensile Yield strength	[MPa]	270.00	410.00	270.00
Modulus of Elasticity	[GPa]	69.00	70.00	69.00
Shear Modulus	[GPa]	26.00	26.00	26.00
Shear strength	[MPa]	210.00	290.00	190.00
Fatigue strength	[MPa]	96.00	160.00	94.00
Elongation at break	[%]	10	7.1	6.30
Hardness (Brinell)	[-]	93.00	140.00	91.00
Melting point	[°C]	580 - 650	480 - 640	580 - 650
Thermal conductivity	[W/mK]	170.00	130.00	160.00
Specific heat capacity	[J/kgK]	900	870	900.00

After comparison of presented materials (Table 3.2), **aluminium alloy 6082-T651 was chosen** as a structural material for further design, due to its favourable combination of low density and high strength.

3.4.1 Surface treatment

Even though materials have already been heat-treated and quality of their surface is high at this point, they are not ready for harsh space environment. There are numerous harmful factors that could potentially damage or degrade material´s surface and jeopardise the mission. To avoid that, operations called **surface treatment** are used. [31] [32]

As a fundamental surface treatment **anodizing** is applied, which is an electrolytic procedure, during which the layer of oxide is created (for aluminium alloys it is aluminium oxide). [31] [32] [33]

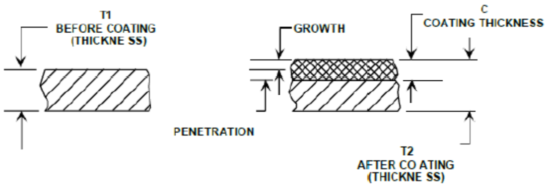
Aluminium oxide then protects treated surfaces against corrosion, cold welding and wear (due to vibrations), which highly increases mission´s safety. [31] [32] [33]

Since all systems and accessories need to work at space environment, layer of the aluminium oxide must be thicker compared to conventional anodizing. This is achieved by **hard anodizing**, specifically **type III hard anodizing**. [31] [32] [33]

After anodizing, there is used so called "secondary surface treatment". For CubeSats, most common is **PTFE coating** (Polytetrafluoroethylene, better known as "Teflon"). This operation is used for smoothening surfaces (roughness control), friction and wear control. [31] [32] [33]

While both operations are used, they are creating protective layer. Layer´s thickness (both anodizing and PTFE coating) should be mentioned on drawing documentation, but if it is not said otherwise, **default thickness** will be used. Its thickness is *0.051 +/- 0.013 mm*, according to NASA/ESA standards. However, if developers find this dimension unsuitable any thickness ranging from *0.025 to 0.076 mm* can be used with *+/- 0.013 mm* tolerances. In that case the exact dimension of the layer needs to be specified. [33]

The creation of the protective layer leads up to *50%* penetration and *50%* growth of the surface (Figure 3.4). [33]



$$T2 = T1 + \frac{C}{2}$$

Figure 3.4 – Final thickness [33]

3.5 Solution approach

With explanation of surface treatment, list of design assumptions is complete. Which means that all of the initial data for following structural design are set.

The only thing that has not been mentioned yet, is the "**game plan**", or **solution approach** to the submitted task.

This issue is addressed at Figure 3.5, where can be seen used approach to structural design and its following FEM analysis and check.

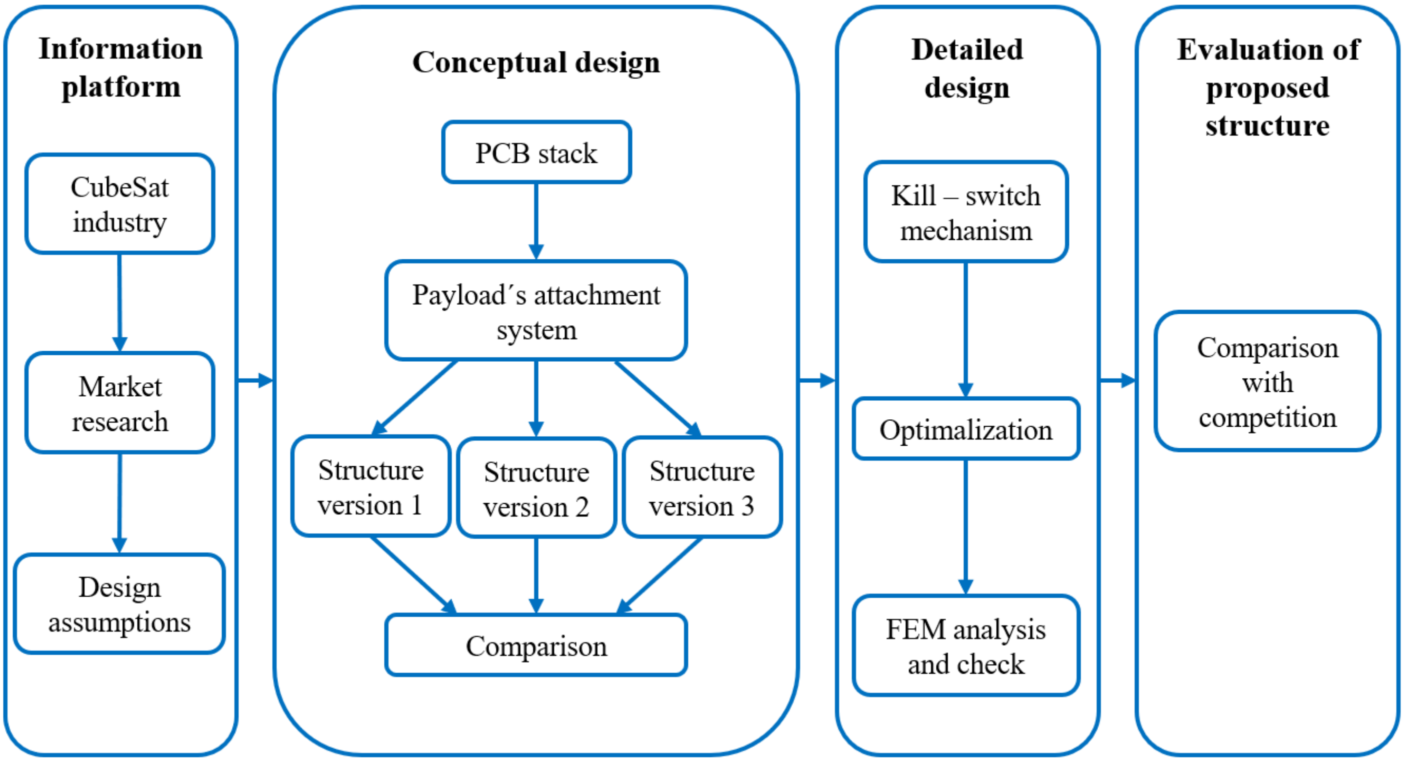


Figure 3.5 – Solution approach

4. Conceptual design proposal of the 12U CubeSat structure

At chapter *2.3 Particular 12U Structures*, was shown that there are different approaches when it comes to design of 12U CubeSat structures. These concepts obtained by previous competition research provided an inside look on how 12U CubeSat structures are being designed.

After completion of information platform (CubeSat industry, market research and design assumptions), initial design proposals were created.

4.1 Initial design proposals

As for this thesis, PCB stack was designed first to created payload´s "**attachment system**", which would later directly affect design of particular components. This led to definition of components of external structural frame, since maximum dimensions were known as-well.

Regarding structural frame itself, 3 versions were created to compare different approaches to design and their properties (stiffness, mass, payload adjustments, …).

4.1.1 PCB stack

PCB stack unit (Figure 4.1) was designed as a cube. Thanks to that it is possible to integrate it in whatever way is more desirable, without worrying about its attachment to the structural frame or its assembling.

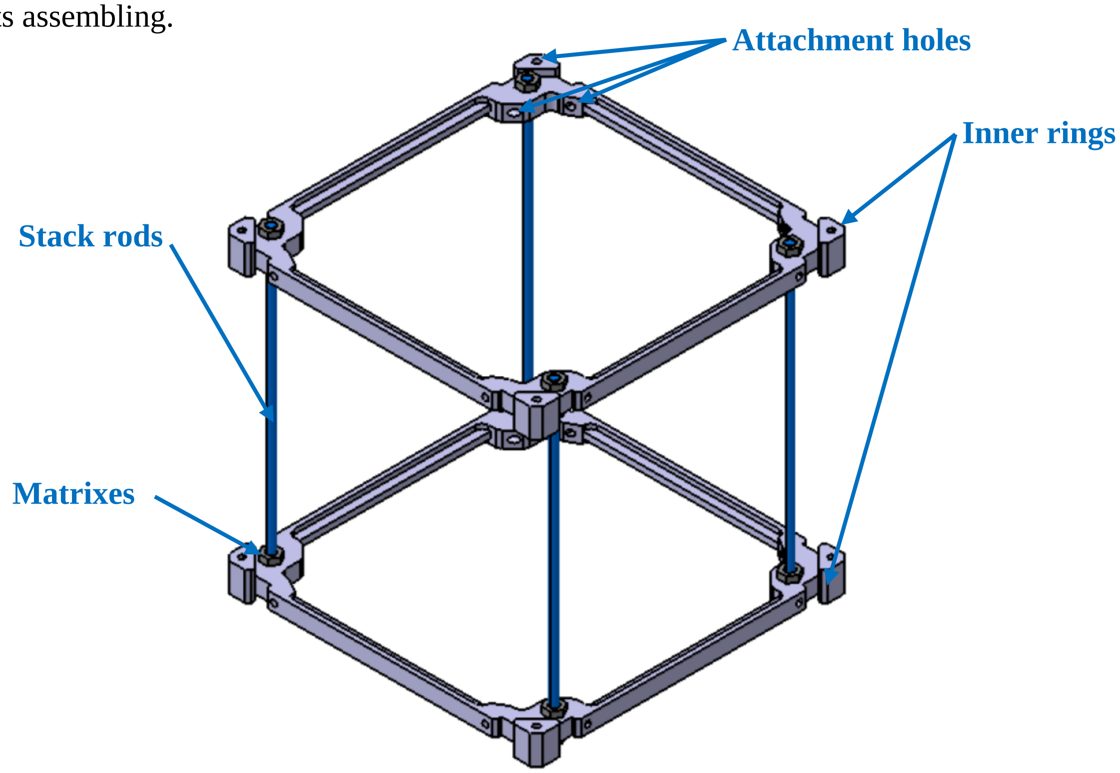


Figure 4.1 – PCB stack design proposal

Creation of the Cube shaped PCB stack also provides other advantages. That is a possibility to integrate stacks in all directions and axis (**horizontal and vertical integration**), which can be seen at Figure 4.2), without affecting Structural stiffness and strength.

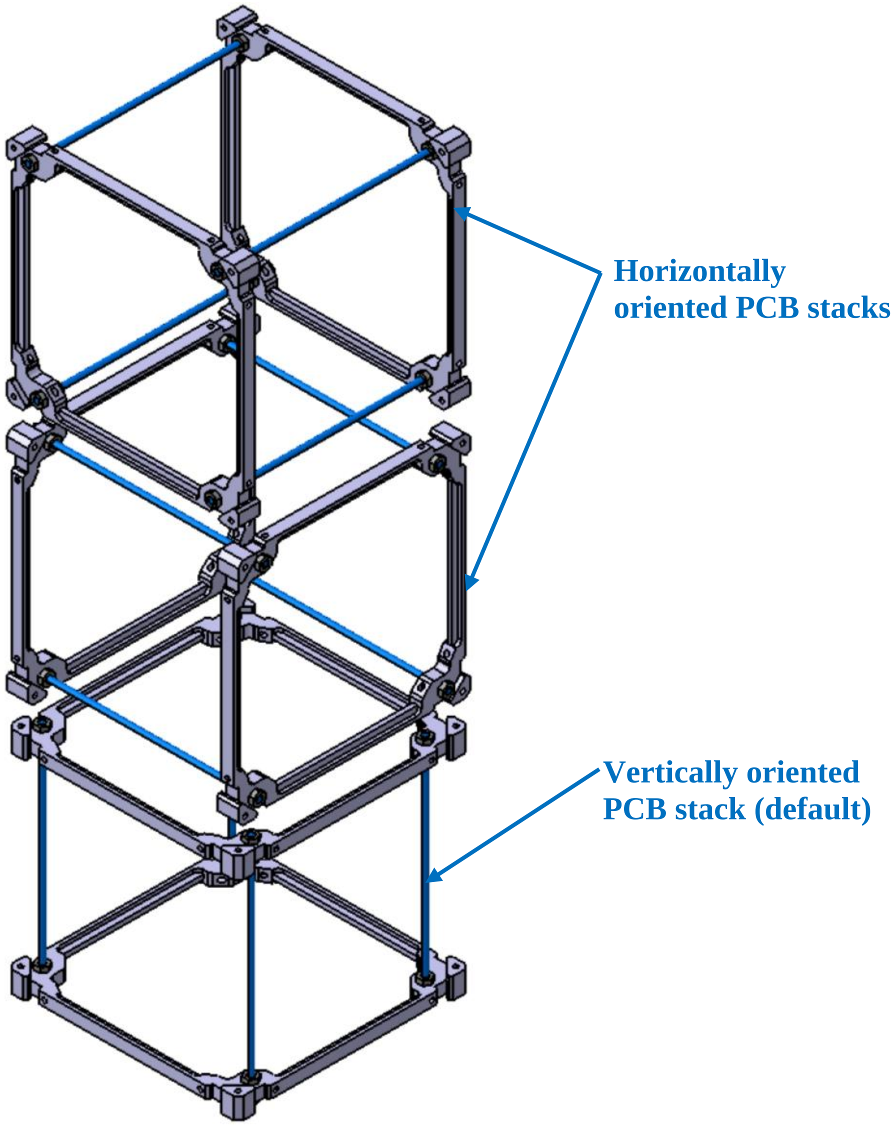


Figure 4.2 – Different integration directions of PCB stacks

Another feature that designed PCB stacks are utilizing is **change of stack´s length in vertical direction** (structural frame is also adjusted to this option). This allows customer to modify stack into whichever length is required. That applies for **shortening** PCB stack (smaller than 1U)(Figure 4.3) as well as **prolonging** PCB stack, by usage of longer stack rods (up to 3U)(Figure 4.4).

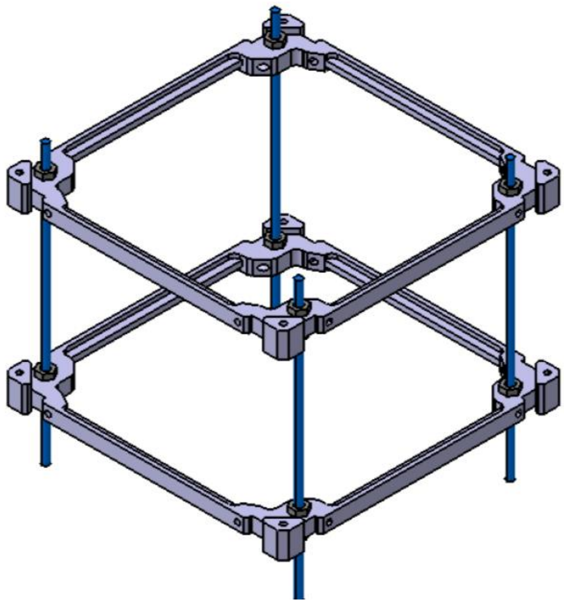


Figure 4.3 – PCB stack with reduced length

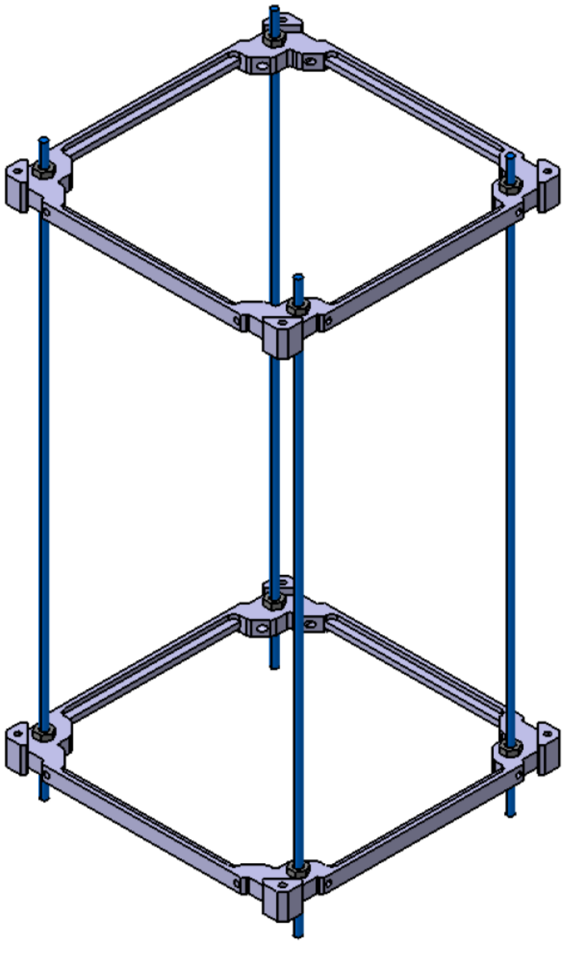


Figure 4.4 – PCB stack with increased length

4.1.2 Version 1

With PCB stack´s design being finished, the focus was shifted to design of structural frame.

First version of proposed structural frame was designed to be accessible and easy to assemble. That led to structure being **the lightest** option. Since its mass is the lowest of all proposed versions, its stiffness is of course the lowest as-well (Figure 4.5).

This approach also offers high modularity (a 6U structural frame can be easily build of used components with slight modifications) and absolute symmetry along all axis, which provides symmetrical behaviour under loading.

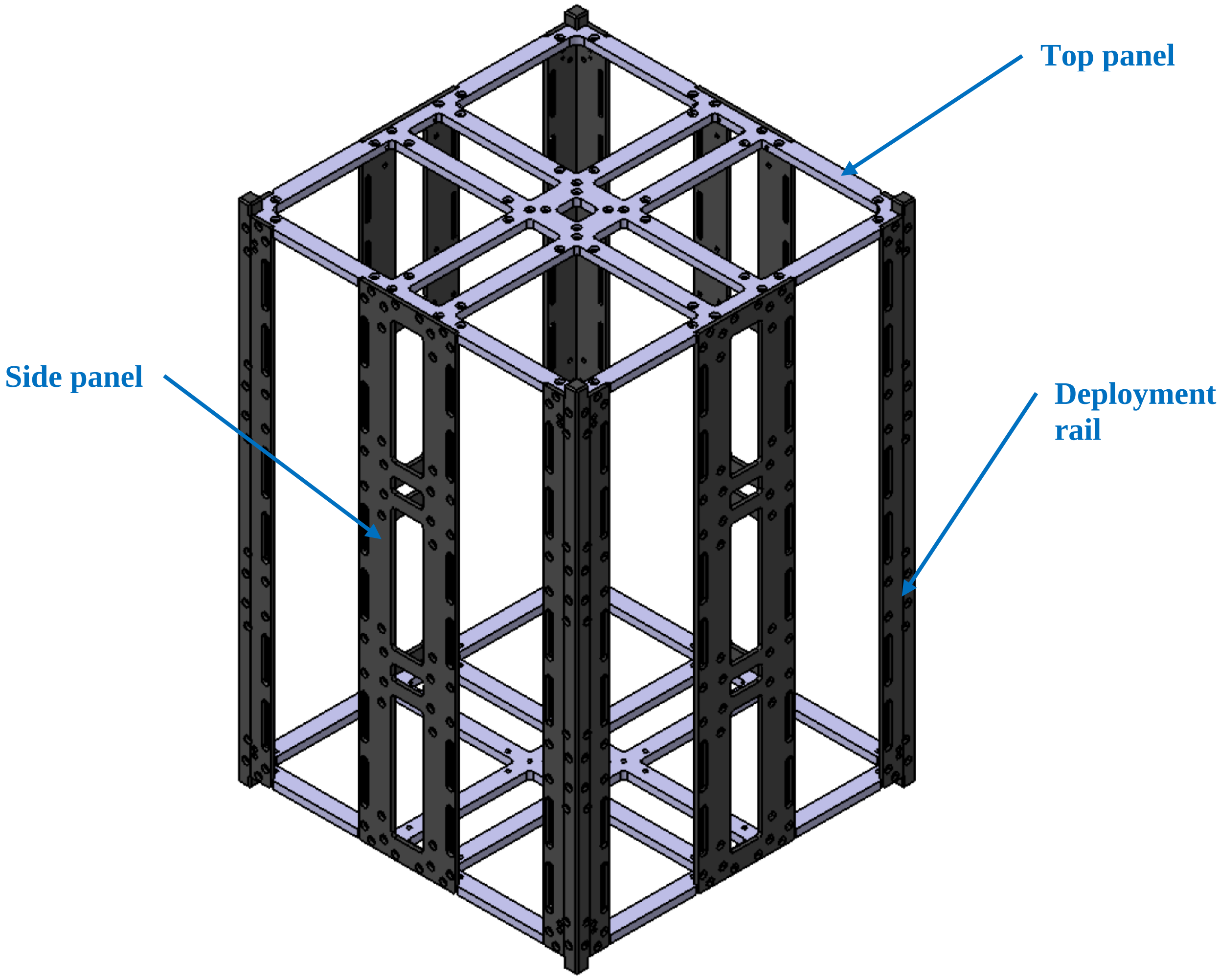


Figure 4.5 – 1st version of proposed 12U structural frame

As can be seen from Figure 4.5, external frame is composed only from 3 types of components (*2x* top panel, *4x* deployment rail and *4x* side panel).

Since structure is obviously less stiff, it was decided to use additional component, to stiffen the middle section and ensure that payload is stacked inside safely. As the middle-part component quite "massive" solution was incorporated.

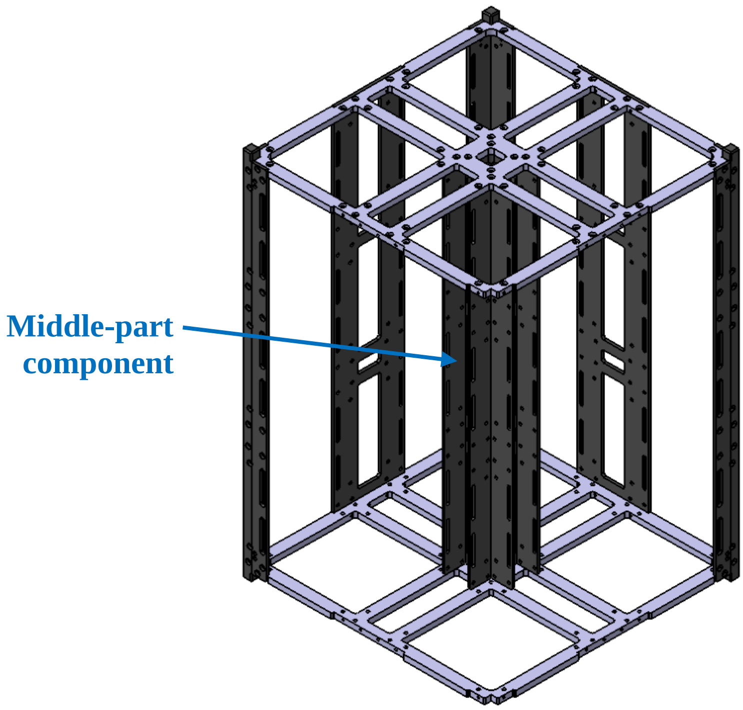


Figure 4.6 – Middle-part component

The required stiffness was achieved by utilization of the "**grid shaped**" rib (Figure 4.6). This part not only provides required stiffness, but also enables optional change of PCB stack´s length in vertical direction, while holding on the initial stiffness (the same number of screws can be utilized to mount PCB stack at all possible positions, including vertical and horizontal orientations). Thanks to this approach, whole structure is highly stiff in transversal directions at all cases (payloads mounting).

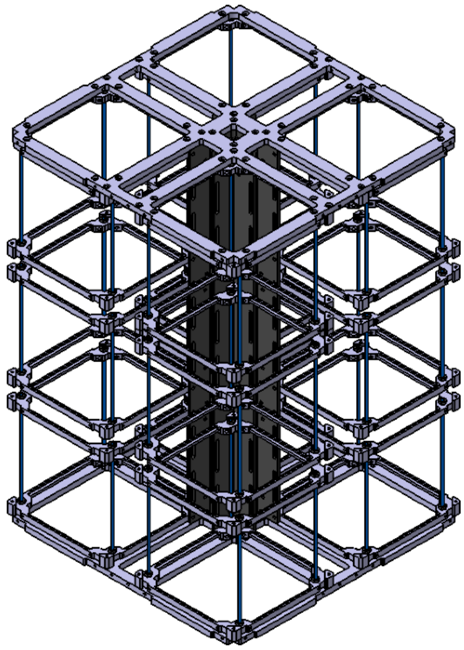


Figure 4.7 – Demonstration of accessibility

Used middle-part component also makes the assembling process a lot easier, since it is possible to connect top panels and the rib together and then integrate payload (Figure 4.7). That is highly beneficial feature for any user, because it allows them to manipulate payload with high comfort, while it is already secured inside of the discussed structure and afterwards connect the rest of components (Figure 4.8).

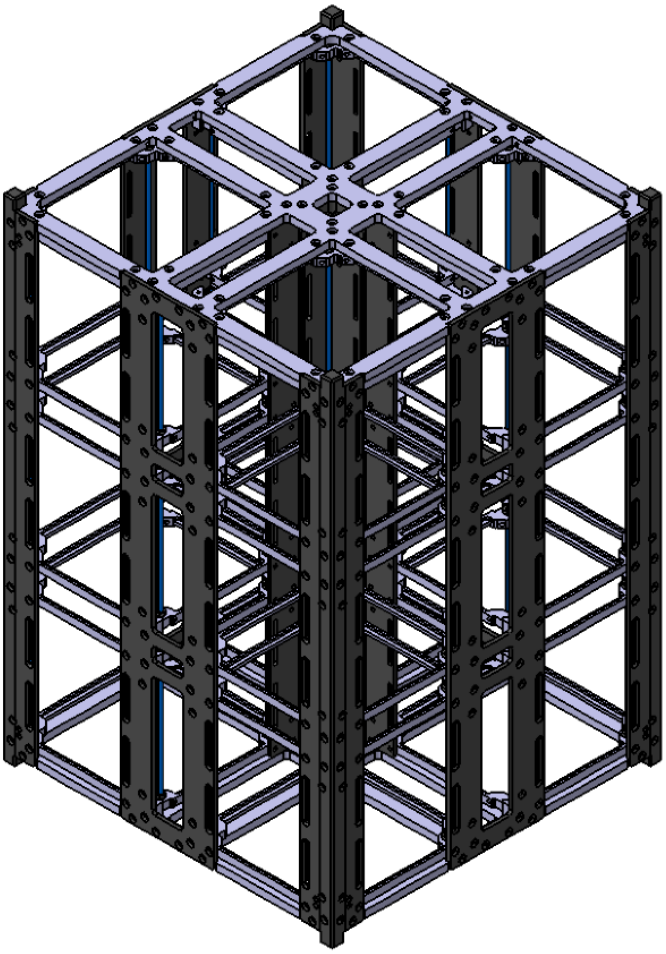


Figure 4.8 – Fully assembled structure (1st version)

4.1.3 Version 2

2nd version takes **opposite approach** to the design. The external structure is designed to be highly stiff by utilization of whole plates, which makes its very easy to manufacture (low loss of material and machining time).

Main reason for its superior stiffness is the fact, that all components are connected with each other. However, since all components are connected together by screws, its assembling will be highly uncomfortable and the accessibility of this particular structure will be significantly lower, compared to previous version.

From the Figure 4.9, it is visible that external frame is again created by 3 types of components (*2x* top panel, *2x* side plate and *2x* deployment rail plate).

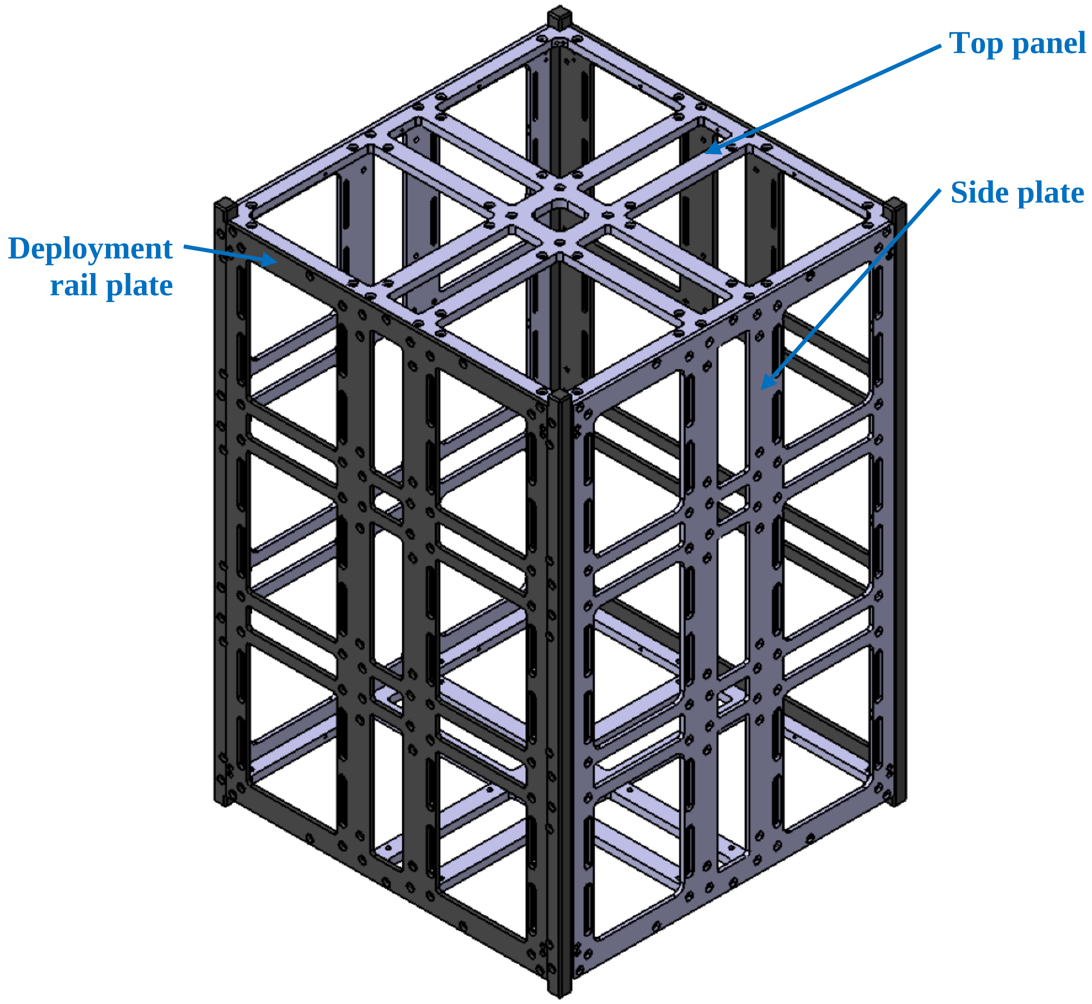


Figure 4.9 – 2nd version of proposed 12U structural frame

Because of its highly robust external frame, middle-part component does not have to be that "complicated", as it was in previous case. Also it is quite necessary for this component to be as light and simple as possible, since the structure is already quite heavy by itself.

For these reasons, the "**cross shaped**" rib (Figure 4.10) was chosen to make the middle part stiffer. Even though it fulfils its purpose, and it is indeed light and simple, it carries couple of disadvantages.

Firstly ribs themselves have to be attached directly to the PCB stacks and are not connected in any way with the external frame. Second disadvantage is the fact that PCB stacks can be utilized only in shape of the 1U payload unit, since ribs can be attached to them only in that case. Therefore length of vertically integrated PCB stacks can be changed, however it will lead to significant decrease of structural stiffness, since they will not be able to be connected to middle-part component.

Even though there is high stiffness provided in lateral direction, just by utilization of its external frame, in transversal direction structure will be weaker, compared to previous version. That is due to its middle part component connecting only PCB stacks.

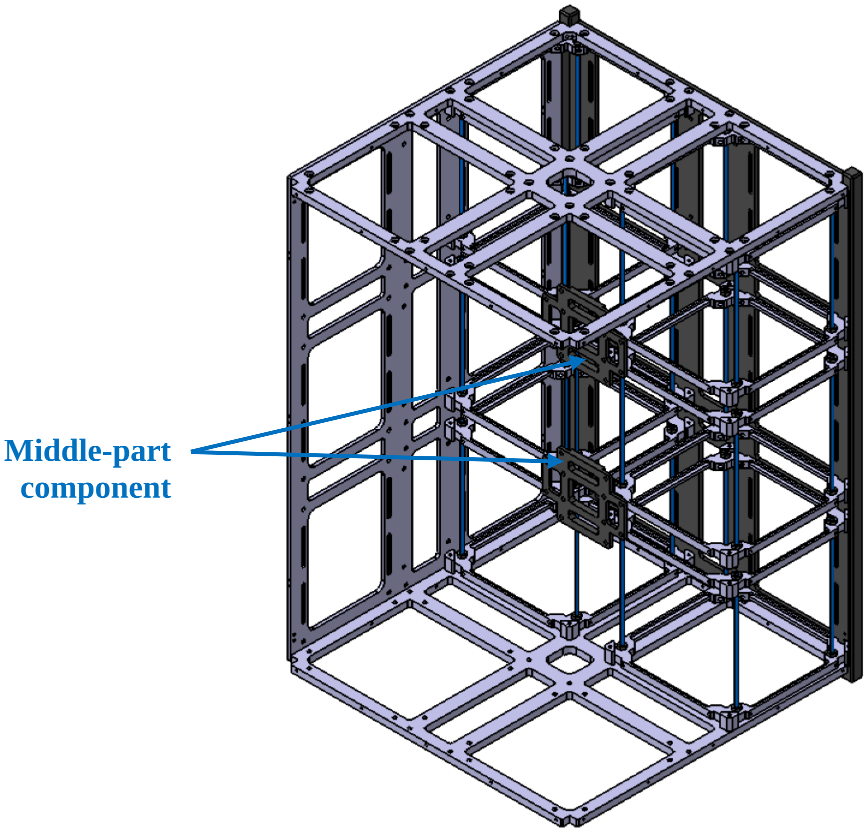


Figure 4.10 – Middle-part component

By utilization of these light ribs, PCB stack have to be integrated in 6U formation by connecting them to either one of the plates first and then connecting PCB stacks together by these ribs. Which can be uncomfortable for potential customer, however, it also leaves users with an option of implementation of 6U payload unit, if needed (Figure 4.11).

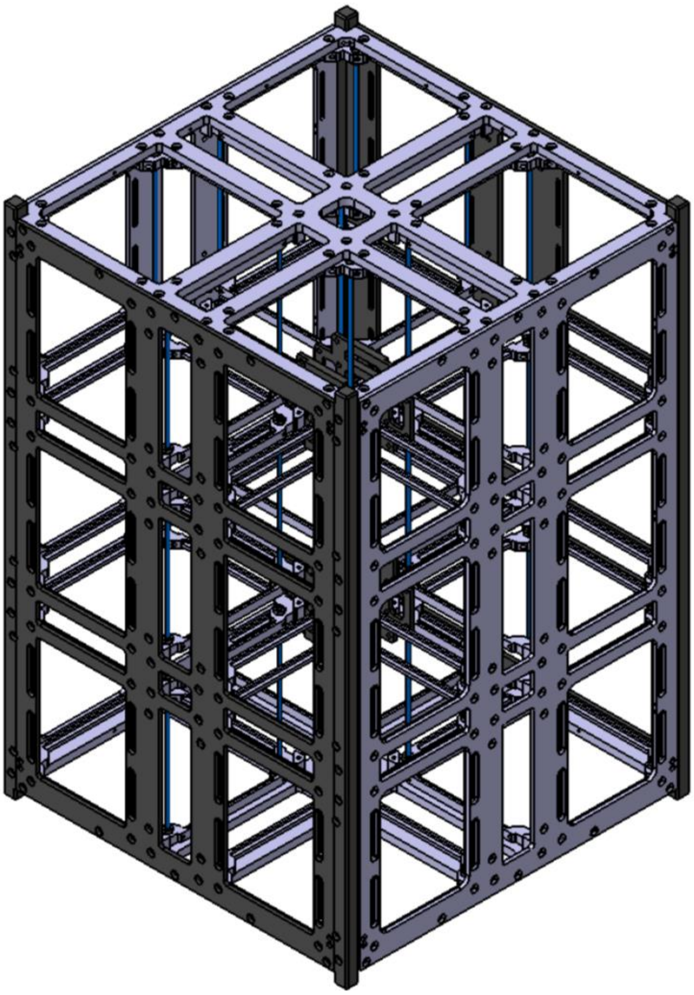


Figure 4.11 – Fully assembled structure (2nd version)

4.1.4 Version 3

Last version is basically combining features of previous proposals. Therefore its stiffness, total mass, modularity and other properties are the middle ground between previous versions.

As can be seen from the Figure 4.12, top and side panels are identical as in 1st version. CubeSat rails are slightly modified, because of utilization of the side plates (slightly modified from version 2), which makes its design significantly more complex, due to the attachment of side plates directly onto deployment rails. They are attached to deployment rails from the outside of the external frame, so that they can be easily removed without any manipulation with rails or payload whatsoever.

Even though side plates are complicating design itself, they are providing quite a lot of stiffness, therefore middle part of the structure had to be only slightly stiffer than in previous case.

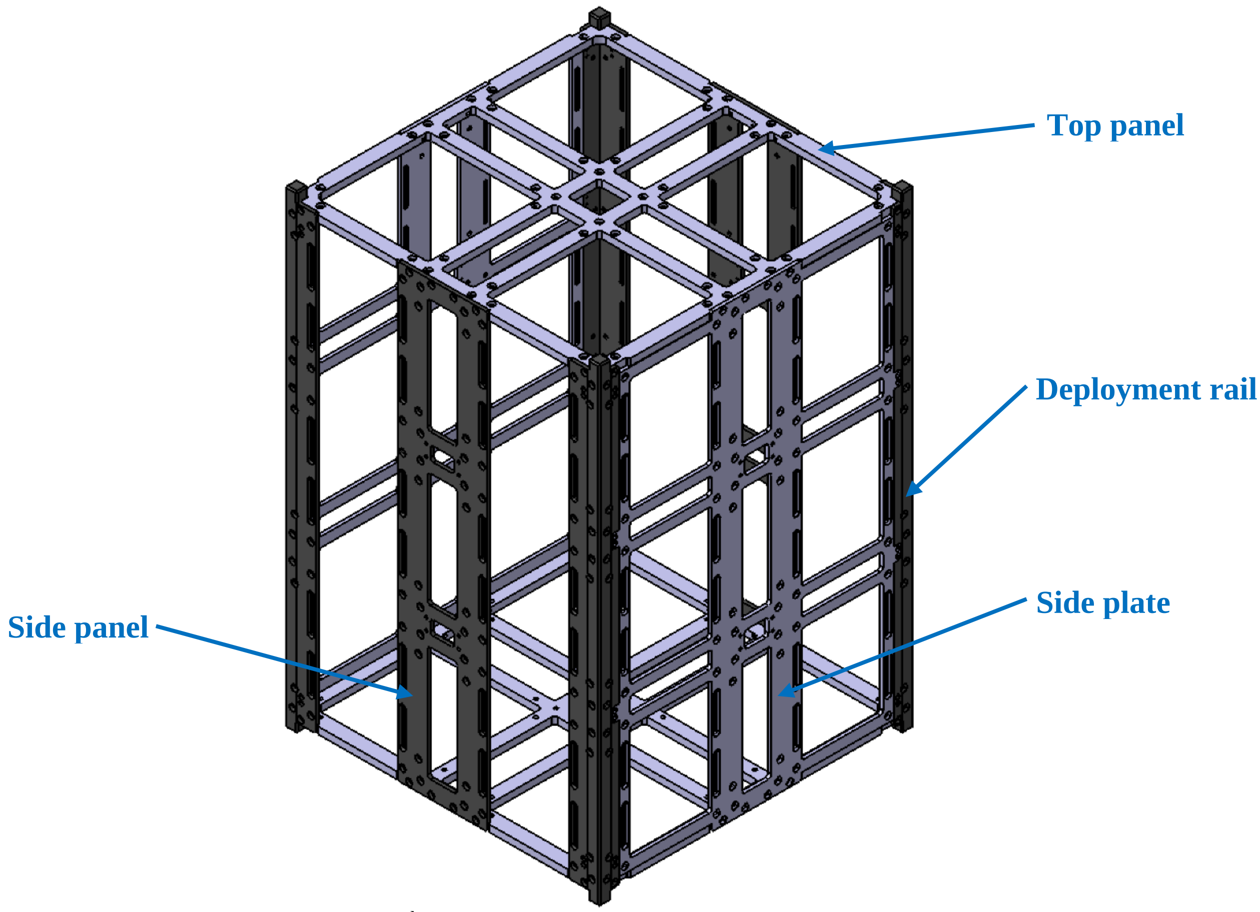


Figure 4.12 – 3rd version of proposed 12U structural frame

For this version, 2 components were used as the middle part of the structure. 2 types of different ribs were designed to create 4 separate 3U payload units and connect the frame together (Figure 4.13).

Thanks to utilization of 2 sets of ribs, whole structure is quite stiff in transversal directions, which will improve its behaviour in this direction, compared to previous version.

However, in this case, just like in previous proposal, modification of PCB stack´s length is limited the same way (if the length is modified it can lead to reduction of structural stiffness).

Structure is then assembled in quite similar was as previously mentioned. This time, payload is integrated into 4 separate 3U units and then connected together creating 2 6U payload units. Whole structure is also highly accessible and stable without side panels and plates being connected, so they can be installed later on (Figure 4.14).

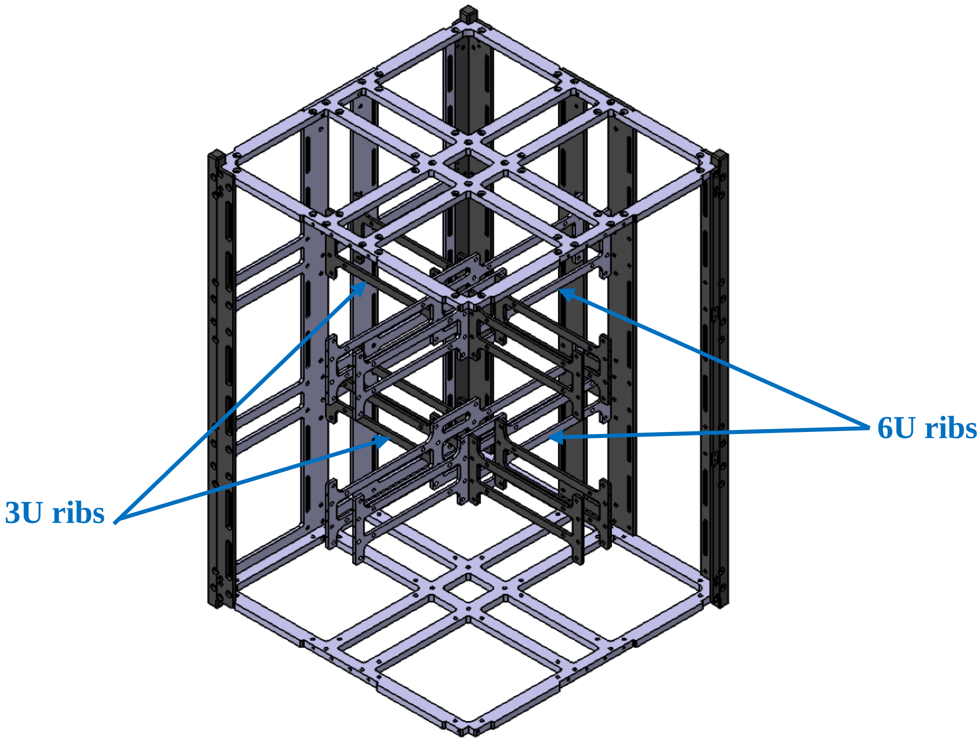


Figure 4.13 – Middle-part component

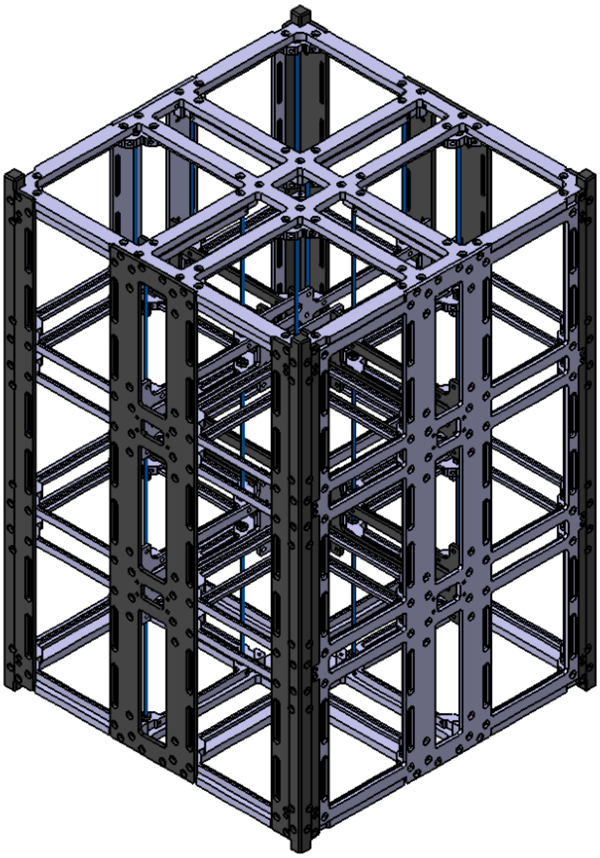


Figure 4.14 – Fully assembled structure (3rd version)

4.2 Modal analysis/stiffness calculation

As for the design features and its capabilities it is possible to decide which structure would be the one to use in more detailed design. However, there is 1 more property, that cannot be compared conclusively, since all structures are implementing different approaches of structural design and their geometry is quite complex. That property is **stiffness** (structural stiffness was predicted, but without particular values it is not verifiable statement).

Therefore simplified modal analysis was performed, to **determine natural frequencies** (value that is directly related to structural stiffness), which added up another qualitative factor for following comparison.

For this task MSC Patran and Nastran were used. It was decided to use FEM software due to high complexity of proposed structures.

4.2.1 Initial assumptions

Before calculations, it was decided to perform "**standardization**" of CAD models of all design versions. This was achieved by usage of the same thicknesses of particular components fulfilling the same function (Table 4.1).

Table 4.1 – Thicknesses of different structural components:

Thickness	Version 1	Version 2	Version 3
[mm]	*[-]*	*[-]*	*[-]*
2	Middle-part component	Middle-part component	Middle-part component
2.5	CubeSat rails, Side panels	CubeSat rail plate, Side plate	CubeSat rails, Side panel, Side plate
5	Top panels	Top panels	Top panels

By this "standardization" results of performed calculations are **comparable** as much as possible and therefore, next to the design features, the stiffness of different proposed structures can be compared.

Author is very much aware of that performed analysis is not absolutely precise, however, for stiffness determination purposes it is sufficient. And since there is not more precise way to determine qualitative value of CubeSat´s structure, due to is complex geometry, possible deviations invoked during these calculations are outweighed by its benefits.

Last assumption that should be mentioned is approach to attachment of PCB stacks to structural frame. To make structures even more comparable, PCB stacks will be integrated in vertical (default) direction in its full length (1U payload) and all inner rings will be attached to external frame with maximum number of screws possible.

4.2.2 Geometry simplification

Even though mentioned CAD models of CubeSat structures are just proposed conceptual versions of design, before importing them into FEM solver, some adjustments had to be perform.

These adjustments are just **simplifications** of current structure´s geometry. Models needed to be modified due to complexity of some design elements.

There are holes for screws with conical heads implemented in design and since these have very little effect on upcoming calculations, they will be transformed into **simple holes** (Figure 4.15).

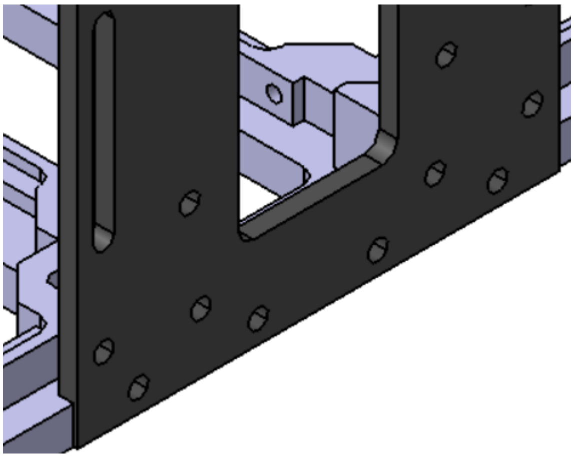


Figure 4.15 – Screw holes

Another simplification that had to be executed, were modifications of machined surfaces. These adjustments apply especially to CubeSat rails and side panels/plates as they are locally adjusted (dozens of millimetres, therefore their impact upon the FEM calculations is not significant). After the adjustments only **smooth surfaces** remained (Figure 4.16).

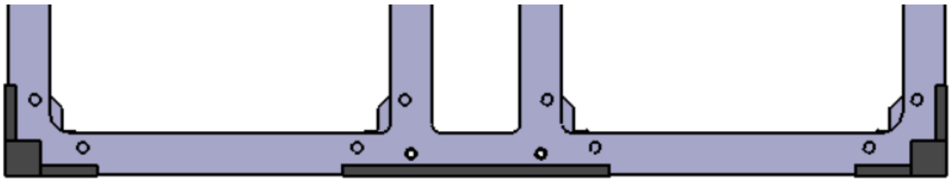


Figure 4.16 – Surfaces after simplifications

Lastly, the simplifications at **PCB stack** sub-assembly design were implemented. Since stack rods and matrixes, which are transferring loads into inner rings, will be replaced by elements at FEM software, they can be removed from the stack, leaving only inner rings (Figure 4.17).

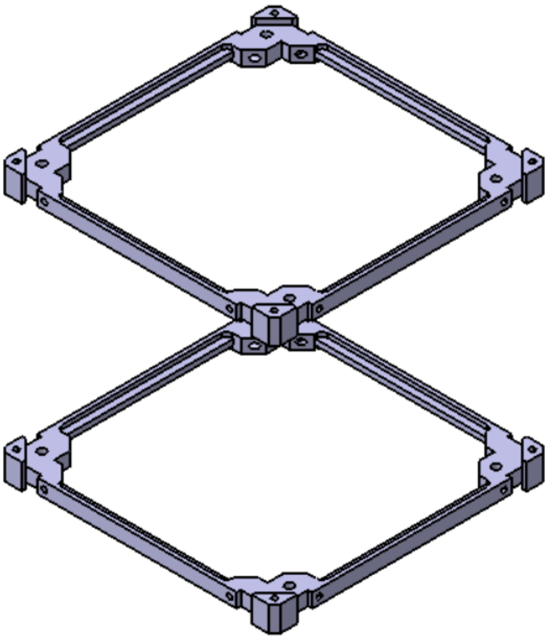


Figure 4.17 – Simplified PCB stack

4.2.3 Meshing

First structure´s body had to be divided using finite elements. Elements used for all structural parts (all of the geometry imported from CAD) were **Tethedral** elements ("Tet")(Figure 4.18).

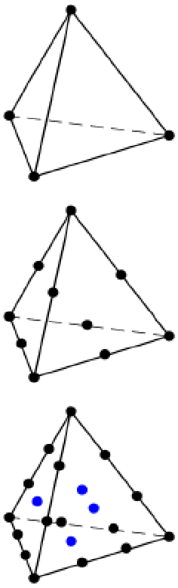


Figure 4.18 – Tet elements [34]

These elements are standard representation of 3D mesh and are able to transfer stress (deformation) in all 3 dimensions. They are usually labelled as "**Tetx**", where "x" stands for number of nodes on the element. This can be seen on Figure 4.18, where, from the top down, are shown elements Tet4, Tet10 and Tet 16. [34]

Another type of the elements used were "**MPC**" (Multipoint constraint) elements," **RBE2**" to be precise. RBE2 are Rigid Body Elements, where the independent element is a single node with 6 degrees of freedom and dependent elements are nodes connected to it. While setting up RBE2 it can be decided which degrees of freedom will be connected (usually all 6 degrees of freedom or all of 3 translations). [35]

This type of the element was used to substitute **screw connections** (Figure 4.19) and to replace **mass/load distribution** (Figure 4.20) from payload to PCB stack´s inner rings.

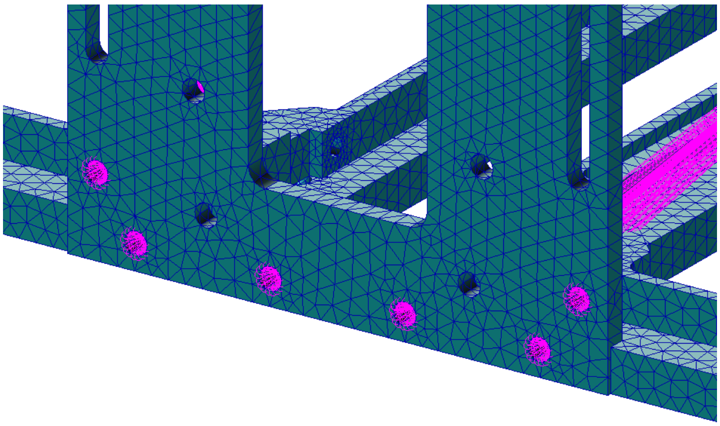


Figure 4.19 – Screws substituted by RBE2 elements

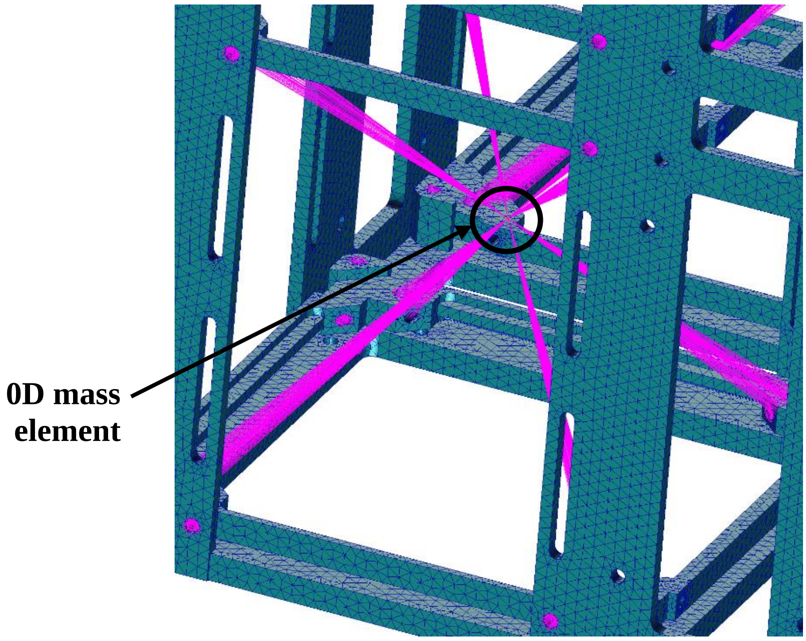


Figure 4.20 – Payload´s mass

Lastly, so-called "**0D**" elements were used. These elements are simply nodes, that had been assigned properties to replace real geometry. In this case, these elements were used to substitute **payload´s mass**. Then they are connected through RBE2 to inner rings, which will assure mass/load distribution from payload (its mass) to inner rings (Figure 4.20).

Using elements Tet10, 0D mass elements and RBE2, a complete meshes of calculated structures were created (Figure 4.21). It is also important to add, that the same **global length** of Tet10 elements was used in all calculated cases.

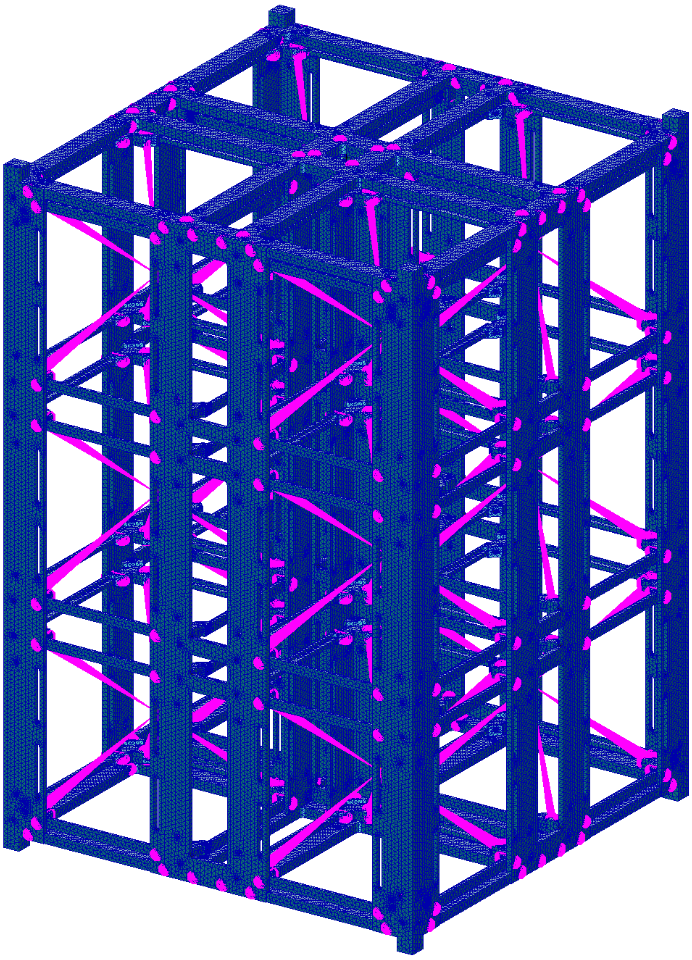


Figure 4.21 – Structure after meshing

Even though modelling PCB stacks just by usage of 2 rings, 0D element, representing payload´s mass, and RBE2 connection is sufficient for stiffness comparison and determination of structure´s behaviour, it does not say much about the way PCB stack (integrated) will behave under loading.

Because of that 2nd round of calculations was performed and this time 1 of PCB stacks was modelled in more details (Figure 4.22). This was achieved by utilization of 4 sets of 1D (beam) elements, which were connected to inner structural rings by RBE2 elements (substitution of matrixes). Another difference was usage of multiple 0D mass elements, which were connected to stack rods by RBE2 connection, substituting PCB boards that are attached to stack rods.

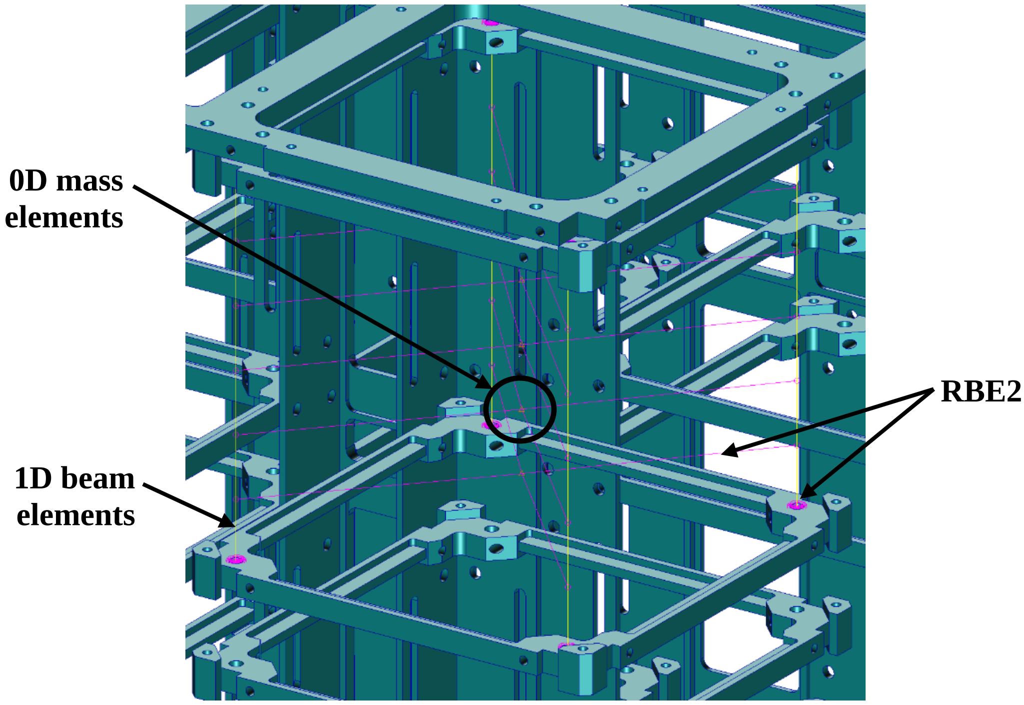


Figure 4.22 – Detailly modelled PCB stack

It is quite clear that modelling 1 PCB stack in different way than others, introduced whole structure with certain asymmetry and it will influence its stiffness (RBE2 connection substitutes stack rods, by creation of "absolutely stiff connection" between mass and inner rings). However, purpose of this additional round of calculations was not to determine stiffness of the structural frame. Instead, it provided information about which structure "provides" payload with more stiffness.

After all elements were set up, properties were assigned to corresponding elements. For all 3D elements, properties of aluminium alloy 6082-T651 were assigned. As for the stack rods (1D beam elements), titanium alloy Ti-6Al-4V (Grade 5) was used, which were implemented based on recommendations and experience of the contractor, due to their low mass and higher strength. Thanks to that, model was ready for weighting (Figure 4.23).

Since previous market research shown, that deployers available for 12U CubeSats are capable of **carrying maximum** of *24kg*, this weight will be considered as maximum total mass of fully loaded CubeSat structure.

After structure´s mass was determined (which was performed for each structure individually), the rest of maximum total mass (*24kg*) was **equally distributed** among all of 12 PCB stacks.

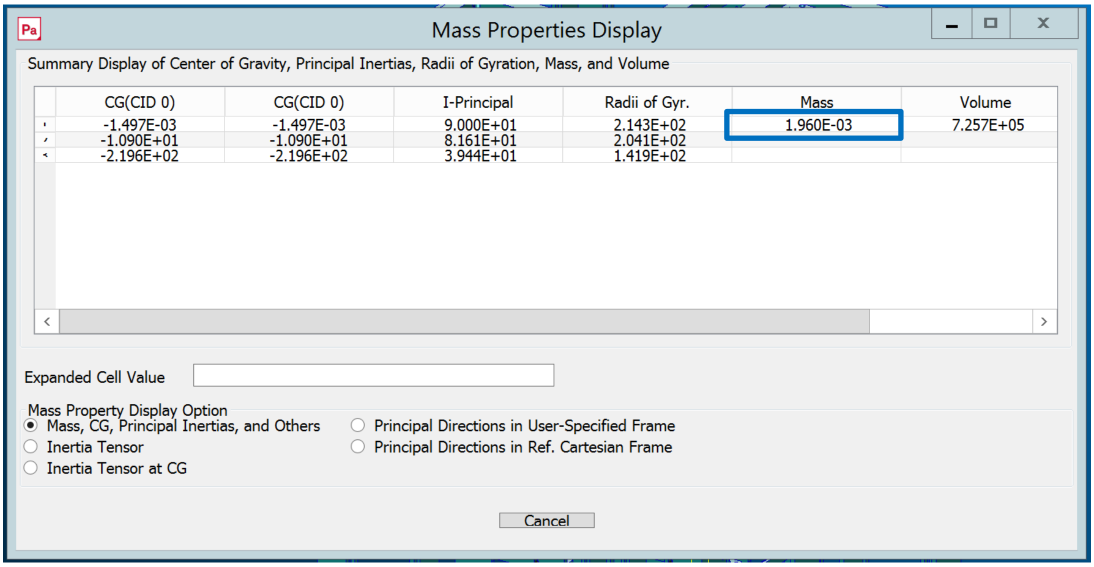


Figure 4.23 – Structure´s total mass determination (in tons)

4.2.4 Boundary conditions

As for boundary conditions, FEM model of CubeSat´s structure had to be fixed in a position that complies with placement in deployer. Therefore, structure was fixed through rails at surfaces, where the contact between CubeSat and its deployer takes place (face and sides of rails)(Figure 4.24).

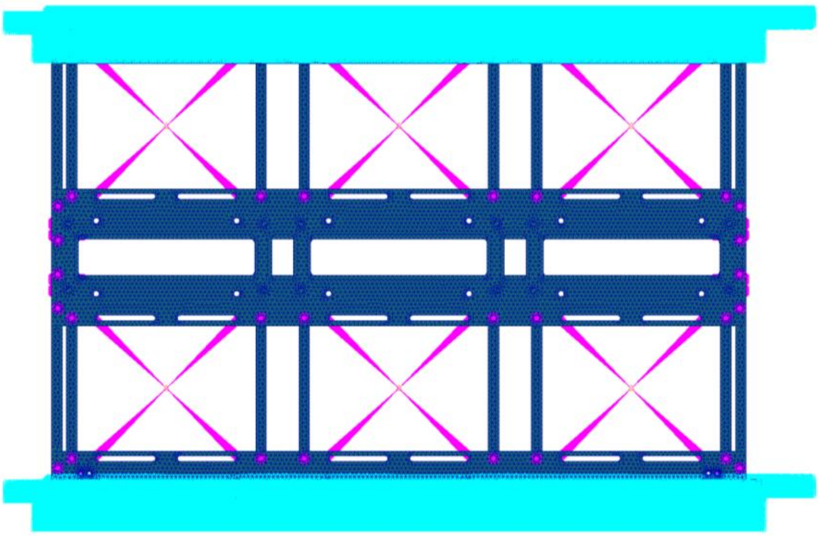


Figure 4.24 – Simulation of contact between deployer and CubeSat

Thanks to that structure is completely fixed in all direction (all degrees of freedom).

4.3 Results

Previously mentioned procedure was applied for all 3 proposed versions (where the **frequency range** of *5 – 2000Hz* was used, since it is a standard range for CubeSat calculations, and it is required by potential launch providers). After results were obtained, natural frequencies and relevant eigenmodes were analysed.

For each version, first 10 eigenmodes were calculated (Table 4.2, Table 4.3 and Table 4.4), however the first one is for comparison purposes the most important. Therefore, only first eigenmodes are shown below (Figure 4.25, Figure 4.26 and Figure 4.27).

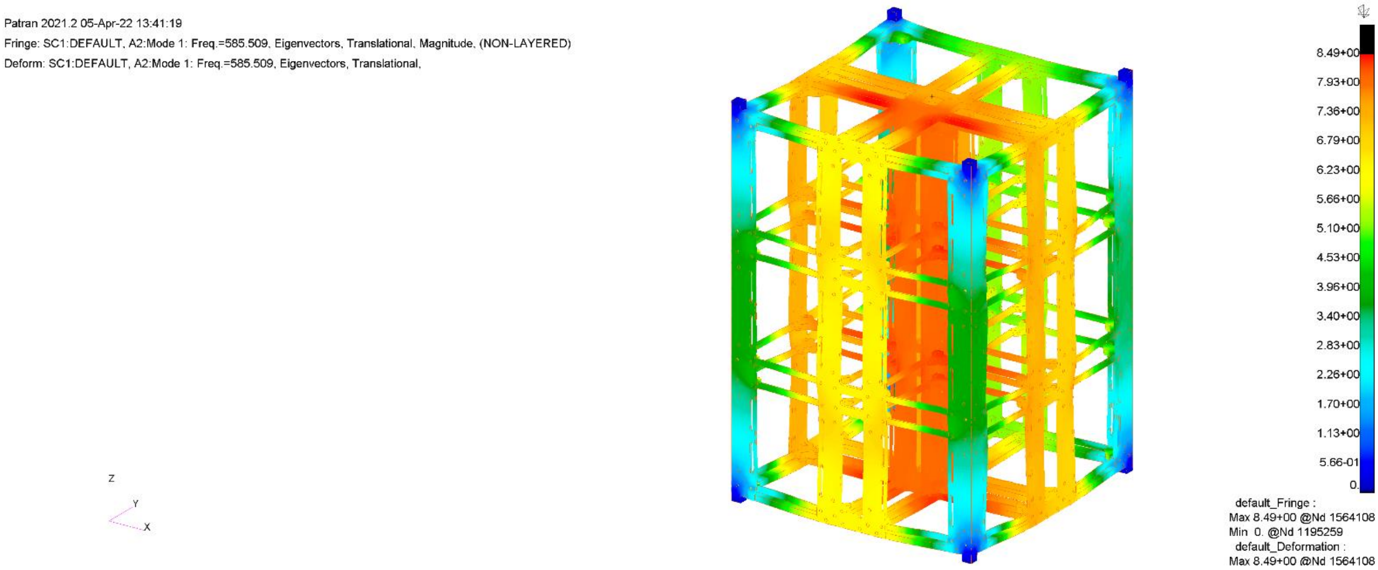


Figure 4.25 – 1st eigenmode of 12U structure Version 1

Table 4.2 – Natural frequencies of 12U structure Version 1:

Eigenmode	Natural frequency
[-]	*[Hz]*
1	585.509
2	666.753
3	801.824
4	852.400
5	858.089
6	871.626
7	962.864
8	997.181
9	1054.870
10	1084.140

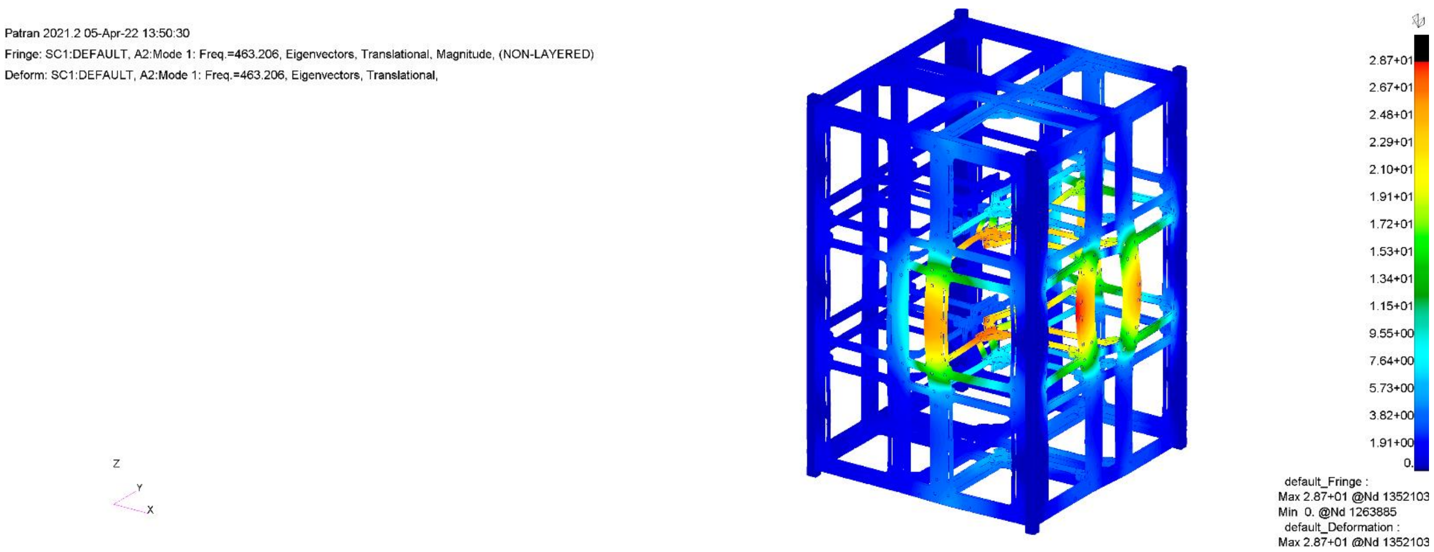


Figure 4.26 – 1st eigenmode of 12U structure Version 2

Table 4.3 – Natural frequencies of 12U structure Version 2:

Eigenmode	Natural frequency
[-]	*[Hz]*
1	463.206
2	464.071
3	484.967
4	485.430
5	620.854
6	634.661
7	655.911
8	711.222
9	743.549
10	755.996

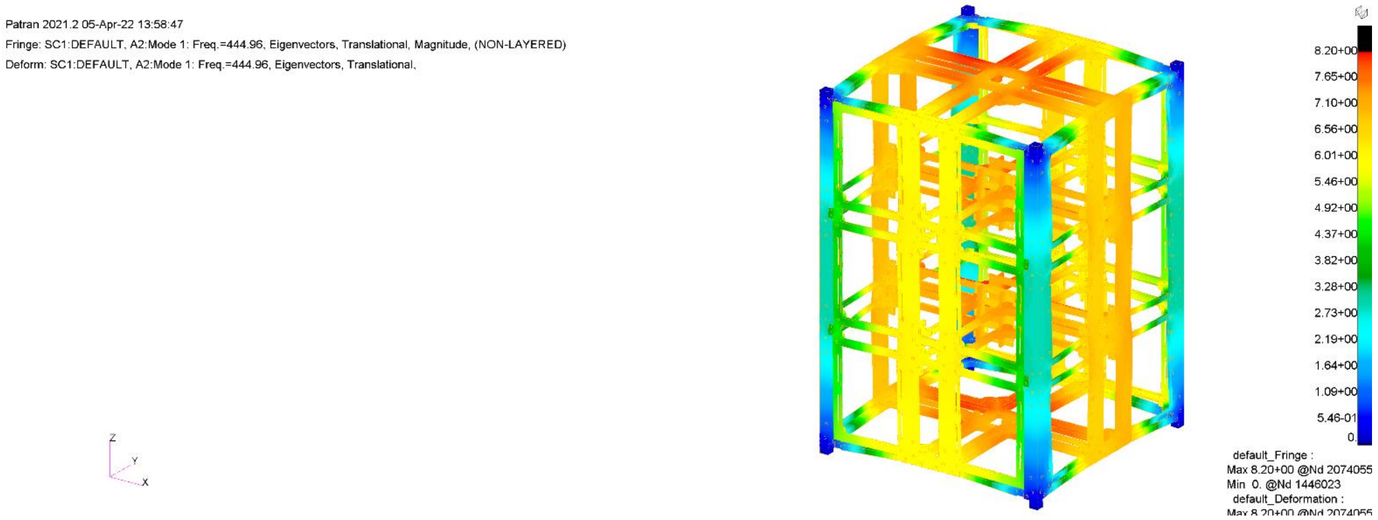


Figure 4.27 – 1st eigenmode of 12U structure Version 3

Table 4.4 – Natural frequencies of 12U structure Version 3:

Eigenmode	Natural frequency
[-]	*[Hz]*
1	444.960
2	497.201
3	509.230
4	521.486
5	548.070
6	597.583
7	625.068
8	727.802
9	762.378
10	776.134

From obtained results, it is clear how proposed structures behave and how their stiffness varies. The 1st version of 12U structure is by far the stiffest option, thanks to its middle-part component. Other structures are than quite comparable (to each other).

This says a lot about structural design of 12U CubeSat, mainly how dependent its stiffness actually is upon its middle-part component.

Another thing that can be observed from presented results, are eigenvectors of designed structures (directions of their oscillation/movement). 1st and 3rd structures are oscillating in lateral direction of the CubeSat. That indicates their stiffness is lowest in that direction, which is logical conclusion since they are stiffened mostly in transversal directions.

2nd structure on the other hand is oscillating in transversal direction (at the middle of the structure), because of its high stiffness in lateral direction. This confirms previous predictions about its middle-part component´s stiffness (how low stiffness it provides).

4.3.1 PCB stack´s behaviour

With that being said, results regarding structural stiffness of all proposed structural frames were compared. However they do not provide an answer regarding PCB stack´s behaviour, so as it was teased, 2nd set of calculations was performed, this time with 1 detailly modelled PCB stack.

Once again first 10 eigenmodes (Table 4.5) were calculated and the 1st eigenmodes are visualized bellow (Figure 4.28, Figure 4.29 and Figure 4.30)

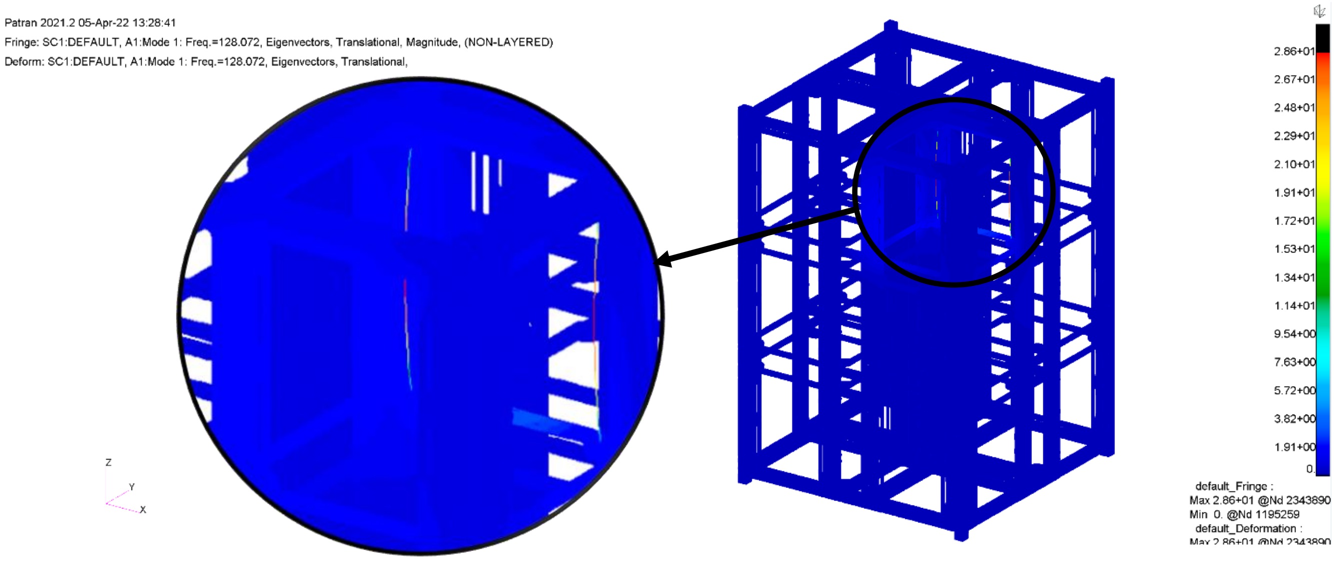


Figure 4.28 – 1st eigenmode with detailly modelled PCB stack (Version 1)

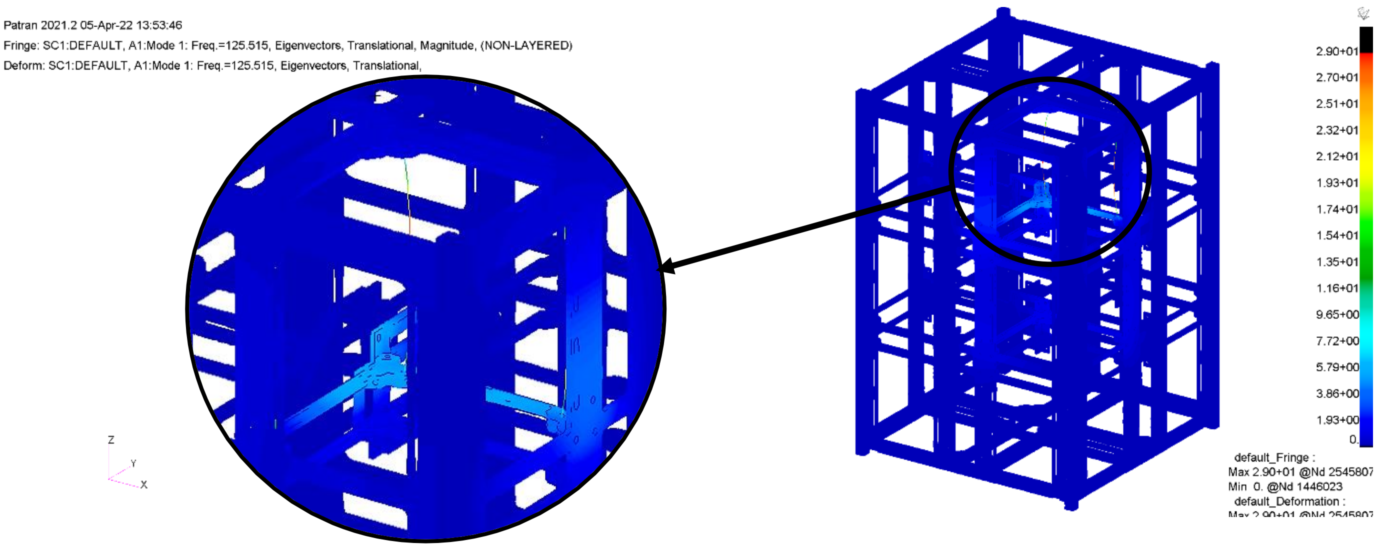


Figure 4.29 – 1st eigenmode with detailly modelled PCB stack (Version 2)

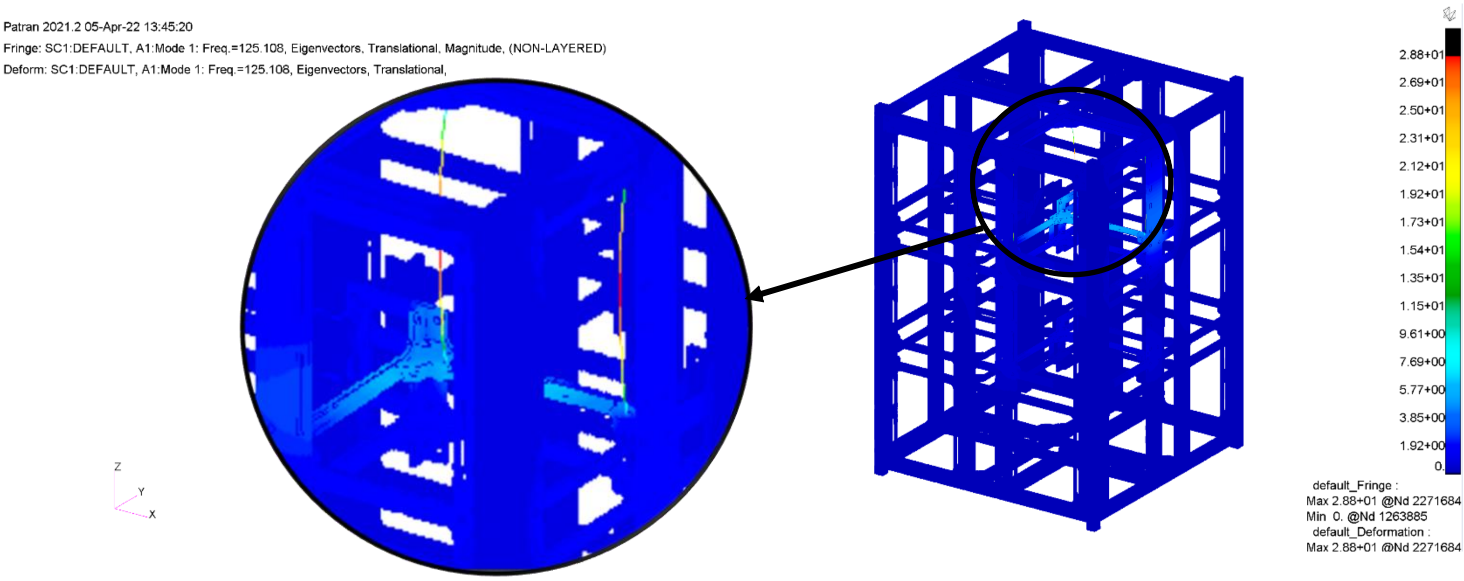


Figure 4.30 – 1st eigenmode with detailly modelled PCB stack (Version 3)

From obtained results it is clear that the 1st natural frequency has significantly decreased. That is caused by introduction of stack rods into the calculations. Since they are made of the real material which has finite stiffness (unlike RBE2 connection), they will begin to oscillate sooner that the actual structure.

Even though natural frequencies has decreased, results only confirm previous conclusions. The 1st proposed structure provides highest stiffness (in this case for integrated payload).

Table 4.5 – Comparison of natural frequencies:

Eigenmode	Natural frequency (Version 1)	Natural frequency (Version 2)	Natural frequency (Version 3)
[-]	*[Hz]*	*[Hz]*	*[Hz]*
1	128.072	125.108	125.515
2	128.891	126.578	126.670
3	256.869	252.367	252.676
4	258.105	255.030	254.789
5	379.278	372.090	364.515
6	380.198	375.046	375.221
7	480.243	378.987	377.271
8	480.748	422.149	440.228
9	546.598	460.216	468.538
10	546.744	476.721	477.831

4.4 Comparison

With structural stiffness (natural frequencies) calculated, all comparable parameters were known. Therefore, final comparison Table 4.6 was created to determine which approach to design would be the most beneficial.

Table 4.6 – Comparison of proposed structure versions:

Version		1	2	3
Total mass (1) [g]		1967	1849 (-5.999%)	1859 (-5.491%)
Number of components (External frame)		3	3	4
Number of components (Middle part component included)		4	4	6
Number of components (PCB stacks included)		6	6	8
PCB stack integration	Vertical (default)	YES	YES	YES
	Horizontal	YES	YES	YES
	Adjustable length (2)	YES	YES *(3)*	YES *(3)*
Assembling simplicity (4)		High	Medium	Low
Accessibility (4)		High	Low	Medium
Manufacturing simplicity (4)		Low	High	Medium
External dimensions [mm]		226.3x226.3x340.5	226.3x226.3x340.5	226.3x226.3x340.5
Natural frequency (first eigenmode) [Hz]		585.509	463.206 (-20.888%)	444.960 (-24.005%)
Natural frequency for detailly modelled PCB stack (first eigenmode) [Hz]		128.072	125.108 (-2.314%)	125.515 (-1.997%)

(1) Stack rods, matrixes and PCB mounting elements are not included
(2) Only for vertically integrated PCB stacks
(3) Middle PCB stack´s length cannot be changed to maintain structural stiffness
(4) Feature has been assigned score point, where high is worth 3 point, medium 2 points and low 1 point

It is clearly visible that the 1st version of proposed structures has highest **total mass** of all, due to its middle part component being designed to stiffened whole structure. Total difference is over *100 g*, which is quite a disadvantage, however it is not necessarily a "deal breaker" since the structure has not been through mass reduction yet and the relative difference is not that high (*5.491%* to *5.999%*).

As for the **number of components** 3rd version has come out as the worst version by far. Since it is utilizing features of previous 2 versions and 2 middle-part components, it has 2 more components than other proposed structures.

It was previously mentioned that there is a possibility of **integration of PCB stacks in different directions** and **optional change of their length**. All structures were design to be able to include PCB stacks in different directions (vertical as well as horizontal). However, due to its middle part component, only the 1st version provides an optional change of PCB stack´s length for all cases of payloads integration. Meaning, that user doesn’t have to worry about stacks dimensions, as it can be attached with the same number of crews at any position.

This advantage is the directly bound to **accessibility** and **assembling simplicity**, which are highly important features for potential customers. Once again, due to its design, the 1st version of proposed structure has come to the top. When considering its accessibility and assembling simplicity it as by far the best option, because it is possible to connect top panels together with middle-part component and then very easily integrate all PCB stacks (see chapter *4.1.2 Version 1*).

This feature comes with obvious disadvantage. Since the middle part component of the 1st structure is manufactured as 1 piece, there is **significant loss of material** due to its complex shape (an estimation of over *92%* material loss was made from the CAD model). Therefore, from manufacturing point of view, the 2nd version has come up as the best option, as it is simply made out of metal plates.

And finally, previously calculated **stiffness** (natural frequencies) of structures. From obtained results is obvious that 2nd and 3rd structures have highly similar stiffnesses (even though their behaviour is different), however the 1st proposed structure beasts them both with its 1st natural frequency being higher by more than *20%* (by *2%* in case of comparing results for 1 PCB stack being modelled detailly).

4.5 Summary

Total mass of all proposed structures is quite similar. Thus, it will not be considered a primary comparison factor. Structure´s **function** (**provided features**), **accessibility**, **assembling simplicity** and calculated **stiffness** are factors of high importance for protentional customer and therefore will be taken as primary comparison factors.

Then from Table 4.6, structural version number 1 is considered the best approach. So from now on, **1st version** will be considered a final concept and it will go through more detailed design, followed by FEM calculations to verify its properties and behaviour (stiffness, strength, …)

5. Detailed design of proposed 12U CubeSat structure

With conceptual approach to design being set, proposed structure can be finished by implementation of particular design nodes and operations.

From presented results it is clear that proposed structure´s stiffness is quite high, which is caused partly by usage of **high number of PCB mounting screws** and partly by **high nominal thickness** of used components.

Number of mounting screws will not be reduced as it provides potential customers with more options regarding their payload's integration/mounting. However nominal thickness of structure´s components will be definitely reduced (globally as well as locally).

5.1 Kill-switch mechanism

Before going straight to the process of optimalization, there is one more feature that has to be discussed. That is of course the **kill-switch mechanism**.

Its function was previously mentioned at CubeSat structure´s analysis (chapter *2.2 12U CubeSat structure analysis*).

Originally, **usual concept of kill-switch mechanism** was intended (Figure 2.2). This approach consists of 3 components (spring, pin housing and pin), which are integrated inside the top of the deployment rail. Because of that deployment rails would have to be highly modified.

Another modification that would have been needed, is modification of 1 inner ring used at PCB stack sub-assembly (designed attachment system would not have allowed combination of designed PCB stack and usual concept of kill-switch mechanism). That would lead to **addition** of 4 new components (kill-switch mechanism and modified inner ring) and complex geometry modifications of deployment rail.

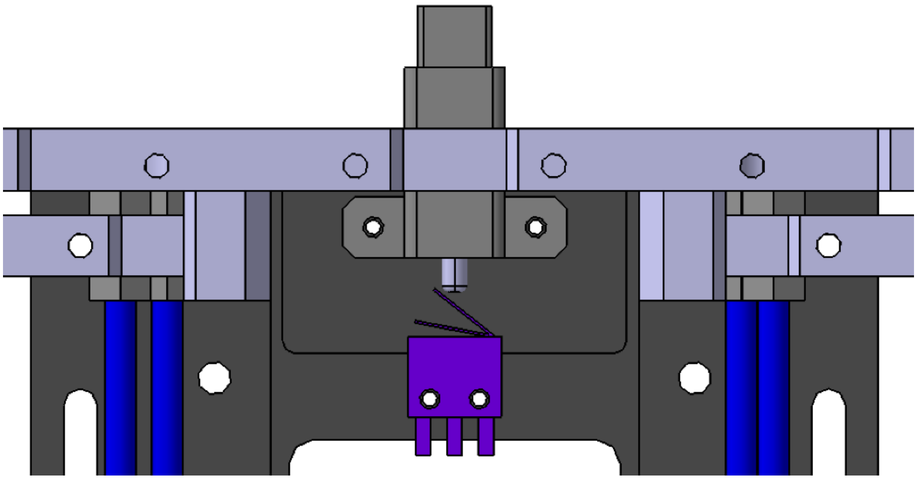


Figure 5.1 – Used kill-switch mechanism

For these reasons, it was decided to avoid traditional approach. More suitable option was designed instead (Figure 5.1). That was achieved by placing kill-switch mechanism into empty space between PCB stacks, which is essentially a lot more esthetical and practical solution.

Whole mechanism is then assembled out of 4 components (pin housing, pin, spring and mechanism´s body/cover)(Figure 5.2), so at the end total number of added components remains the same as it would have been in the case of conventional concept.

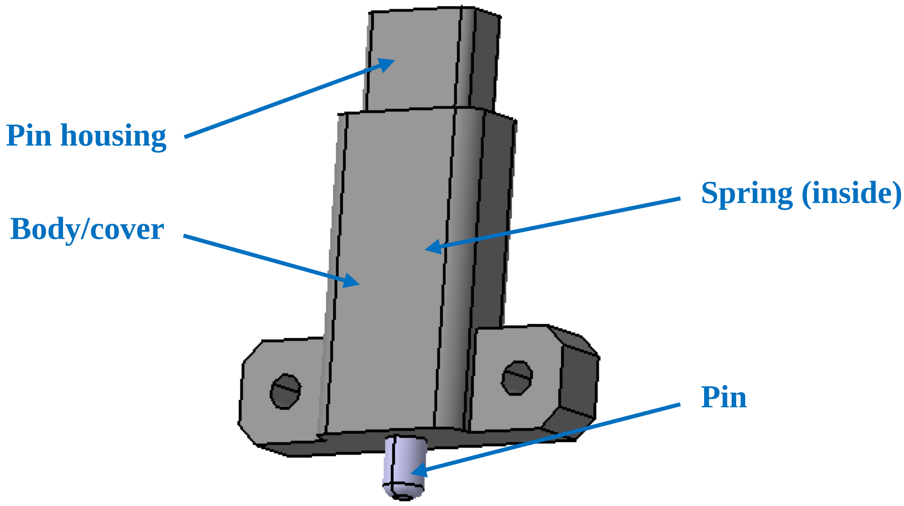


Figure 5.2 – Kill-switch mechanism sub-assembly

Because of integration of kill-switch mechanism at mentioned position, only small adjustments of structural frame were necessary. Windows and thread wholes were added to top and side panels for safe and comfortable integration (Figure 5.3).

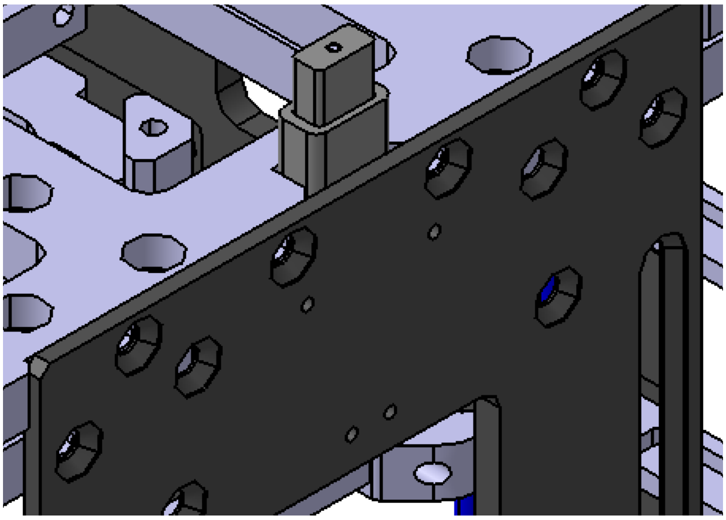


Figure 5.3 – Structural frame´s adjustments

Whole mechanism and the kill-switch itself are screwed to couple of opposite side panels, which makes them both **completely independent** upon the rest of structure as-well as **easily accessible**. Also, in order for each component to remain symmetrical, both kill-switch mechanism and the kill-switch can be attached to any side panel and integrated in any position (both kill-switch mechanisms have to be facing the same direction)(Figure 5.4).

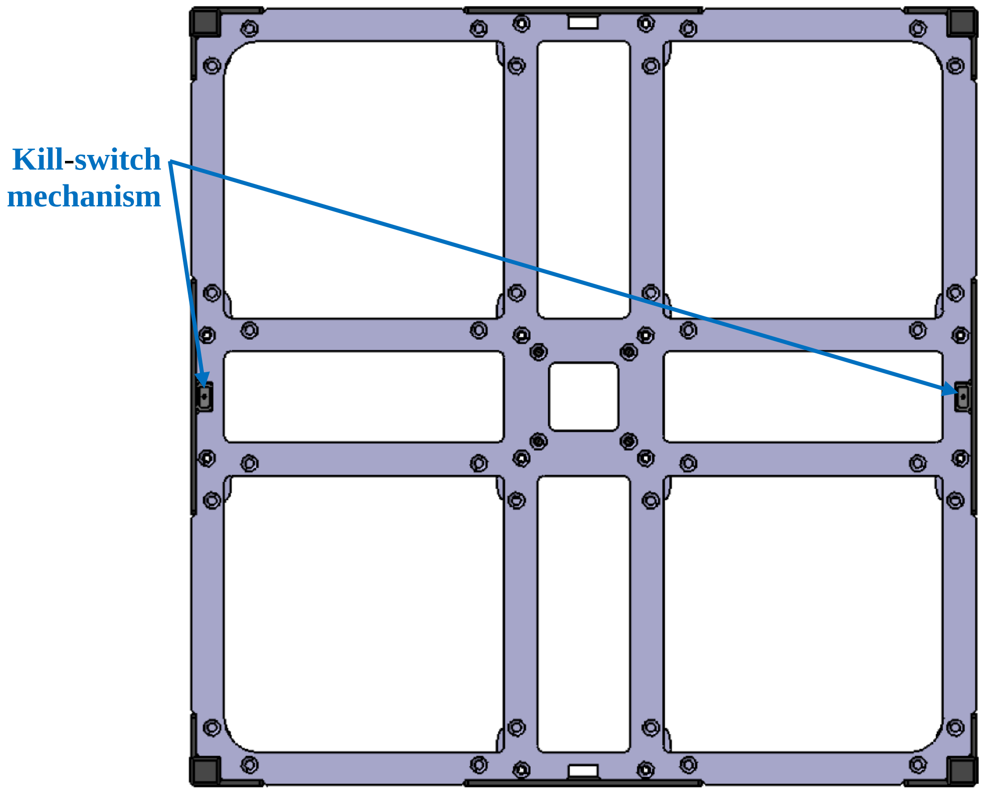


Figure 5.4 – Integration of kill-switch mechanism

As a kill-switch, **Panasonic AV4** miniature switch was used. It has hinge lever to assure safe and easy compression. Figure 5.5 displays switch´s external dimension envelope, which was also used to design proper compression of the switch at CAD model.

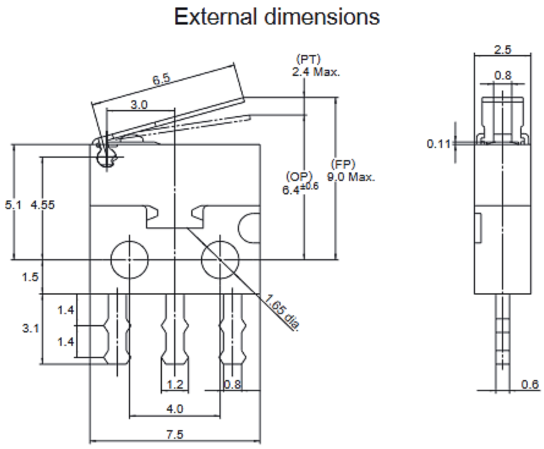


Figure 5.5 – Panasonic AV4 miniature switch (dimensions in mm) [36]

5.2 Attached components

Even though whole structural frame was designed in respect to payload´s parameters (in this case PCB stacks), it is important to acknowledge that there will be some "external" components attached to the outside of the structural frame (Antenna systems, solar panels, shear panels, …).

Another fact that should pointed out is that these components are attached to CubeSat structure by screws, which are mostly using the same spacing (by most of companies included in CubeSat industry). That saves a lot of work to CubeSat developers, since there is only need for 1 attachment system.

Usage of these components is also highly dependable upon particular mission. Therefore, since in this case it is not quite possible to design entirely universal structure, a default version of the structure was be set, with optional modification based on requirements of potential customer.

Proposed design was adjusted for attachment of *6x1U* solar panels at all sides, *4x1U* solar panel at the bottom and *2x1U* solar panels (designed by company SPACEMANIAC [37]) with *2* antenna systems (for *6U/12U* CubeSats designed by company ISISPACE [38]) on the top of structure (Figure 5.6 and Figure 5.7). It is possible to also utilize bigger solar panels (up to 6U solar panel wall at sides and 4U at the top/bottom), as they have the same thread hole spacing as used 1U panels.

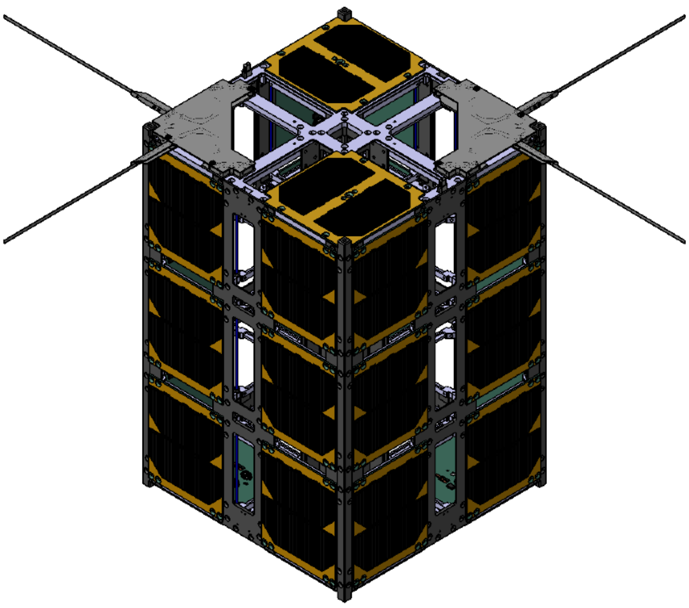


Figure 5.6 – Attached components (top isometric view)

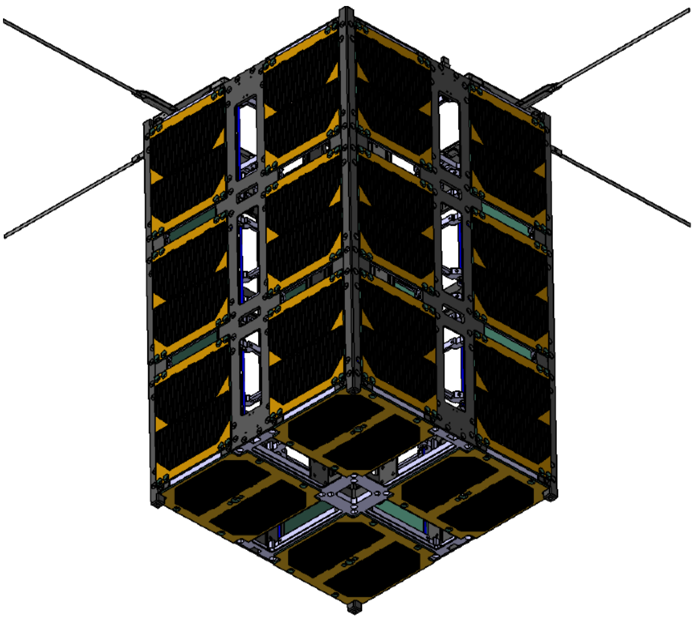


Figure 5.7 – Attached components (bottom isometric view)

Along with mentioned adjustments, threaded holes at each end of the deployment rail were created for usage of so-called pin plungers (Figure 5.8).

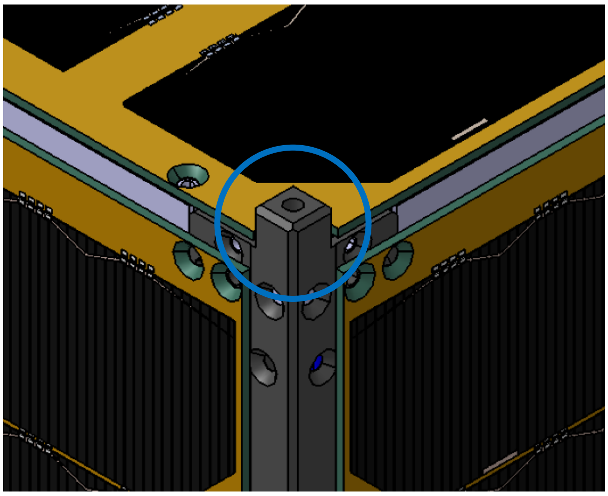


Figure 5.8 – Deployment rail adjustment

Those serve as units that help the separation of CubeSat from the deployer (Figure 5.9) by creation of additional force during separation process.

Figure 5.9 – Pin plunger [39]

5.3 Mass reduction

By preformation of above-mentioned adjustments, due to integration of kill-switch mechanism, structure´s optimalization has indirectly begun. In this case, by using word "**optimalization**", so-called **mass reduction** is meant.

First step in this process was reduction of nominal thickness of individual components, as previously teased. That by itself led to significant loss of total mass. However, results from previous calculations suggested that the stiffness of proposed structure is high. Therefore further mass reduction was performed, this time by locally removing material.

This was done so thanks to the knowledge of shape of the 1st eigenmode of discussed concept. Material was removed from locations that were least deformed and preserved in highest possible amount at locations where transfer of the loading was highest.

By preformation of these operations, total mass of structure was significantly reduced (by *24.453%*)(Table 5.1).

Table 5.1 – Structural mass after mass reduction:

	Before mass reduction	**After mass reduction**
Total mass [(1)] [g]	1967	1486 (-24.453%)
(1) Stack rods, matrixes and PCB mounting elements are not included		

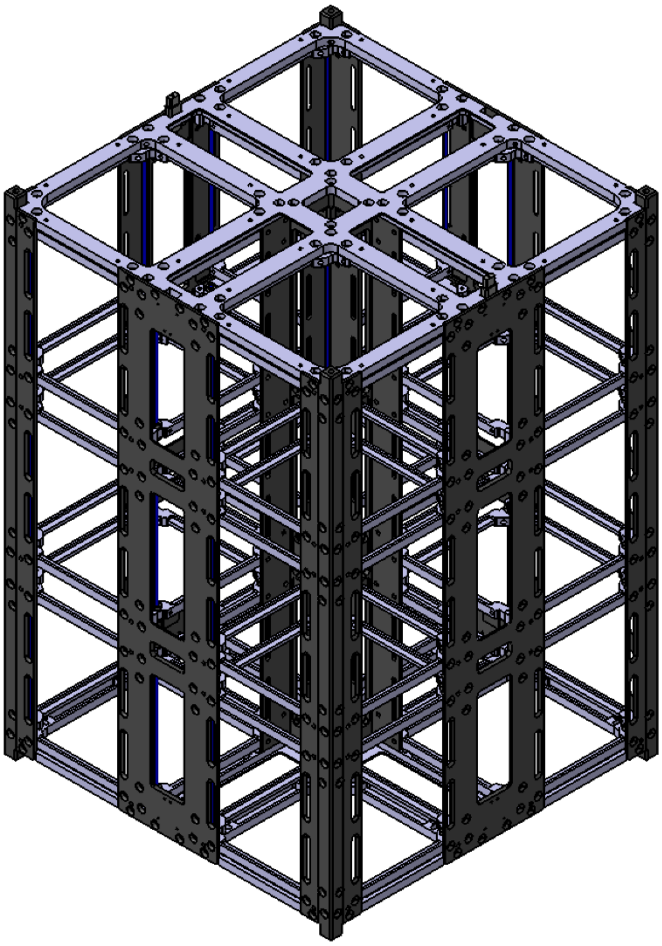


Figure 5.10 – Final design of proposed structural frame

5.4 Summarization of design

Before moving onto FEM analysis and check of the structural design, a "**design check**" was performed to verify whether all prescribed requirements were fulfilled (chapter *3 Design assumptions*).

Most of them were immediately implemented at the beginning of conceptual design. These were assumptions regarding structure´s features and accessibility of integrated payload. All of these parameters were discussed and verified in multiple occasions (during conceptual design), so they are considered to be satisfied. As for the total mass, that was mentioned while optimizing structure.

However, there is one more feature that was mentioned and was not assigned high priority during conceptual design, since the ultimate goal of this thesis is design of 12U CubeSat structure. This feature is **modularity**.

Even though it was not prioritized, this feature was indeed preserved. Thanks to performed design and mass reduction, it is possible to utilize most of designed components and only with slight adjustments **assemble 6U CubeSat structure** (Figure 5.11). Both 6U and 12U structures are also easily modifiable, if necessary.

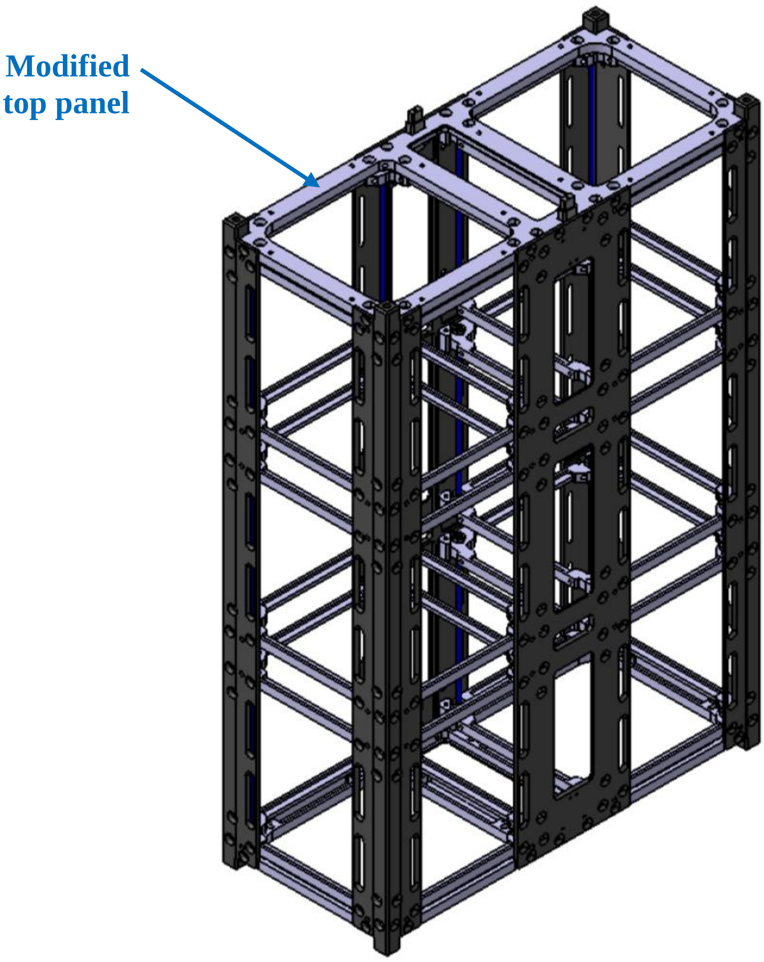


Figure 5.11 – Modularity verification

From Figure 5.11 can be seen that deployment rails, side panels, PCB stacks and whole kill-switch mechanism (including used micro kill-switch) are identical. Only component that had to be modified was top panel, since the cross-sectional area of 12U CubeSat is different from 6U CubeSat.

5.5 Analysis and check of the structure

With process of mass reduction and presented summarization being finished, it is necessary to verify that structure is still able to distribute loads, while preserving its stiffness.

Therefore, more detailed FEM analysis was performed, to determine whether structure is capable to perform as designed or if it needs to undergo any further optimalization.

For following calculations, MSC Patran and Nastran were used once again.

5.5.1 Geometry simplification

Before importing created CAD model into the FEM pre-processor, some modifications had to be done, due to model´s complex geometry.

CAD model was adjusted/simplified in the same way as in previous cases, so that afterwards there would be only smooth surfaces (only external surface, which are not affecting calculations) and PCB stacks were represented only by inner rings (Figure 5.12).

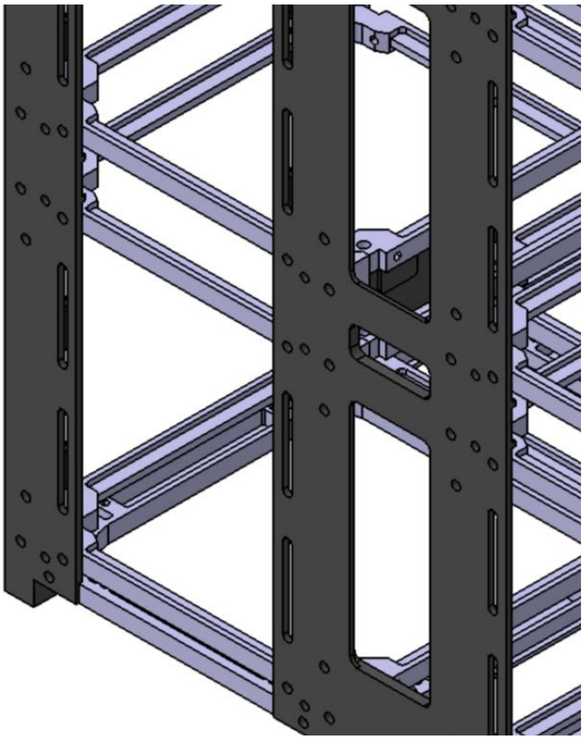


Figure 5.12 – Simplified CAD model

5.5.2 Meshing

Regarding the FEM model itself, Tet10 elements were used for structural components, 1D (beam) elements were used to substitute stack rods and 0D elements to substitute mass of payload, antennas and solar panels (Figure 5.13).

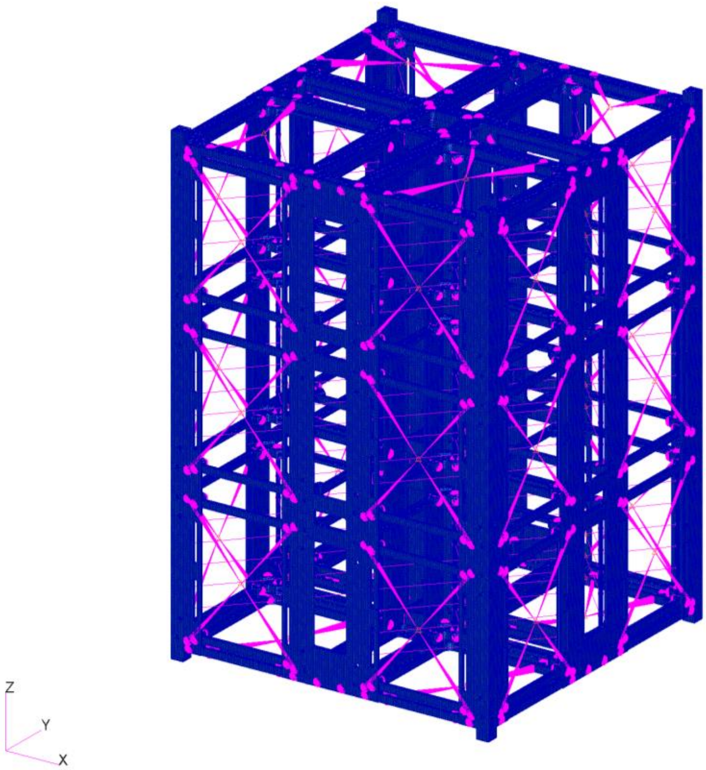


Figure 5.13 – Complete mesh of final structure

This time, all PCB stacks were detailly modelled (using 1D, 0D and RBE2 elements, as featured before in chapter *4.2.3 Meshing*), since their behaviour is of higher importance now. Solar panels and antennas were also included in FEM model, however they were substituted by 0D mass elements and connected to relevant thread wholes by RBE2 connections (Figure 5.14).

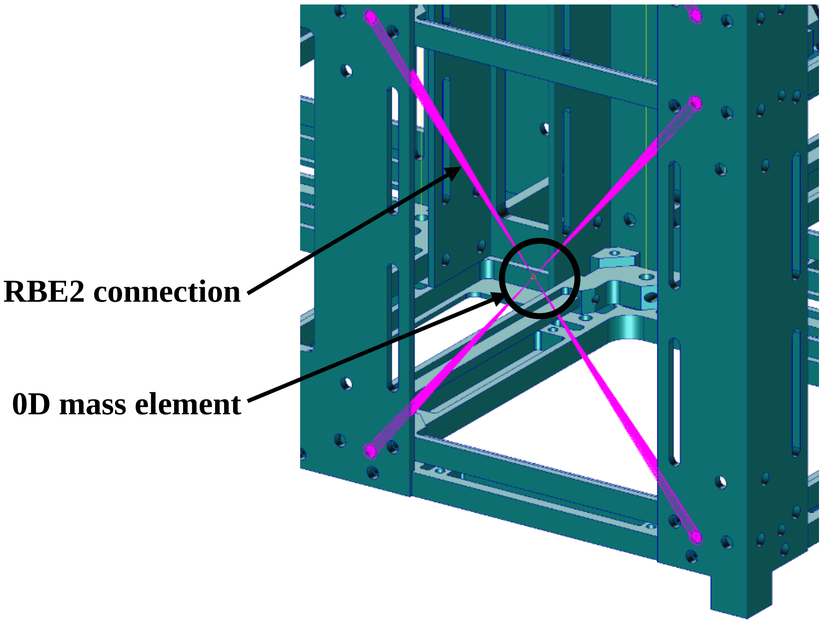


Figure 5.14 – FEM model of side solar panel

These simplifications were chosen due to the fact, that their behaviour is not interesting for following calculations and only their influence upon structure is important.

Properties (Table 5.2) were assigned to particular components in similar way as in previous calculations and total mass of created FEM model was again set to *24kg* (as it is maximum limit of optional deployers).

Table 5.2 – Used structural materials and total mass of particular components [37][38]:

Component	Quantity	Material	Total mass *[g]*
Structure (1)	/	Aluminium 6082-T651	1548 (2)
Stack rods	48	Titanium Ti-6Al-4V (Grade 5)	96
Solar panels	30	/	1500
Antennas	2	/	230
PCB boards (payload)	60	/	20640

(1) Primary structural components included (deployment rails, side panels, top panels, middle-part component and inner rings)
(2) Mass calculated by FEM pre-processor is slightly higher than the mass of detailed CAD model, due to performed geometry simplifications

As for the boundary conditions, those were set in the same way as it was in the case of previous calculations so that structure would act like it was inside of deployer (Figure 5.15).

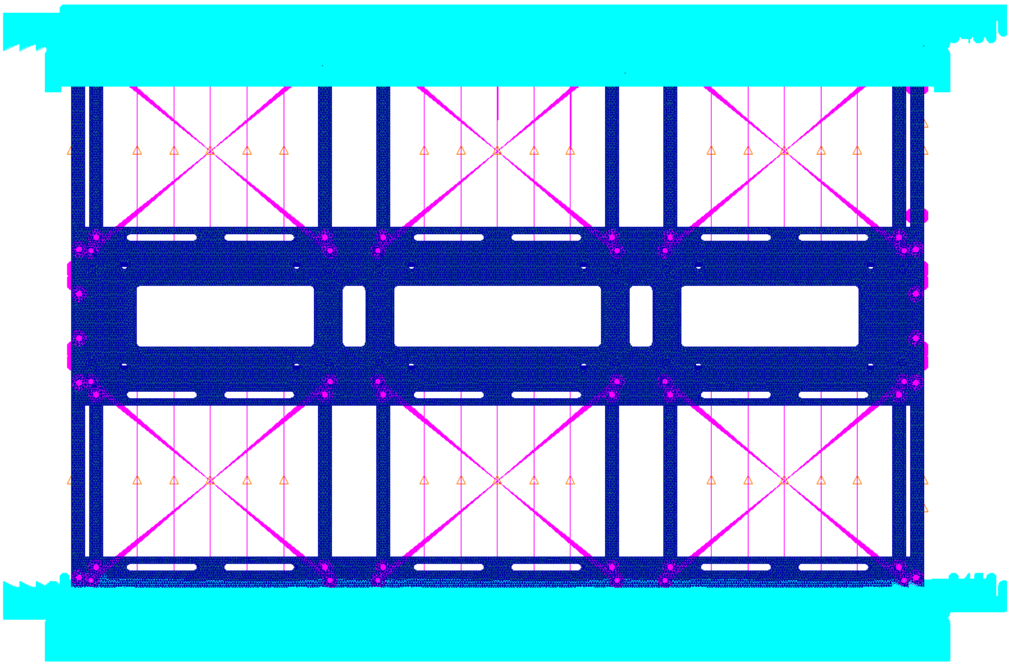


Figure 5.15 – Boundary conditions

5.5.3 Modal analysis

Most important verification of proposed structure (within the scope of this thesis) was preformation of modal analysis, as it determines structural stiffness and conclusively shows structures behaviour under dynamic loading.

As it was in previous calculations, **frequency range** of *5 – 2000Hz* was used.

This time however, 40 eigenmodes were calculated since the FEM model is more complicated, compared to previous cases (1st eigenmode is visualised at Figure 5.16). All calculated eigenmodes are shown at the Table 5.3.

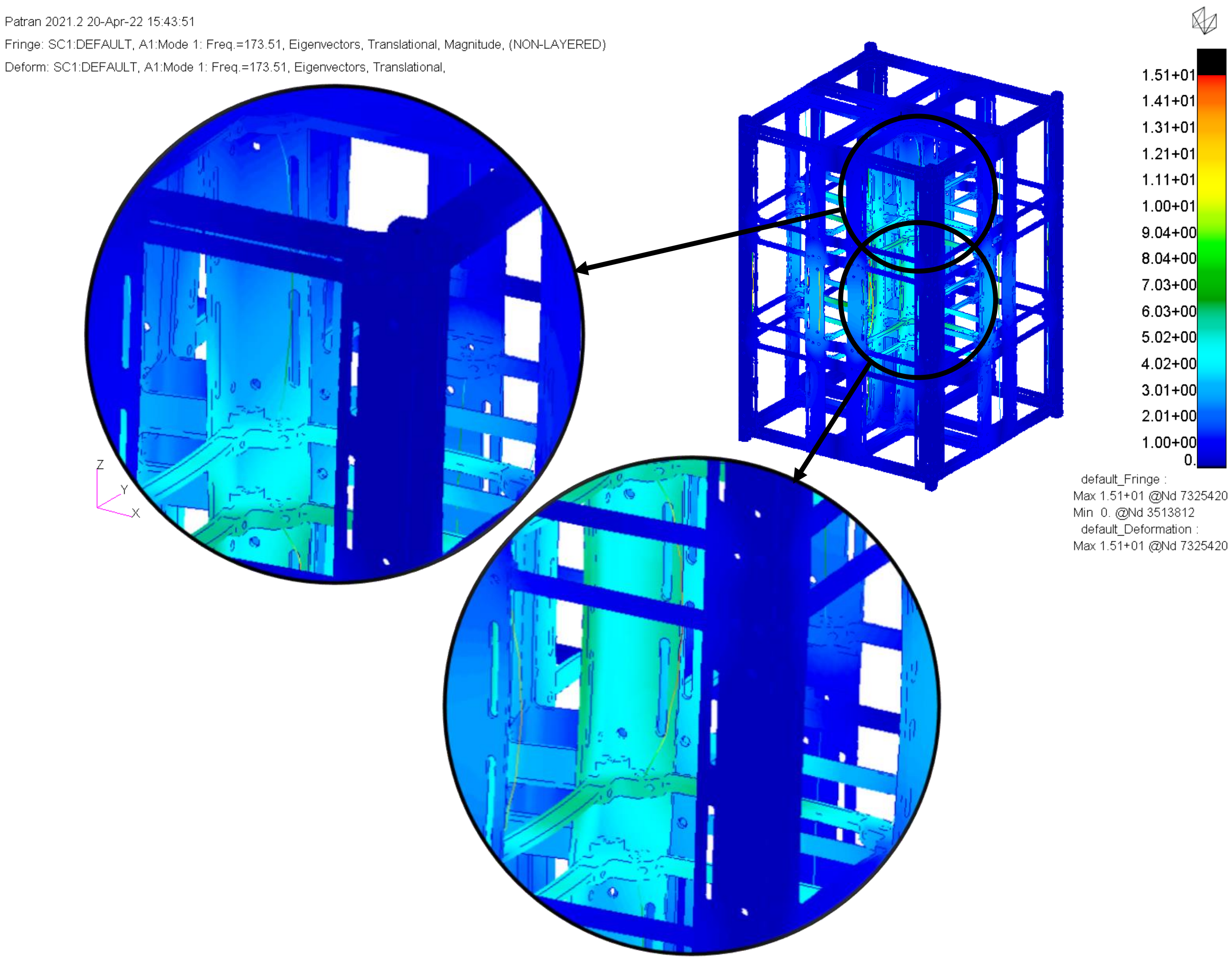


Figure 5.16 – 1st eigenmode of proposed structure

Table 5.3 – Natural frequencies of proposed structure:

Eigenmode	Natural frequency
[-]	*[Hz]*
1	173.510
2	175.622
3	176.623
4	188.258
5	188.416
…	…
10	191.396
…	…
20	195.426
…	…
30	408.751
…	…
40	415.758

From obtained results can be seen, that 1st natural frequency is equal to *173,510Hz*. This value is higher than values obtained in previous calculations (see chapter *4.3.1 PCB stack´s behaviour*). That is caused by utilization of solar panels and antennas into the calculation, which have their own mass and therefore payload´s mass had to be reduced, so that FEM model would comply with the total mass limit of *24kg*.

From Figure 5.16 can be seen that PCB stacks are behaving as expected, highest load distribution is located at the middle between 4 middle PCB stacks and middle-part component. PCB stacks located at the top and bottom are distributing load mostly between inner rings located closer to the middle and the middle-part component.

It is also clear, that at this value of natural frequency, most of the movement/oscillation will be performed by stack rods. That is shown at Figure 5.16, where inner rings are oscillating rather low, compared to stack rods (details of Figure 5.16).

In the scope of this thesis, lowest value of *115Hz* was set as a **limit value**. This was decided based on requirements prescribed for different LVs, where Vega was found to be the strictest one when it comes to natural frequency limits (these data were obtained from [40]).Therefore, proposed structure has **passed performed analysis**.

5.5.4 Quasi-static analysis

Next up is an analysis to check structure´s behaviour under **quasi-static loading.** Quasi-static loading is a combination of static and dynamic loading, caused by steady accelerations (e.g. start of rocket´s launch). The dynamic response of this loading is so small that it can be neglected. Thus, quasi-static loading can be replaced by static loading (since they are equivalent). [6] [7] [8]

This type of loading is given by quotient of structure´s accelerations and gravitational acceleration, which are all located at **CoG**, and is calculated for extreme case scenarios (based on LV). [6] [7] [8]

Table 5.4 – Strength structural requirements [40]:

Qualification method	Safety factor in respect to material´s ultimate strength
Strength analysis	2.00 x limit load
Strength test	1.25 x limit load

For following calculations, loading of *15g´s* was implemented in all axis (this value was requested by the contractor). However, this value had to be recalculated before importing into pre-processor (MSC Patran accepts values of acceleration in $mm{\cdot}s^{-2}$)(Figure 5.17).

With this knowledge, previously created mesh was slightly adjusted. Inertial loads were applied to the structure (at Figure 5.17 is shown example of inertial loading in z). This way previously defined mass of particular components will, in combination with inertial loads (so-called "**g-loads**"), created a force.

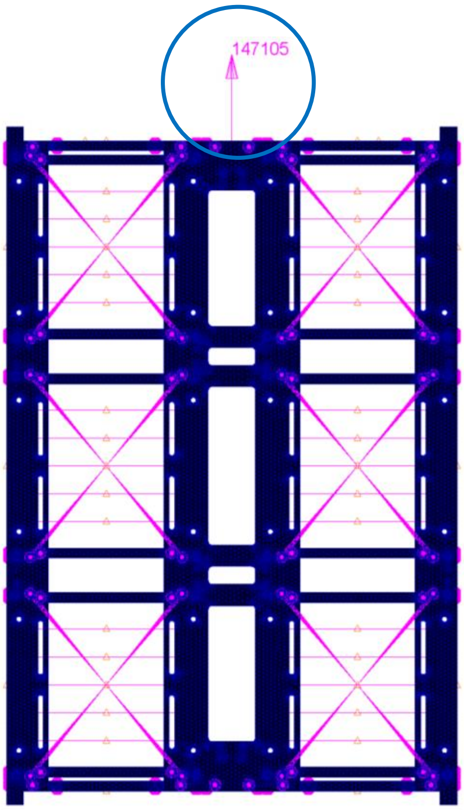


Figure 5.17 – Application of loading

At Figure 5.18 and Figure 5.19 were visualised displacements at axis y and z (each picture contains detail of exact location of maximum displacement). Calculations at axis x were not performed, since the structure is symmetrical and therefore displacement and stress results would have been the same, as for axis y.

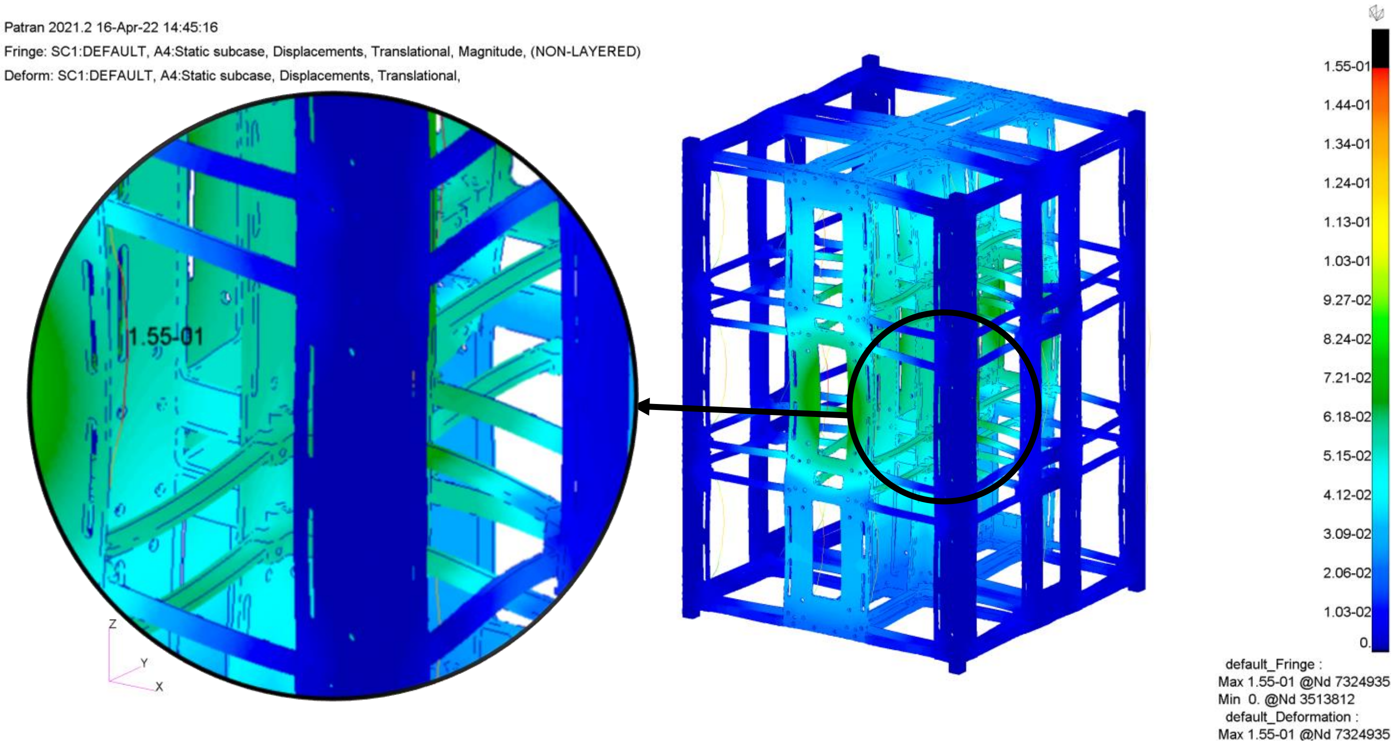


Figure 5.18 – Displacement in case of y axis loading

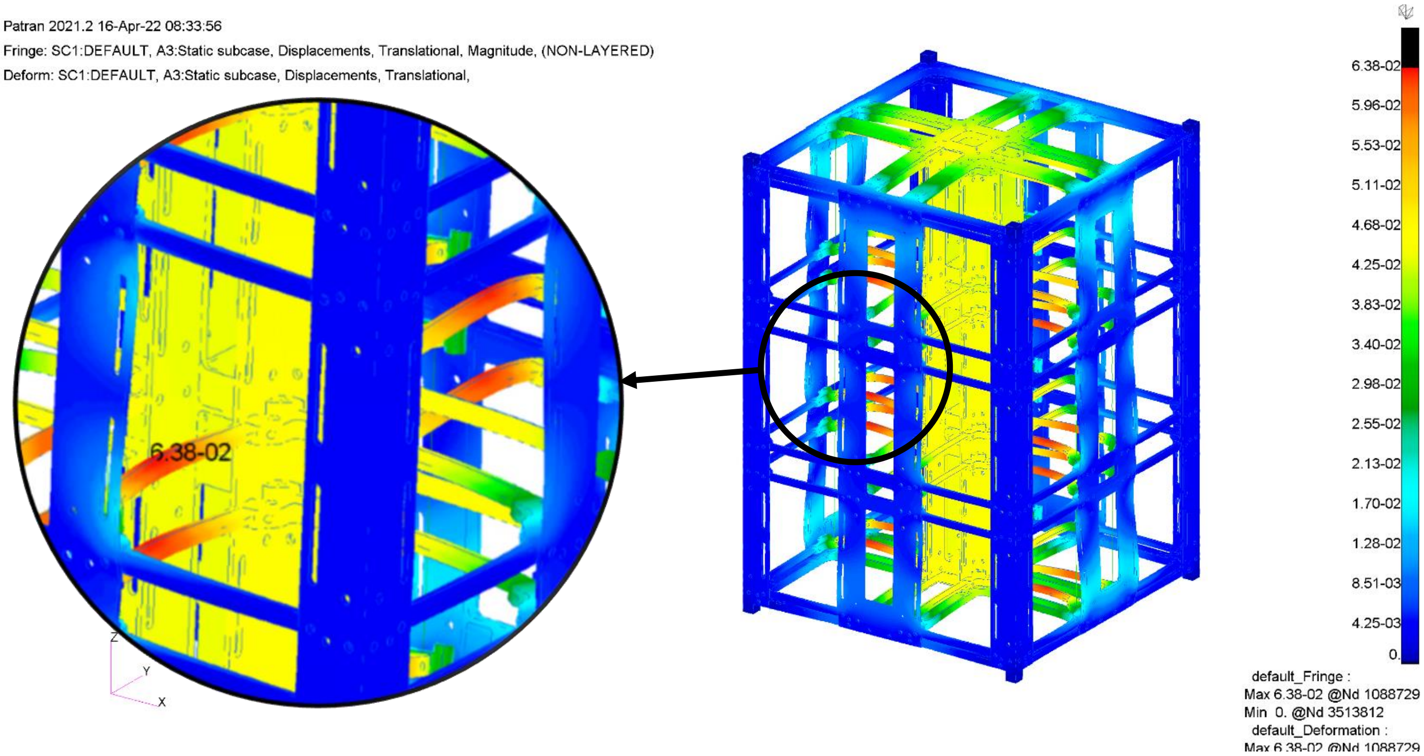


Figure 5.19 – Displacement in case of z axis loading

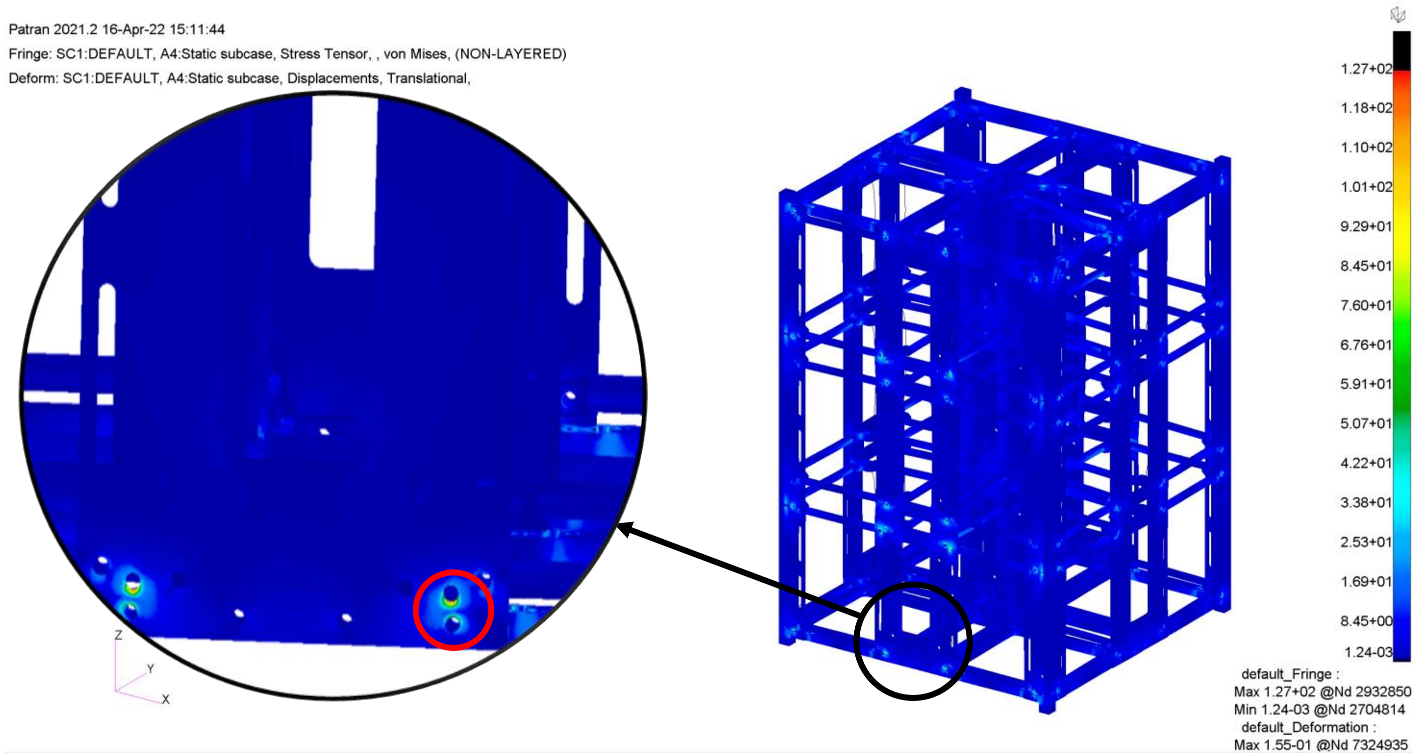


Figure 5.20 – Stress in case of y axis loading

It can be seen that the basic philosophy of the structure is still preserved. Structure is distributing loads through its middle-part component into top panels.

Maximum stress was found in the case of loading in y axis direction (Figure 5.20). It is visible that highest concentrations of stress are generally located around screw holes and locally at inner rings.

It is important to note, that by utilization of simplified screw connection (2 RBE2 elements) calculated value of maximum stress is **exaggerated** by used software (MSC Nastran). In reality this value would be lower. However, even with this knowledge, calculated value will be used, as it represents worse loading case scenario. Therefore, calculated safety factor will be lower and thus structure will be compared to higher criteria.

Within completed calculations, maximum stress and displacement had to be analysed in order to evaluate structure. Therefore, maximum value of calculated stress was compared to material´s strength limits (yield and ultimate strength of aluminium alloy 6082-T651).

All results of mentioned calculations are summarized at Table 5.5.

Table 5.5 – Analysis summary:

Applied loads	*[g]*	15 *(1)*
Maximum stress	*[MPa]*	127.000
Loading case	*[-]*	y axis
Location	*[-]*	PCB attachment screw hole *(2)*
Maximum displacement	*[mm]*	0.155
Loading case	*[-]*	y axis
Location	*[-]*	stack rods *(2)*
Safety factor in respect to material´s yield strength	*[-]*	2.126
Safety factor in respect to material´s ultimate strength	*[-]*	2.520

(1) Loads were applied at longitudinal and transversal axis
(2) Exact location is marked at attached figures

From Table 5.5 it is clear that even though maximum value of stress is quite high, lowest calculated value of safety factor is *2.126*. By comparison of this result with requirements set in Table 5.4, it is safe to say, that proposed structure has **passed performed analysis**.

5.6 Summary

From presented calculations can be seen, that designed structure would be under high loadings during the potential launch. However, structure has proven to be able to distribute acting loads quite effectively, due to its stiff design.

With its high 1^{st} natural frequency it satisfies all potential requirements (standards, launch providers, deployer providers, …). So it is safe to say that structure has passed modal analysis and it is able to provide payload with safe environment.

As for performed quasi-static analysis, even with high g-loads applied, the structure has shown high resistance to steady loads. This conclusion is supported by lowest calculated value of safety factor being higher than *2*. Thus, structure has successfully fulfilled demanded requirements in this particular analysis, despite being compared to higher criteria that necessary.

With this knowledge, performed design and its FEM verification, turned out to be **successful**. Even after structure was detailly designed and optimized, kill-switch mechanism and attachment components were introduced into the system, it preserved its capabilities and properties. Therefore, no further adjustments and optimalization were performed or needed in the scope of this thesis.

6. Evaluation of structure´s marketability

Since structure is now in presentable state, it is only fair to compare it with competing structures presented at previous market research (see chapter *2.3 Particular 12U Structures*).

6.1 Comparison with competition

It is important to point out, that not all calculations, which are needed to certify such a CubeSat, were performed in the scope of this thesis and not all information regarding competing structures are available (such as natural frequencies, structure´s behaviour under loading, production complexity, …).

So structures will be compared **only based on parameters that are available** and in their default constellation (optional modifications were neglected, as they are depended upon specific requirements). That will conclude structure´s dimensions, mass, features and properties that will directly affect potential customer (Table 6.1).

Table 6.1 – Comparison of proposed structure with competition:

<table>
<tr><th colspan="2">Structure</th><th>Proposed design</th><th>ISISPACE</th><th>SM12</th></tr>
<tr><td colspan="2">Primary mass (1) [g]</td><td>1486</td><td>1500 (+0,942%)</td><td>1430 (-3,769%)</td></tr>
<tr><td colspan="2">Total mass [g]</td><td>1716</td><td>2000 (+16.550%)</td><td>1750 (+1.981%)</td></tr>
<tr><td colspan="2">External dimensions [mm]</td><td>226.3x226x3x340.5</td><td>226.3x226x3x340.5</td><td>226.3x226x3x340.5</td></tr>
<tr><td colspan="2">Kill-swich mechanism</td><td>YES</td><td>YES</td><td>YES</td></tr>
<tr><td rowspan="3">PCB stack orientation</td><td>Vertical (default)</td><td>YES</td><td>YES</td><td>YES</td></tr>
<tr><td>Horizontal</td><td>YES</td><td>YES (2)</td><td>YES</td></tr>
<tr><td>Adjustable length (3)</td><td>YES</td><td>YES (4)</td><td>YES (4)</td></tr>
<tr><td colspan="2">Accessibility (5)</td><td>High</td><td>Low</td><td>Medium</td></tr>
<tr><td colspan="2">Simplicity (5)</td><td>Medium</td><td>High</td><td>Low</td></tr>
</table>

(1) Stack rods, matrixes and PCB mounting elements are not included
(2) Only for modified PCB stacks only
(3) Only for vertically integrated PCB stacks
(4) Restricted in default structure option
(5) Feature has been assigned score point, where high is worth 3 point, medium 2 points and low 1 point

From presented table it is clear that as for the **total mass**, which includes secondary mass (stack rods, PCB mounting elements, …), proposed structure came out as the most beneficial option. It is lighter by *1.981%* compared to SM12 structure and by *16.550%* to ISISPACE structure, which are both satisfying results, because more payload´s mass can be integrated.

As for the external dimensions and kill-switch mechanism, all of presented structures are the same, so these parameters will not have an influence upon comparison.

Another feature of high importance is an **optional integration of PCB stacks**, where all 3 structures are offering vertical orientation as a default option. However, for other optional orientations they differ.

For example, in case of horizontal orientation, ISISPACE structure is abusing modified PCB stacks, which is an increase in total amount of needed components. Other structures do not carry the same disadvantage and therefore, are considered superior in this context.

As for the adjustable length of PCB stacks, ISISPACE and SM12 structures are slightly restricted, regarding this feature. Proposed structure, on the other hand, offers comfortable adjusting of PCB stacks (shortening and prolonging), which makes a assembling a lot easier and more comfortable.

As for the **accessibility**, proposed structure is the number one choice by far. Thanks to its middle-part component it offers easy access to integrated payload (see chapter *4.1.2 Version 1*). Therefore, even more complex adjustment can be made, before assembling whole structure.

When considering structure's **simplicity**, manufacturing and assembling processes were both included. However it is important to point out, that both of these parameters were considered mostly from design engineer point of view and potential material´s loss, since no specific data are provided by competition regarding this subject (before signing a formal contract).

Out of all compared structures, ISISPACE structure was determined to be the simplest one, because of its utilization of plates at structural design. Therefore potential material loss will be lowest.

6.2 Summary

After taking in count all presented parameters, **proposed structure** was proclaimed to be **the most beneficial option** out of all compared structures. This decision was made strictly based on presented parameters of which, the proposed structure was either equal or even superior compared to other structures. Only parameter, that the proposed structure lacks is manufacturing simplicity, because of its high material loss (at its middle-part component).

Discussion and recommendations

Presented structure was designed in accordance with prescribed requirements to fulfil compulsory CubeSat standards and requirements based on performed market research and to satisfy requirements of the contractor (VZLÚ).

Even though only "default" version of proposed structure was designed, structure was created, so that potential modifications were easy to implement (since it is expected that structure will be modified in further development). For example, if different components were attached to external frame (from the outside), it would be rather easy to change hole spacing without major effect upon the structure.

An issue that was found in structural design, was usage of titanium stack rods. Originally, they were used, because of their low mass, high strength and based on recommendations and experience of the contractor. However, it is generally known fact that titanium is much more expensive than stainless steel, which is otherwise used for stack rods in CubeSat industry.

Therefore, further calculations should be performed, this time with stainless steel stack rods. So that it could be truly evaluated whether implementation of titanium stack rods is indeed needed or even worth it (based on price/performance ratio).

Speaking of calculations, structure was proven to be strong and stiff enough (in the scope of modal and quasi-static analysis) to protect the payload. Even though the structure was checked, thus one of the goals of this thesis was fulfilled, it would be optimal and for further development even necessary to perform further calculations (sine, random vibration and shock analysis).

These calculations could potentially discover structure´s deficiencies, that could lead to another optimalization process.

After that structure would have to be manufactured and tested so that calculations could be verified, which would eventually lead to its certification. This would also provide an inside of financial estimation of structure´s price.

Lastly it is important to address presented comparison of proposed structure with competition. It was already mentioned that this comparison was performed only based on available data and that the proposed structure came out as a winner, strictly based on compared parameters.

With further calculations, optimalizations, potential manufacturing and testing of the proposed structure, the comparison should be performed again, this time with consideration of wider spectrum of parameters.

For further development is recommended to:

- Perform additional calculations to verify structure´s behaviour under vibrational and shock loadings

- Perform calculations of more payload´s integration cases, where PCB stacks would be integrated in different directions and in case of vertical orientation, their length would be either reduced or increased.
- Perform calculations with stack rods made out of stainless steel to verify, whether it is possible to utilize them and to check their price/performance ratio compared to used titanium stack rods.
- Manufacture and test structure in accordance with standards to check analysis results
- Perform more detailed comparison of proposed structure based on more data (price, certification, …)

Conclusions

VZLÚ has recently began its integration into the CubeSat commercial industry by development of series of 1U – 3U CubeSat structures. This thesis was written in cooperation with VZLÚ, and its purpose is to help with development of larger CubeSat structures (12U CubeSat).

Market research was performed to evaluate options and create list of requirements regarding 12U structural frames and analyse their design. This research was extended by optional dispensers (developed by European companies), which increased amount of data gathered in created list.

Following preformed competition research, an entire chapter was dedicated to summarization of initial data for following design. That helped to evaluate possible options regarding structural materials, dimension envelopes (internal and external), which provided a first look at the design of 12U CubeSat structural frame.

Within information platform being created (market research, design assumptions, …) a conceptual design was presented. Attachment system for payload´s integration (PCB stack) was created first as it directly affects design of particular components (hole spacing, nominal thicknesses, …).

That led to introduction of 3 designed structural approaches. All of proposed structures were designed in different way to evaluate which approach would be the most optimal one. Even though design features were ready to be compared, structural stiffness and strength could not be conclusively compared, due to complex geometry of proposed structures. Therefore a modal analysis was used to determine, which structure would provide highest stiffness. Thanks to performed FEM analysis, all qualitative parameters, to compare proposals, were available.

From the comparison, 1st version came out as the most beneficial approach. Therefore, it was decided to design the structure in more details. Structure was adjusted for integration of so-called kill-switch mechanism and attachment of other components (solar panels, antenna systems, …).

These modifications were followed by a process of optimalization, so-called “mass reduction”, since total mass of the structure was significantly higher than competition.

Right after optimalization of the structure, more detailed round of FEM calculations was performed. These calculations included modal analysis, to verify structural stiffness, and quasi-static analysis, which provided an information of structure´s behaviour under steady acceleration loading. The structure turn out to be resistant and passed performed calculations, which meant there is no need for further design modifications and structural design, including its check, were considered finished.

Proposed structure was then evaluated in context with competing structures, which were introduced in previously performed market research. This comparison was done strictly based on presented parameters, from which proposed structure came out as a most optimal solution.

Following this comparison, engineering discussion and a list of recommendations, for further development, were created to increase quality of designed structure. However, assigned goals of this thesis were successfully completed.

Lastly, drawing documentation was created, based on request of the contractor. That included drawings to support potential manufacturing and assembling process of the structure. Regarding this thesis only drawing of 12U CubeSat assembly was included (it can be found in the appendix list).

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List of abbreviations and symbols

CAD	Computer Aided Design
Cal Poly	California Polytechnic State University
CDS	CubeSat design specification
CoG	Centre of Gravity
ESA	European Space Agency
FEM	Finite Element Method
g	gravitational acceleration
ISS	International Space Station
LV	Launch Vehicle
MPC	Multipoint constraint
NASA	National Aeronautics and Space Administration
PCB	Printed Circuit Board
RBE	Rigid Body Element
SSDL	Space Systems Development Laboratory
Tet	Tethedral
U	CubeSat unit
0D	non-dimensional
1D	one-dimensional
3D	three-dimensional

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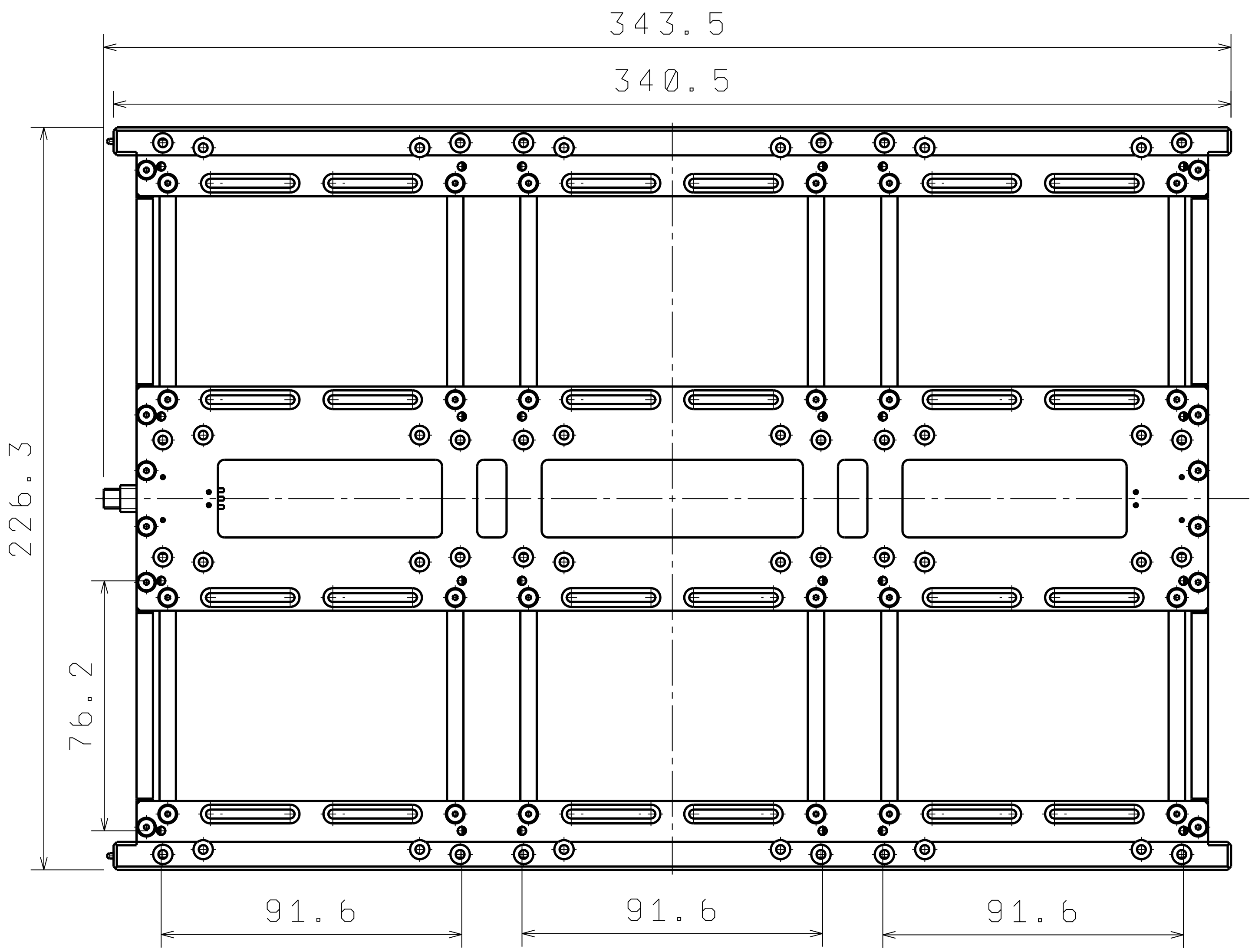
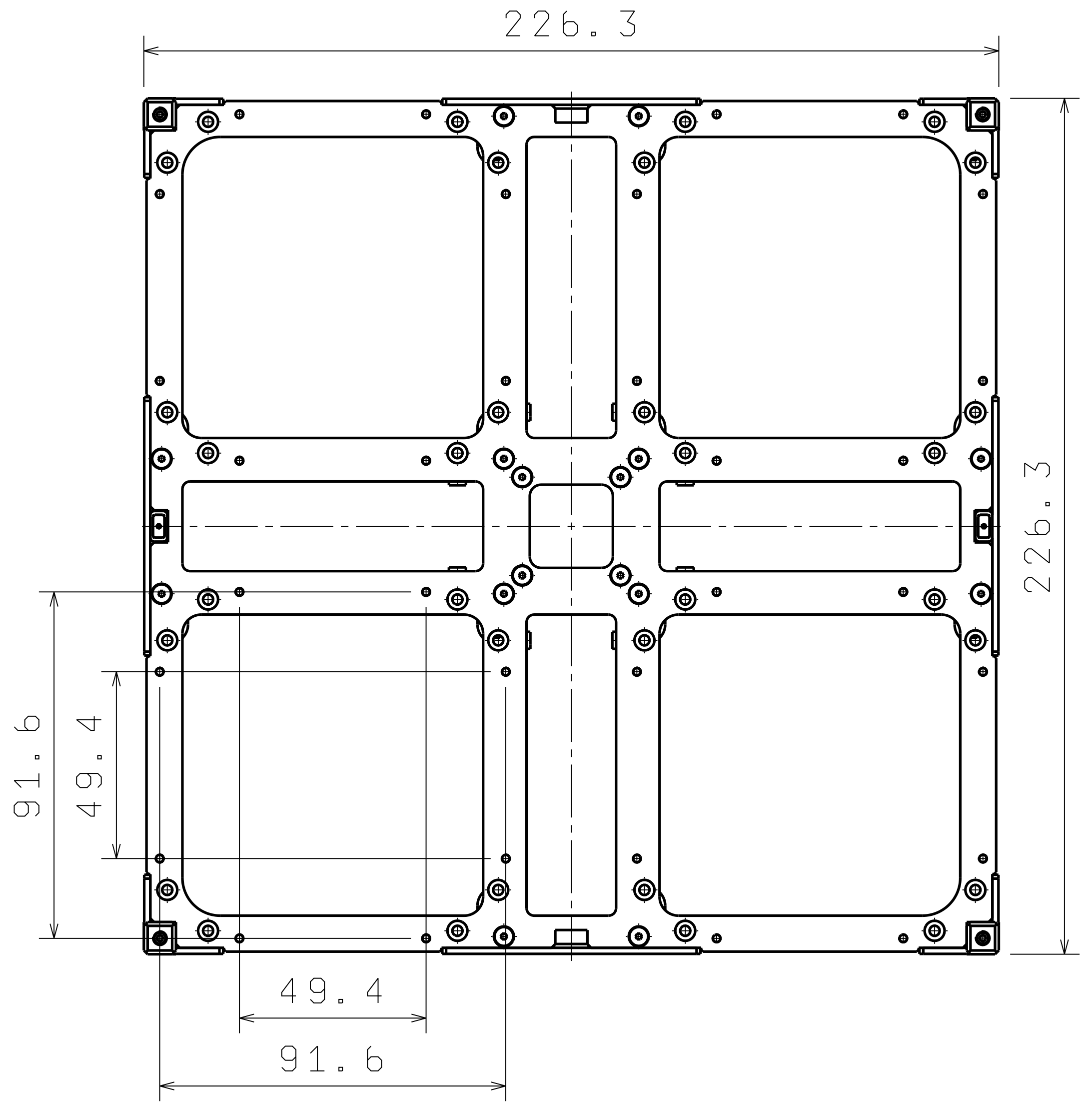
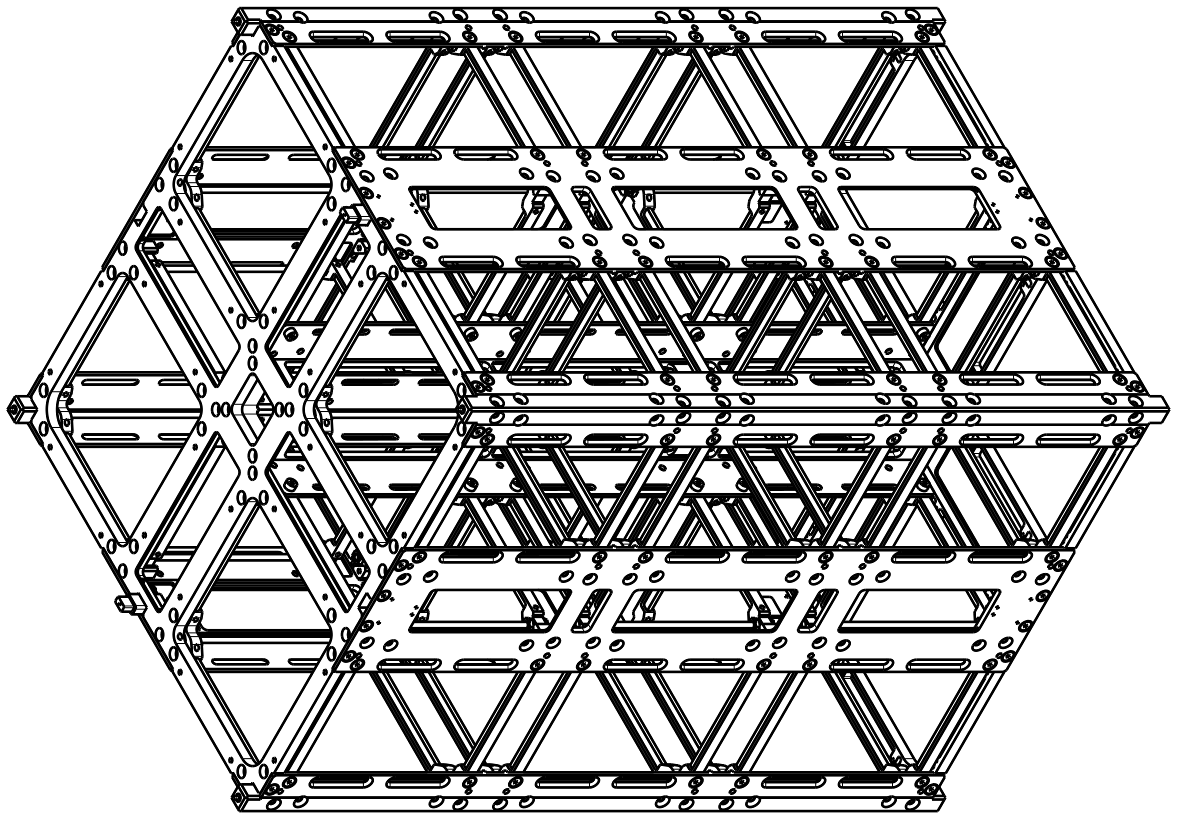
Appendix list

Appendix A - 12U CubeSat structure drawing







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CELKOVÉ ROZMĚRY 226.3x226.3x343x5		VÝCHOZÍ DOKUMENT (3D MODEL) 12UCubeSat structural frame_12UCubeSat structural frame_v9-A		
KRESLIL Matěj Kopecký	DATUM 25.4.2022	NAZEV 12U CubeSat structure		
SCHVÁLIL Milan Junas	DATUM 6.5.2022	FORMAT A3	ČÍSLO VÝKRESU IAE/CS-12CubeSat_v9/13-A	REV 1
NAVRHNUL Matěj Kopecký	DATUM 25.4.2022	MĚŘÍTKO 1:2	HMOTNOST (kg) 1.716	STRÁNKY 1/1