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FACULTY OF MECHANICAL ENGINEERING

FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AEROSPACE ENGINEERING

LETECKÝ ÚSTAV

DESIGN PROPOSAL AND ANALYSIS OF THE 3D PRINTED 1U CUBESAT FRAME

NÁVRH A ANALÝZA 3D TISKNUTÉHO 1U RÁMU DRUŽICE TŘÍDY CUBESAT

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

AUTHOR Bc. Ondřej Kilián

AUTOR PRÁCE

SUPERVISOR Ing. Václav Lazar

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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 and analysis of the 3D printed 1U CubeSat frame

Brief Description:

1U („one–unit") CubeSats are small satellites with the unified dimensions about 100x100x100 mm and weight up to 1.3 kg. Recently, the 3D printed materials were used for the structural parts of these satellites. A Fused Deposition Modelling (FDM) printer located at International Space Station increases the potential of the 3D printed parts to be used for the satellite´s structure. However, an appropriate material selection, design modifications and it´s analysis is crucial for the further development.

Master's Thesis goals:

1) Review of the utilization of the 3D print considering CubeSat construction.
2) Selection of the suitable materials for the space applications, printable with the FDM 3D printers.
3) Design proposal of the 3D printed 1U CubeSat frame.
4) Structural analysis of the proposed frame design.

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. Director of the Institute	doc. Ing. Jaroslav Katolický, Ph.D. FME dean

ABSTRAKT

Tato diplomová práce se zabývá tvorbou a následnou analýzou 3D tisknutého rámu pro satelit třídy CubeSat. Tento CubeSat je konstruován podle standartu „CubeSat Design Specification" z Kalifornské polytechniky revize 14. Unikátní přístup, jakožto použití 3D tisknutého plastu je bude potřeba podrobit následným reálným testů které nejsou v rámci této diplomové práce, jelikož použití 3D tisknutých plastů není zahrnuto v tomto standartu. Modelování a tvorba podpůrných materiálů pro generaci G-kódů a pro následnou MKP analýzu je provedeno v programu Autodesk Inventor Pro 2020. Tyto podpůrné materiály jsou ve formátu STEP. G-kódy pro 3D tisk jsou tvořeny v programu PrusaSlicer 2.4.1. MKP analýza je provedena v programu MSC Patran a MSC Nastran kde generace sítí, zavádění sil a umístění okrajových podmínek je použit program MSC Patran. Následná řešení je provedeno v řešiči MSC Nastran a poté interpretace výsledků je provedena díky vizualizacím zpět v programu MSC Patran. Celkový design je považován za úspěšný, jelikož splňuje veškeré požadavky na něj kladené a zároveň je adekvátně zkonstruován, aby vydržel zatížení na něj kladené během vypuštění na oběžnou dráhu kolem země.

ABSTRACT

This thesis contains the process of design and subsequent FEM analysis of a CubeSat class satellite with accordance to the "CubeSat Design Specification" from Californian Polytechnic State University revision 14. The software used for the design and generation of supportive materials is the Autodesk Inventor Pro 2020, generation of the G-code for printing is done in the PrusaSlicer 2.4.1. software and the analysis are done in the MSC Pantran and MSC Nastran software package. The overall design is considered as successful as it meets all the criteria, and the analysis shows that it can withstand the loads present in the launch process to the earth's orbit.

KLÍČOVÁ SLOVA

CubeSat, satelit, MKP analýza, 3D tisk, rám satelitu, PEEK

KEYWORDS

CubeSat, Satellite, FEM analysis, 3D printing, satellite frame, PEEK

ROZŠÍŘENÝ ABSTRAKT

Tato práce se zabývá řešením konstrukčního zadání satelitu třídy CubeSat velikosti 1U. Tento satelit je zkonstruován podle standartu „CubeSat Design Specification” z Kalifornské polytechniky revize 14. Tento standart stanovuje velikost ližin CubeSatu na 100x100x113,5 mm a stěny X a Y mohou přesahovat rovinu ližin o 6 mm v daném směru. Standard udává použití materiálu na rám CubSatu hliníkové slitiny, ale povoluje použití i jiných materiálů, pokud bude prokázána nezávadnost a nemožnost kontaktního svaru s ližinami dispenzoru a neovlivnění dalších CubeSatů a jejich vybavení. Vnitřní rozměry jsou stanoveny sadou požadovaného vybavení, které vychází z projektu mého vedoucího a jeho týmu BUTCube.

Konstrukce

Tento rám CubeSatu je koncipován tak, že má PCB „stack“ postaven ve směru osy Z CubeSatu a je připevněn k hornímu a spodnímu panelu. Celkový rám se skládá ze šesti panelů, kde panely +-X a +-Y jsou totožné a zdvojené. Horní a spodní panely jsou odlišné kvůli koncepci integrální klece na PCB „stack“. Na každém panelu se nachází přimontován jeden solární panel (pro X a Y panely jsou jiné solární panely než pro panely horní a spodní) a centrální vybavení panelu které jsou připevněny šrouby s šestihrannou hlavou M3 různých délek záležící na centrálním vybavení. Toto vybavení se skládá ze čtyř detektorů slunečního záření, které se nacházejí na panelech +-X, -Y a -Z, jednoho panelu s konektory, který se nachází na +Y panelu, a sestavy kamery, která se nachází na +Z panelu. Integrální klec na PCB „stack“ je zkonstruován z horního a spodního panelu (+Z a -Z panely), čtyř šroubů s kuželovou hlavou M3x100, distančních trubiček dané velikosti k zajištění správné separace pěti deskami s plošnými spoji (PCB). Tato podsestava se následně zasune do rámu tvořeného ostatními čtyřmi panely, které tvoří objímku přenášející zatížení do ližin dispezoru. Další podsestavou je sestava kamery, která se skládá z kamery samotné a adaptéru pro centrální pozici panelu rámu, což umožňuje použití různých kamer pouhou změnou adaptéru. Poslední podsestavou je sestava kill switche, která zajišťuje prevenci nechtěného spuštění CubeSatu při jeho vypuštění na požadovanou oběžnou dráhu.

Výroba a kompletace

Všechny vyráběné komponenty byly navrženy tak aby se dali co nejjednodušeji vyrobeny metodou 3D tisku za použití nejmenšího množství podpor. Toto bylo dosaženo tím, že je pro každý panel designovaná jedna stěna s minimálním počtem tvarových prvků k dosažení jedné hladké stěny, která bude sloužit jako základová vrstva při tisku. Materiál použitý pro tisk je Victrex® PEEK 450G, který má vysoké termální a mechanické vlastnosti v homogenní formě a jsou pro něj i dostupné

mechanické vlastnosti v 3D tištěné formě a doporučené nastavení tisku. Generace G-kódu byla provedena v programu PrusaSlicer 2.4.1. Jednotlivé panely jsou spolu spojeny lepidlem Master bond EP29LPSP, které je určeno pro vesmírné použití a má pro to potřebné certifikace.

MKP analýza

Příprava MKP analýzy byla provedena v programu MSC Patran a následné řešení bylo provedeno v řešiči MSC Nastran. Celkové řešení je prováděno jako lineární kvůli malé deformaci panelů, kde maximální deformace byla naměřena $3{,}6616 \cdot 10^{-4}$ mm. Díky vysoké symetrii rámu bylo možné zmenšit počet zatížení na pouhý 7 případů. Prvky použity pro vytvoření MKP sítě jsou prostorové prvky Tet4 s maximální délkou hrany 7 mm a méně pro citlivé oblasti jako díry pro šrouby nebo styčné lepené plochy mezi panely, které byly modelovány jako roviny. Zatížení bylo vyvoláváno ve středech gravitace jednotlivých komponentů o velikosti zrychlení 6 g. Propojení mezi těmito středy gravitace komponentů a jejich upevňovacími body je provedeno přes MPC RBE 2 prvky. Okrajové podmínky byly zavedeny do kontaktních ploch ližin CubeSatu, které působily proti zavedenému zatížení. Z analýzy vyšlo že maximální zatížení působící na rám je v místě připevnění PCB „stacku“ k hornímu a spodnímu panelu a toto zatížení činí 8,56 MPa, což je pod hranicí maximálního zatížení i pro směr vrstev tisku.

Závěr

Rám CubeSatu byl navržen úspěšně a splňuje veškeré požadavky na něj kladené, jak z geometrického hlediska, tak i z hlediska zatížení. Připevnění veškerého vybavení je splněno a navržení všech potřebných konstrukčních uzlů bylo též splněno.

BIBLIOGRAPHIC CITATION

KILIÁN, Ondřej. Návrh a analýza 3D tisknutého 1U rámu družice třídy CubeSat. Brno, 2022. Dostupné také z: https://www.vutbr.cz/studenti/zav-prace/detail/139816. Diplomová práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Letecký ústav. Vedoucí práce Václav Lazar.

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DECLARATION OF AUTHORSHIP

I, Bc. Ondřej Kilián, declare that this master's thesis is my own work and the result of my own original research. I have clearly indicated the presence of quoted or paraphrased material and provided references for all sources.

Brno, 20.05.2022 ……………………………………………………

Bc. Ondřej Kilián

Table of contents

1. Introduction

The goal of this thesis is the design and subsequent analysis of a 3D printed CubeSat frame that can support a set of given equipment paraments which include the solar panels and solar detectors, interface panel and the PCB (printed circuit board) stack. The design is done in compliance with the Cal Poly CubeSat standards rev. 14.

The subsequent analysis will be done with MSC Patran and MSC Nastran software where the meshing will be done in MSC Patran and then MSC Nastran will be used as a solver. Then the results will be the interpreted back in the MSC Patran. The supportive 3D models for the analysis will be created in Autodesk Inventor Pro 2020 and they will be exported into STEP and the STL format for respective uses. These files will be used also for the generation of the G-codes for printing processes.

The main inspiration for this project is the 3D printing CubeSat project of ESA (European Space Agency) that focuses on the development and implementation of 3D printed CubeSat bodies for cheaper and faster missions. Also, the aim of this particular design is the ability to be manufactured, assembled and launched from the ISS (International Space Station) and also to be able to be launched in a standard way via a rocket.

2. Research

2.1 CubeSat overview

CubeSat is type of picosatellite defined by standardised specifications for ease of delivery to desired destination (low to high planetary orbits, deep space exploration). This delivery is done by standardised dispensers for example P-POD, ISIPOD, CSD and other specialised dispensers that can carry multiple CubeSats at once or only one of the maximal size its designed for. Sizes of CubeSats are given in “Unit” sizes (1U, 2U, 3U,…) that are included in universal standards from Californian Polytechnic State University (CDS Rev. 14) (1).

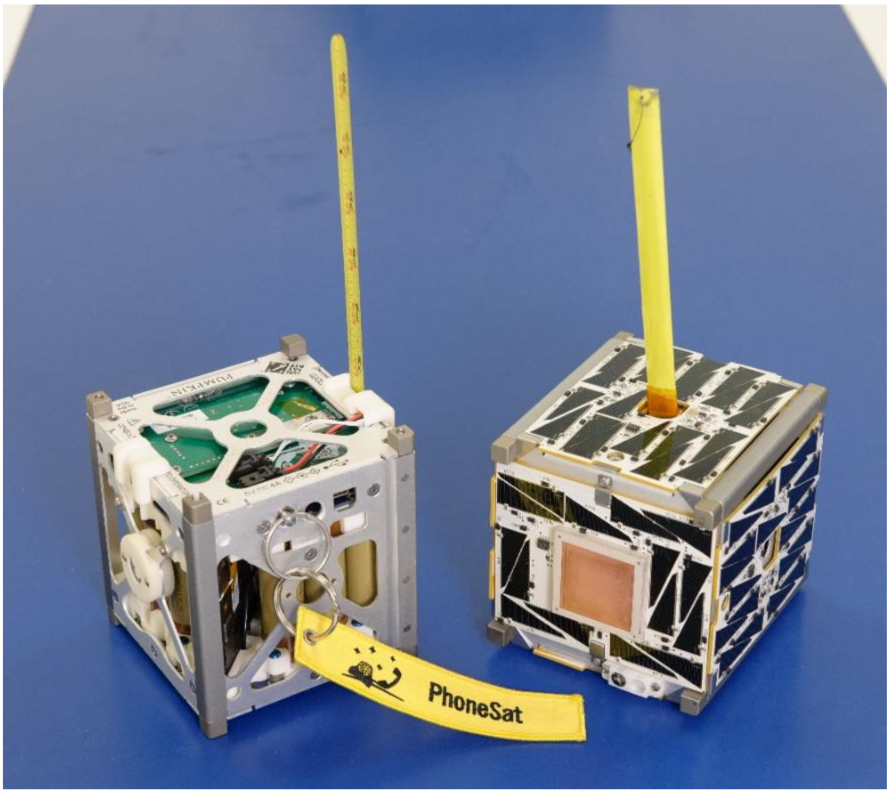


Figure 1 1U CubeSats (10)

One unit (i.e. 1U) is defined as a cube of 100 x 100 x 100 mm with rail extension in Z axis of 7 mm in Z+ and 6,5 mm in Z- directions (1). The smallest CubeSats are 0,25U (25 x 25 x 25 mm) and the largest can by up to 27U (300 x 300 x 300 mm) and anything in between. (1) The basic purpose of a CubeSats frame is to interface all the internal and external parts of the CubeSat such as the payload, external deployable and static solar panels, and its support systems and furthermore it makes contact with the dispenser in which it’s carried. The majority of the parts, like solar panels, other power components or instruments, can be bought from other manufacturers thanks to the high level of standardisation. This approach can significantly lower the price for single unit.

2.2 Standards

The standard used in design of this CubeSat frame is “CubeSat Design Specification” from Californian Polytechnic State University which is recognised by NASA (National Aeronautics and Space Administration) and ESA (European Space Agency). The most important sections for my design process are 3.1 “General Requirements”, 3.2 “CubeSat Mechanical Requirements”, appendix B, section 1 “1U CubeSat Design Specification Drawing” and appendix C, section 1 “1U CubeSat Acceptance Checklist” which are defining dimensions, loads and materials for frames of CubeSats. (1) In addition, each agency has its own additional standard and guidelines that outline preferred design choices in hardware and software used on these crafts. These additional guidelines are especially important if there is a necessity for interlink compatibility with other old and/or new satellites and infrastructure.

2.3 Materials

2.3.1 Standard aluminium alloys

Section 3.2.15 of CubeSat Design Specification states that “Aluminum 7075, 6061, 5005, and/or 5052 will be used for both the main CubeSat structure and the rails.” then section 3.2.15.1 allows use of other materials if proper procedure is adhered to and DAR (Deviation Wavier Approval Request) is submitted. (1) From this it can be derived that 3D printed materials might be viable if proper testing is conducted.

Material	Tensile strength Rm [MPa]	Yield strength Re [MPa]	Elongation ε [%]	Young’s modulus E [GPa]	Poisson’s ratio μ [-]
EN AW-7075	530	470	8	71,7	0,33
EN AW-6061	290	250	9		
EN AW-5005	165	120	4		
EN AW-5052	195	89,6	7		

Tab. 2-1 Mech. properties of aluminium alloys (2)

The main reason why aluminium is dictated to be the material of choice is to prevent friction and contact welding. These phenomena can occur for example when two pieces of steel contact each other while their oxide layer was previously removed by rubbing and scraping the oxide layer of outside the earth atmosphere where the oxide layer has no chance of reforming. These problems may occur especially on contact surfaces of rails on the CubeSat and the dispenser. Therefore, aluminium alloys are preferred.

2.3.2 3D Printed materials

The first category of 3D printed materials are 3D printed metals which would be ideal for this application as they provide nearly the same material characteristics as standard metals with a bonus of creating light and rigid structures, unfortunately these materials are not printable in micro gravity as these materials are created through powder metallurgy.

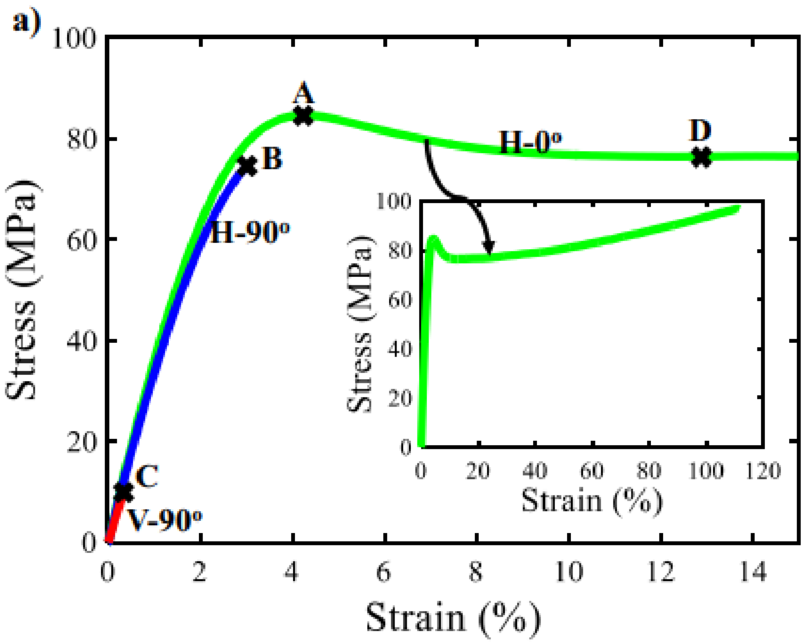


Figure 2 Stress-strain diagram of the tested material (3)

Second category of materials are 3D printed plastics which can be divided into low printing temperature plastics such as PETG, PLA, PVB that are printed at 210-270°C and high printing temperature plastics such as PEEK that is printed at around 410°C. The low printing temperature plastics are great at hobby level projects but are unsuitable for this application. This is where high temperature plastics may come into use. PEEK is a lightweight material with tensile strength between 72-83 MPa depending on the orientation of the layers. The printing method for PEEK is FDM (filament deposition method) which is also used to establish the mechanical properties in tab. 2-2. (3)

Layer orientation	H-0°	H-90°	V-90°	PEEK 450G
Young's modulus, E_t [GPa]	3,8 ± 0,03	3,54 ± 0,05	3,03 ± 0,01	4,0
Tensile strength, σ_m [MPa]	82,58 ± 1,03 (at yield)	72,88 ± 1,92 (at break)	9,99 ± 0,94 (at break)	98 (at yield)
Tensile elongation, εb [%]	110,97 ± 5,31	2,91 ± 0,14	0,33 ± 0,03	45
Poisson's ratio, ν [-]	0,44 ± 0,02	0,43 ± 0,01	0,37 ± 0,005	-

Tab. 2-2 Victrex® PEEK 450G mechanical properties for different layer orientations (3)

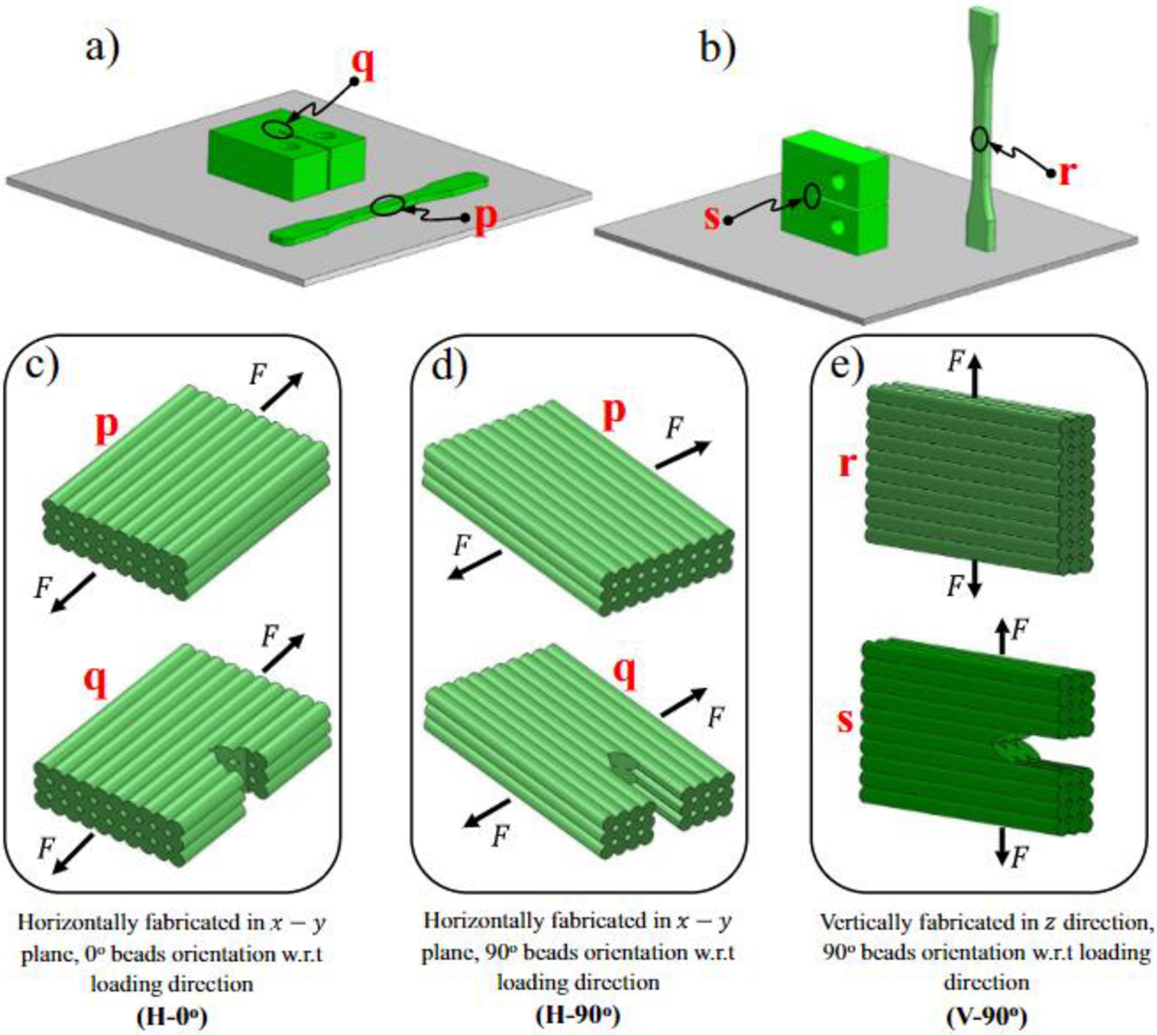


Figure 3 PEEK layer orientation (3)

2.3.3 Adhesive solutions

Adhesive compounds used in aerospace applications must pass a set of standards similar to materials and other equipment. The major concern is the outgassing of the material in space to limit any potential influence of these compounds on the sensory equipment of surrounding CubeSats or any other machinery. (1) Therefore, there are special adhesives developed for aerospace industry that pass these standards.

Master bond EP29LPSP

This two-part adhesive epoxy compound is a specially developed adhesive compound for PEEK parts that is NASA ASTM E595 compliant (low outgassing) which makes it the perfect candidate for application in this project. Also, it's able to withstand cryogenic temperatures up to 4K is electrically insulative. Alternatives are also EP21LVMed and LED403Med that are used in medical applications. (4)

2.4 Internal systems

Internal systems of a CubeSat widely vary from mission to mission to accommodate necessary equipment to collect desired data. Some CubeSats can be equipped with devices to collect atmospheric data in lower to higher orbits of earth or other planets, or to detect electromagnetic radiation in visible and non-visible spectrum and other uses. Included in these internal systems has to be support equipment for the devices stated earlier to supply power (Batteries, solar panels), stabilise and direct the CubeSat (usually reaction wheels or gyroscope) and command module that communicates and directs all the parts and communicates with ground control. In tab. 2-2 can be seen weight distribution of different parts from selection of CubeSats. (5) Mechanical column are parts of the frame. For my CubeSat Frame I will use a model case of internal and power systems that are going to be set models with dimensions and weight that are comparable with the aforementioned selection of CubeSats in tab. 2-2.

Mission/Weight [g]	*Mech.*	*Control*	*Coms.*	*Power*	*Stab.*	*Payload*	*Other*	*Sum of IS*
czCube	150	50	150	150	100	350	-	800
AdeSat	330	110	130	200	80	70	20	610
AAUSat	131	50	193	190	160	170	-	763
Robusta	200	150	250	250	-	150	-	800
Leicester CubeSat	170	74	165	164	105	160	20	688
Move	330	50	230	220	100	200	-	800
SedSat-II	300	50	100	225	100	200	-	675
PilsenCUBE	270	80	180	440	100	-	50	850

Tab. 2-3 Weight distribution over different parts of CubeSat (5)

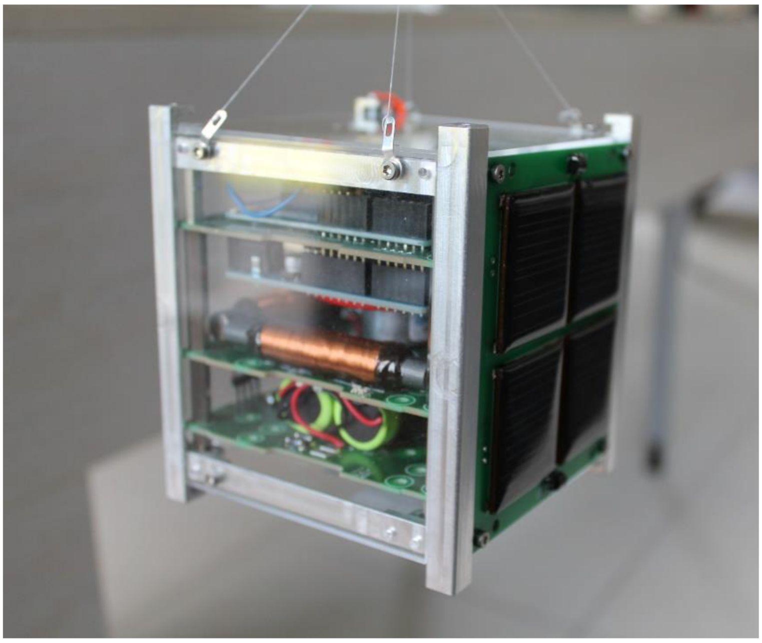


Figure 4 Internals of a CubeSat (10)

2.4.1 Solar panels

Solar panels for CubeSats are divided into two main groups and those are static surface solar panels and extendable solar panels. Extendable solar panels provide bigger surface area covered with solar cells which can produce more power output in exchange for higher weight of the construction and higher design complexity. Static solar panels have less overall surface area and thanks to that produce less power, but they are much simpler in construction, and they are lighter. In the smallest cases (i.e., 1U, 2U) of CubeSats usually there is no need for extendable solar arrays thanks to their low power consumption and sometimes there is no need for full coverage of all sides of the CubeSat with static solar panels. The power consumption of a CubeSat is dictated by the type of mission that's to be conducted with the particular CubeSat.

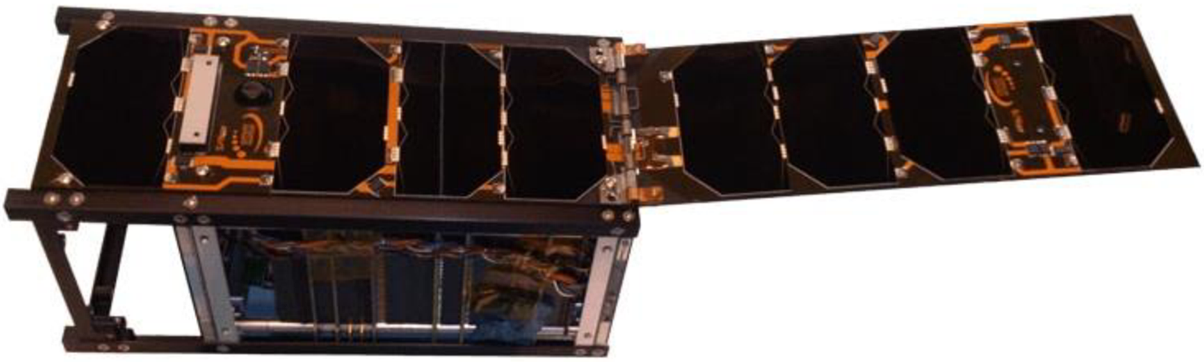


Figure 5 Example of extendable solar array (6)

2.5 Delivery systems

CubeSats are delivered to the orbit via various methods such as P-PODs (Poly Picosatellite orbital deployer), ISIPODs (ISIS Payload Orbital Dispenser) which can carry 3U worth of CubeSats at once. P-PODs serve as the interface between the CubeSat and the launch vehicle. One launch vehicle (rocket) can carry multiple P-PODs. The ISIPODS serve the same purpose as the P-PODs only they are mounted on the International Space Station to which the CubeSat can be delivered and subsequently assembled and launched from the station. This arrangement significantly cuts down on cost of launch for single picosatellite because there can by hundreds of CubeSats delivered on a single rocket. These rockets can be of varying sizes from the smallest like Rocket Lab Electron or Virgin Orbit that can carry from 200-500 kg of payload to low earth orbit to the biggest rockets like SpaceX Falcon Heavy that can carry up to 64 t to low earth orbit or 3500 kg to Pluto. (7) (8) (9)

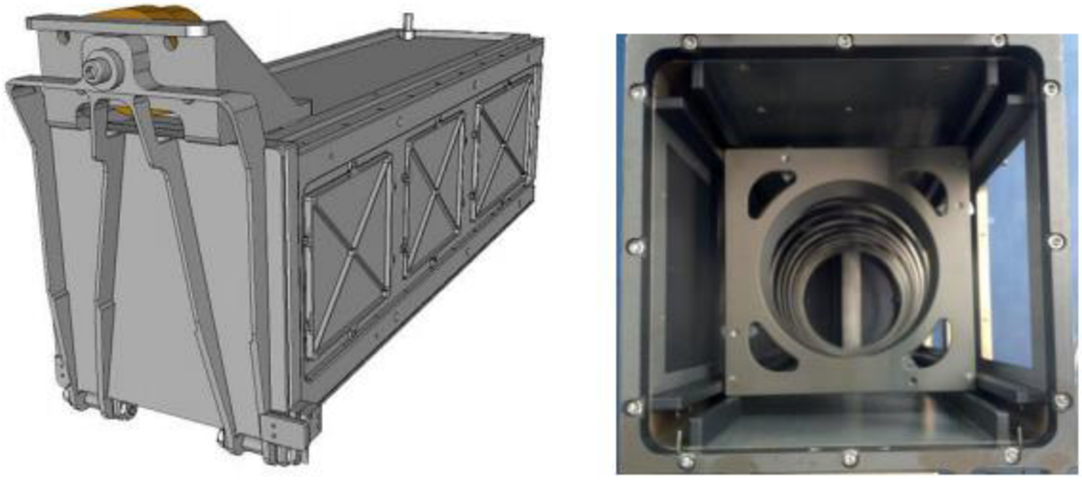


Figure 6 3U P-POD (11)

The dispensers interact with the individual CubeSats only through the rails on the CubeSat. When there is reached the target altitude the locks are released, and the satellites are dispensed out via set of two separation springs located on the -Z faces of the rails on the CubeSat. (1)

Figure 7 Virgin orbit rocket launched from carrier craft B747 "Cosmic girl" (13)

2.6 FEM overview

Finite element method (FEM) is method that can solve complex structural loading via numerical approach to the problem. As inputs is used information about the material, analytically calculated external loads on tested part and CAD model of tested part. This method is also used for fluid mechanic simulations, heat transfer simulation, mass transport simulation and others. There is also a plethora of available solvers for example ANSYS Granta or MSC Nastran. Ansys is the most widely known company providing software for FEM solvers and preparation software. FEM package form MSC is also used very heavily, and I will use this software for my analysis.

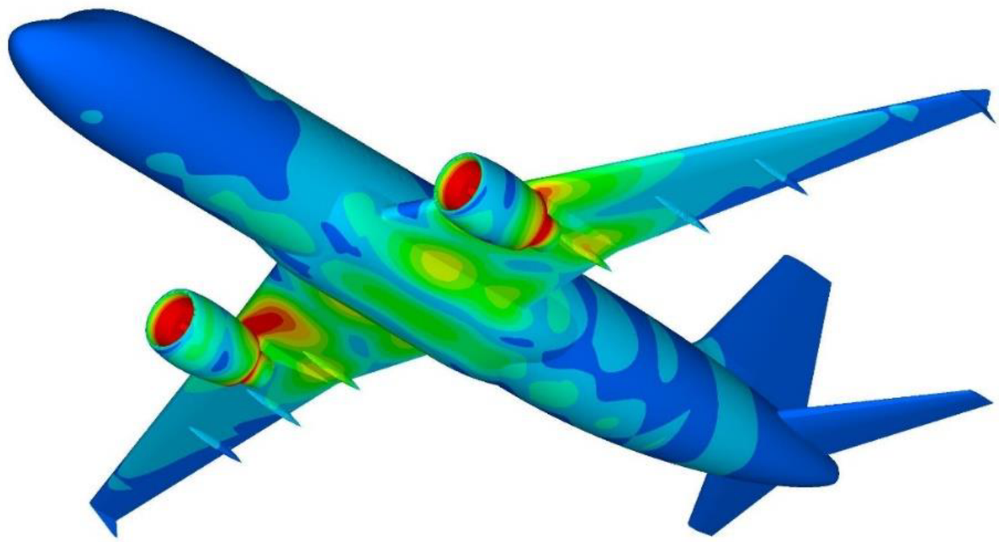


Figure 8 Solution of FEM method (12)

3. Definition of internal systems

As this master's project is a part of bigger project, we must define the relevant information to the design of the loadbearing frame such as mounting positions, weight and maximal dimensions.

3.1 Internal systems

The internal systems are the printed circuit boards of the CubeSat. The overall space for these systems must be minimally 85 x 82,5 x 88 mm with mounting solution for four M3 through holes with 75 x 75 mm spacing in rectangle pattern. The distance between the PCBs has to be 8,51 mm to accommodate the connecting interface between them. On the Z- side of the PCB stack, there has to be minimally 25 mm of space from the Z- frame panel to accommodate the battery packs. On the Z+ side there must be minimally 18 mm of space from the Z+ frame panel. The minimal caring capacity is 1650 g with the solar panels and other components.

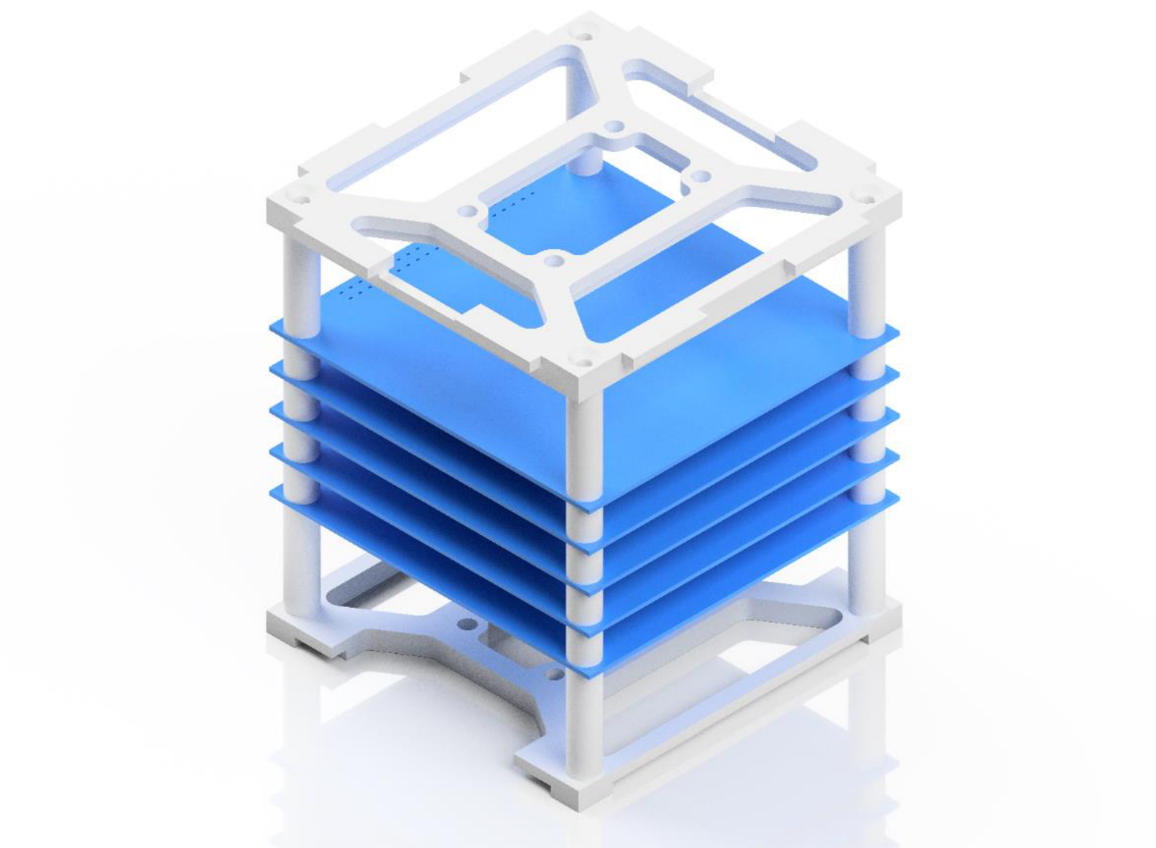


Figure 9 Example of PCB stack with correct spacing

3.2 Solar panels

As these are custom made solar panels, then the mounting positions are in nonstandard locations in comparison with industry standards. Standard mounting locations for these panels are in the in the corners or on the sides which is not the case for these panels. The mounting is done via four M3 bolts in the centre of the panel in a 39 x 23 mm rectangle pattern. This mounting solution is for both side solar panels and for the top and bottom solar panels. (i.e. figure 9). The wight of the Z +/- solar panels is 32 g each and the X/Y solar panels are 30 g.

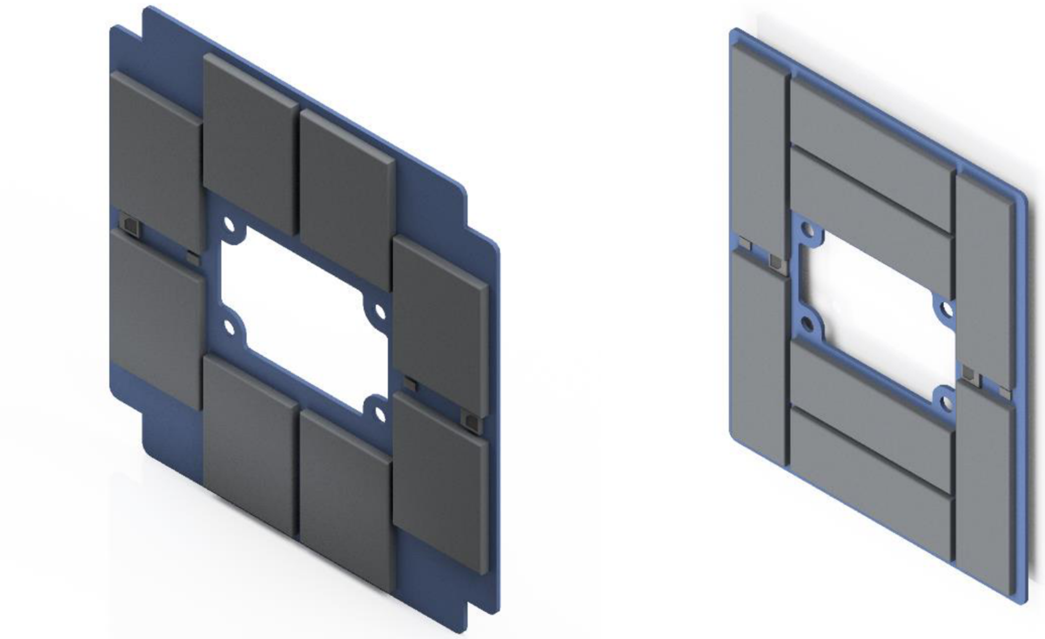


Figure 10 Top/bottom solar panel (left), Side solar panels (right)

3.3 Other components

The other components are the solar detectors that measure the amount of sunlight facing the solar panels, therefore these components are in four out of six centre parts of the solar panels. Other two are occupied by the interface panel and in the last one there is the camera. This camera is used as the main payload of the CubeSat. This is due to the fact, that the BUTCube project is still in development and not all the components are 100% confirmed and chosen. For this reason, the camera cannot be built in the frame but rather mounted to an adapter which will be mounted to the frame.

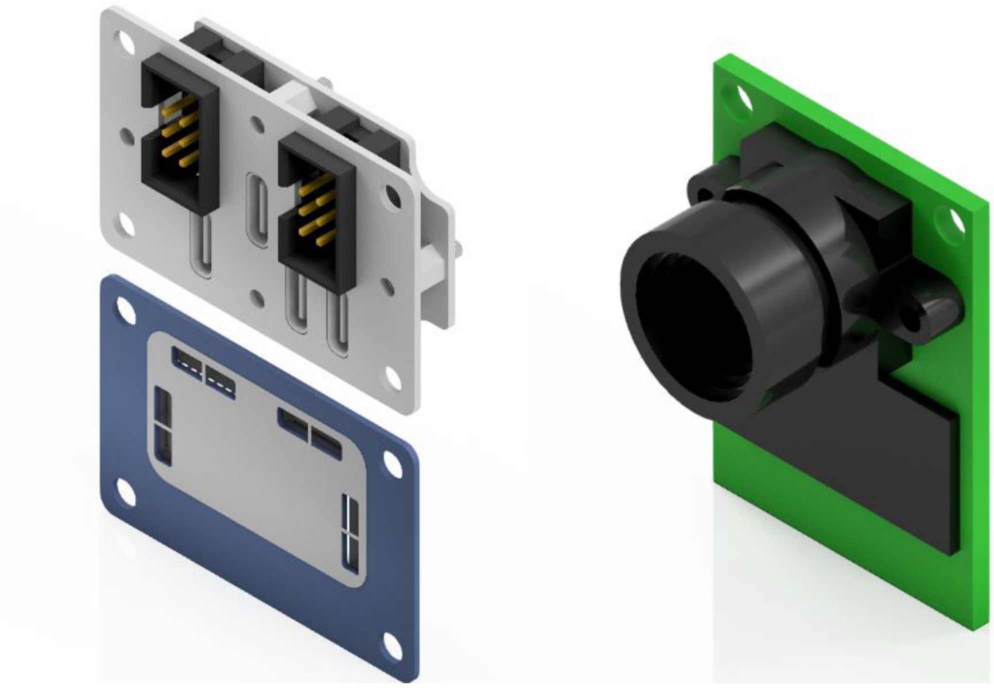


Figure 11 Interface panel (top left), solar detection panel (bottom left), camera placeholder (right)

The weight of the camera is 6,61 g. The weight of the interface panel and the solar detectors has to be approximated, because these parts are not finalized within the BUTCube project group. Therefore, the weight of these parts was taken from their CAD models with use of the appropriate mass densities of each part. Then the wight of the interface is 8 g and the weight of one solar detector is 6 g each.

The kill switches used are four PANASONIC AV 402461 that will ensure the need for redundancy set by the Cal Poly standards. The weight of these switches is 0,267 g each.

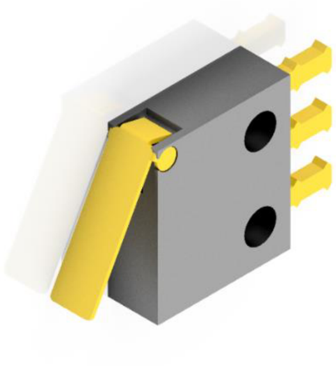


Figure 12 Model of the kill switch

4. Design proposal

The philosophy of the finalized design presented in this thesis was to make a frame of a CubeSat which would be made out of a plastic material that would be able to be printed in space (i.e. International space Station, and other future space stations and space craft). This presents the ability to launch on to the orbit only the internal components and other electronics, which would reduce cost to the whole endeavour. Although this is possible with this design, this frame is also able to support the launch the CubeSat in a assembled state in the more standard way of delivery to the orbit via a dispenser on a rocket or similar delivery device.

The 3D printed material brings many interesting challenges into consideration such as printing orientation for optimal load distribution and the necessity to use supports in the printing prose of certain shapes, but also brings advantages in form of possible new shapes that would be impossible to make with the standard manufacturing methods.

Design of the frame also uses minimal number of fasteners in between 3D printed parts and this was achieved using adhesives.

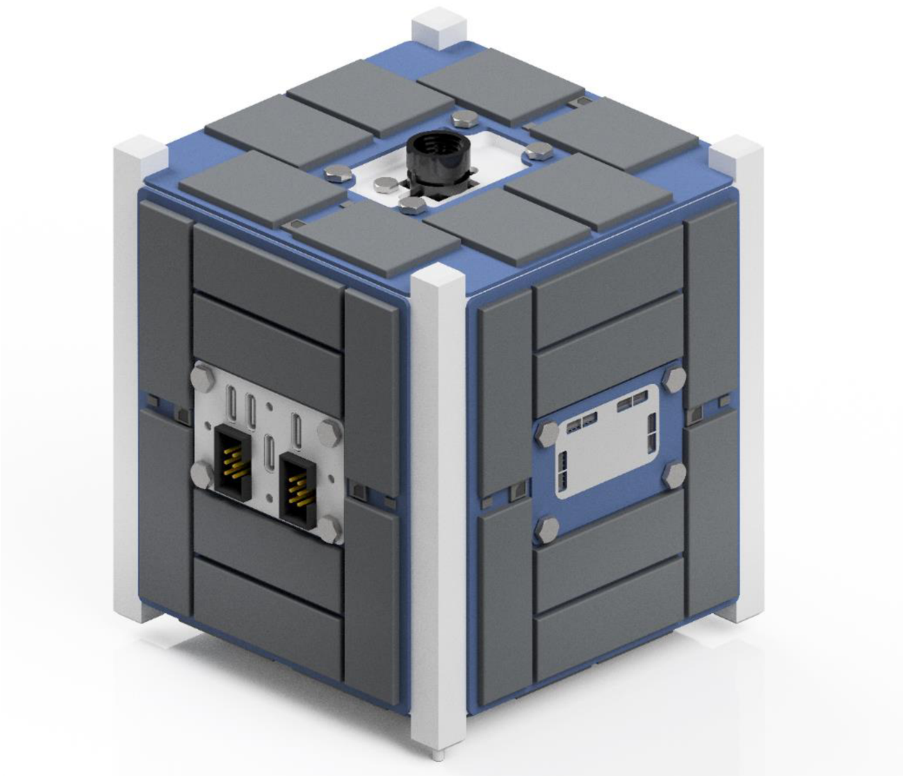


Figure 13 Assambly of the designed CubeSat

4.1 Model design

This whole design is divided into two major sub-assemblies. Those are the PCB stack and the sleeve.

4.1.1 PCB Stack sub-assembly

The PCB stack subassembly is composed from Z+ and Z- panels connected by four M3x100 DIN 963 bolts with four low profile M3 ISO 4036 nuts. In between these panels are five PCBs distanced with PLA stand-offs that ensure the correct spacing for the bridges between the PCBs which is 8,51 mm. The space between the Z- panel and the most bottom PCB is 25 mm and the space between the Z+ panel and the top PCB is 20 mm counting in the necessary space for the camera.

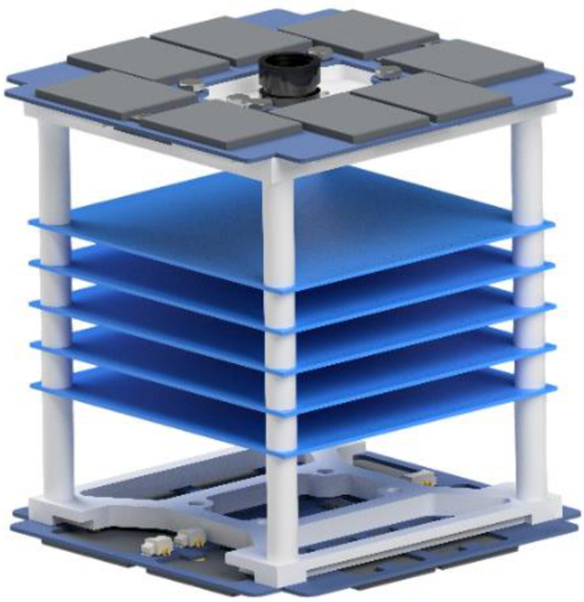


Figure 14 PCB stack subassembly

On the Z+ and Z- panels are also mounted two solar panels, one on each panel, with four M3x12 DIN 933 bolts and M3 ISO 4036 nuts. On the Z+ panel there is also mounted the camera assembly in the centre of this panel. On the Z- panel there Is one of the solar detectors mounted with the same nuts and bolts.

Z+/- panels

Both these panels are made with four 3,5 mm for the mounting of the solar panels to the frame and to mount the camera assembly and the bottom solar detector. Structure of these panels is made so they have high enough strength to support the PCB stack and also to be rigid enough so there is no unwanted flex in the structure. Two of the four sides of these panels have cut-outs to accommodate the power and control connectors to the solar panels mounted on them. To ensure correct glue up the are shape elements on both panels that into their counterparts on the sleeve assembly.

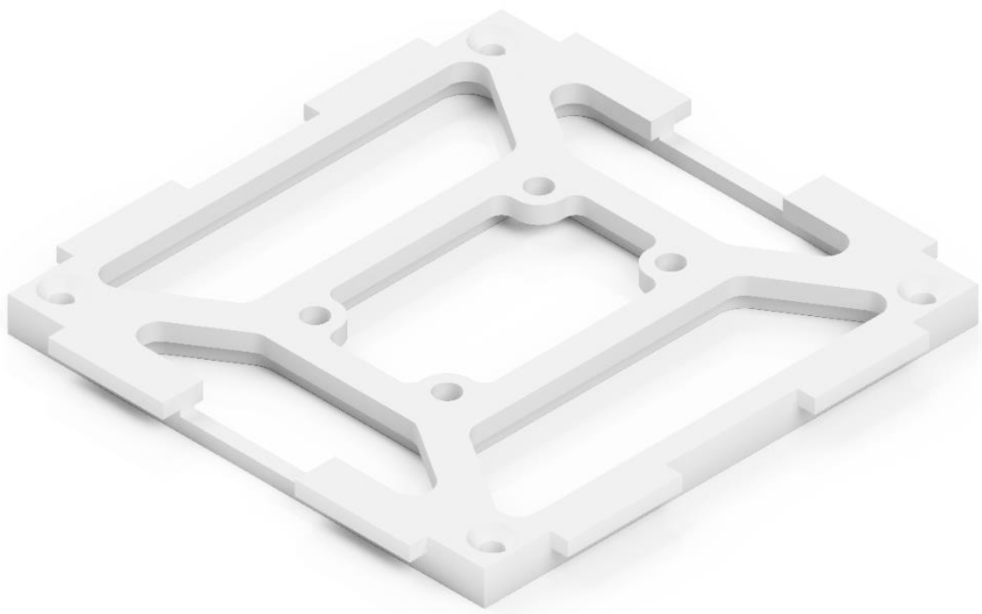


Figure 15 Z+ panel

The correct spacing between these two panels is accomplished via the stand-offs and the thickness of the PCBs. The Z+ panel has in its corners four tapered holes to accommodate the head of the flathead bolt, so it sits flush with the surface of the panel and does not interfere with the solar panel. The Z- panel has in its four partial hexagonal holes for the low-profile nut and partially it is a standard 3,5 mm hole for the M3x100 bolt connecting the two panels.

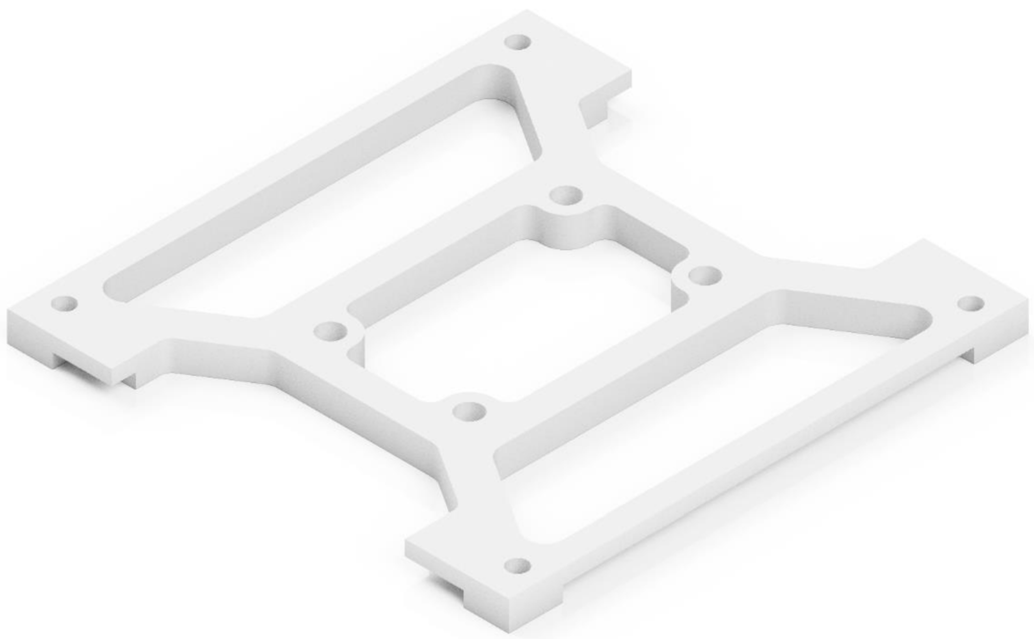


Figure 16 Z- panel

Camera assembly

Camera assembly is mounted to the centre of the Z+ panel with same M3x12 bolts, same bolts as the solar panels. The camera assembly is comprised of the camera adapter and the camera. Camera is mounted to the camera adapter via set of two M2,5x8 bolts. This design allows for easy exchangeability with other camera adapters for different cameras that fit into the centre opening of the panel.

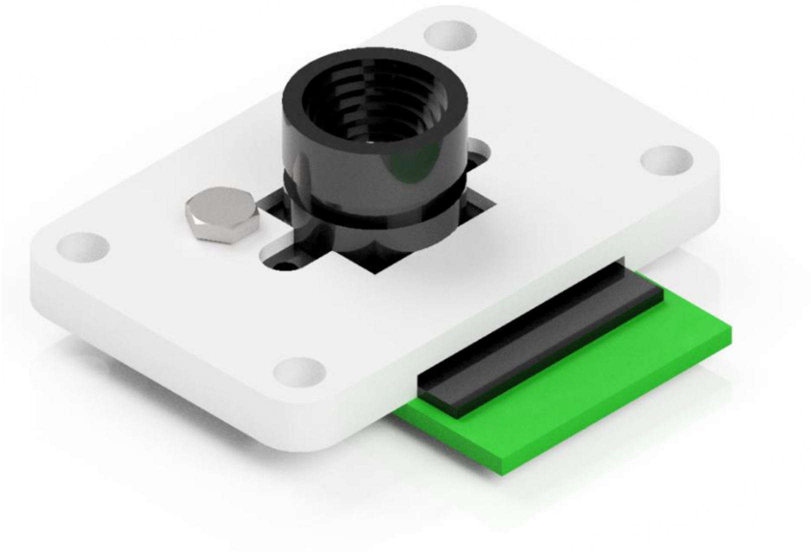


Figure 17 Camera assembly

4.1.2 Sleeve sub-assembly

The sleeve sub-assembly is the structural component into which the PCB stack sub-assembly slides into and gets glued into. Also, the separation spring, kill switch and the rest of the components. The interface panel is also in one of the centre portions of the side panels and the rest are occupied with the solar detectors.

Figure 18 Sleeve sub-assembly

All of the sides are covered with the side solar panels. The location of the connectors for these solar panels are located in a way, that there is no need for cut-outs in the side panels like it was needed for the top and bottom panels.

Rail panel

The rail panels would be the X+/- panels of the CubeSat. On both of these panels are mounted solar detectors and solar panels which are fastened with four M3x6 with low profile nuts. On the Z- side of the rails there would be the separation spring with 8-36 UNF-2B thread as specified by the standards. The tread would be tapped directly into an undersized hole printed in the panel. The surrounding material would be fulfilled in the 3D printing process. The other rail would have the kill switch assembly.

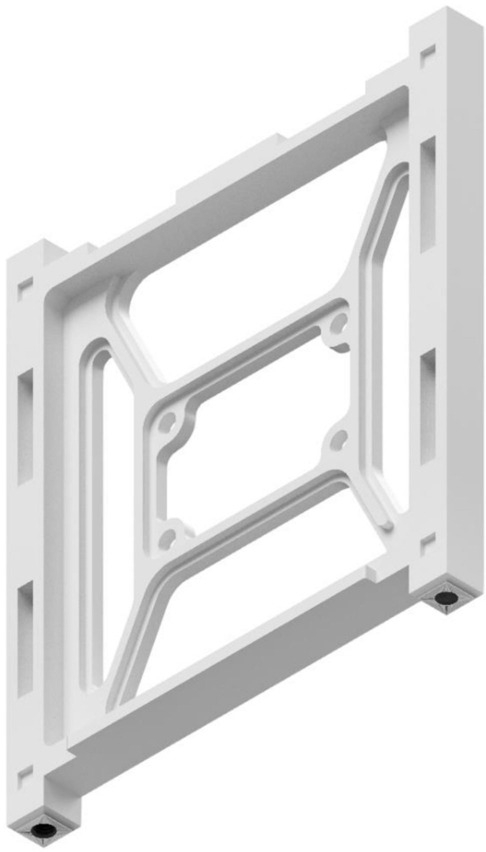


Figure 19 Rail panel

Both of the rails on this panel have two indexing indents on the top and bottom of the rail and there are also two long deeper grooves. The long grooves are there to transfer load between the rail panel and the support panel. On the top and bottom of the panel are the indents and protrusions the fit into the counterparts in the PCB stack sub-assembly.

Support panel

The support panels connect the two rail panels to finish the sleeve. These panels are the Y+/- panels. One of the panels has the interface panel in its central part and the other one has the last solar detector. On the sides of these panels are the protrusions that fit into the rail panel.

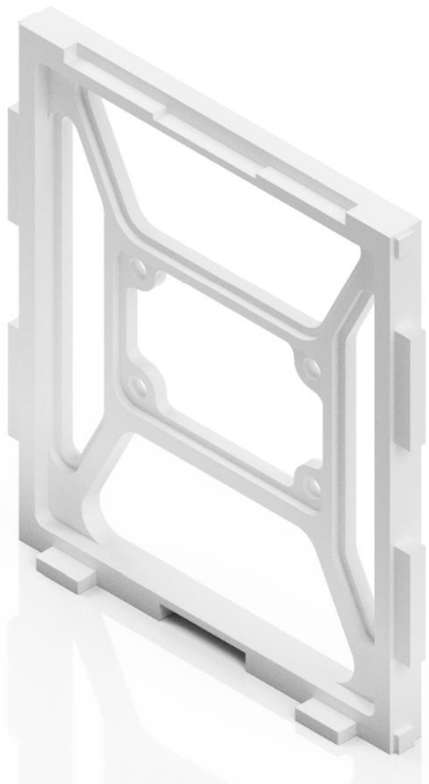


Figure 20 Support panel

On The top and bottom of these panels are also indents to accommodate the connectors of the Z+/- solar panels.

Kill switch assembly

These kill switches constitute the function of a failsafe, so the CubeSat doesn't turn on its own while its still in the dispenser. For this purpose, were chosen switches that are off while their lever is compressed. On each rail part the kill switch assembly contains two kill switches for extra redundancy.

Each kill switch assembly therefore contains two kill switches, plunger, action piece, action spring and two pins with slight overlap with which are the kill switches connected to the rail part. The kill switch lever has to be shortened to accommodate the action spring in the uncompressed state, so they don't interfere with each other.

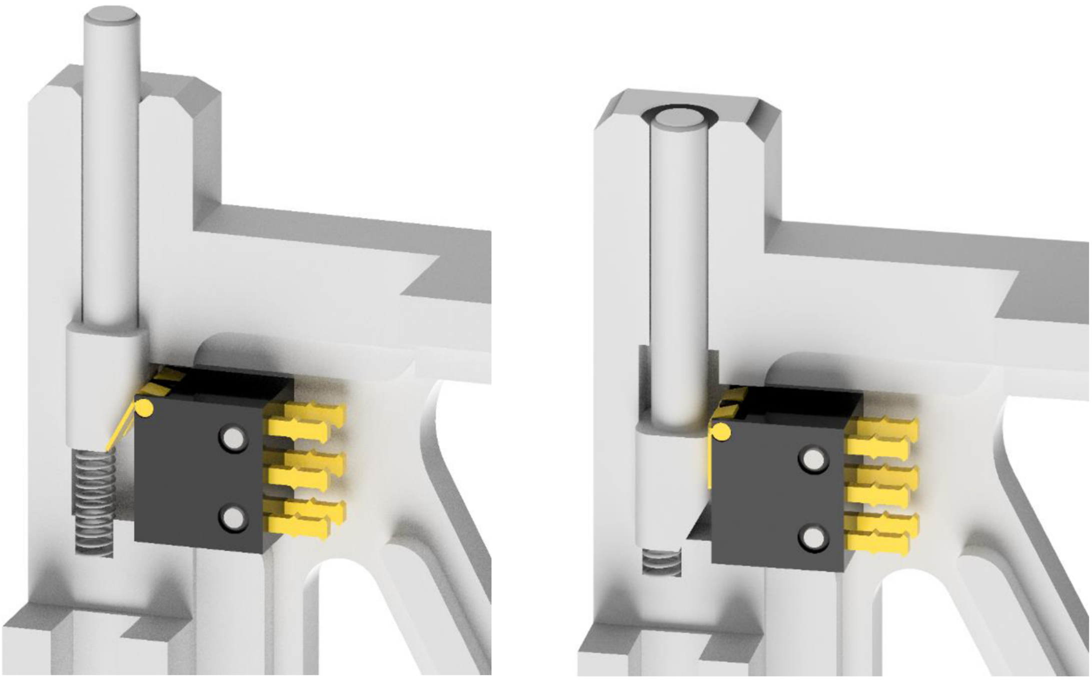


Figure 21 Uncompressed (left) and compressed (right) kill switch assembly

The action will be compressed while the CubeSat is still in the dispenser in contact with other CubeSats or the structure of the dispenser. Upon the release from the dispenser the CubeSat becomes active.

4.2 Materials and glue up

4.2.1 Materials

All the parts that are in contact with the dispenser or other CubeSats in these dispensers are made from PEEK plastic such as the rails or the Kill switch plunger, or machined aluminium alloys like the plunger of the separation spring or the nuts and bolts holding on the equipment of the CubeSat. This is to prevent contact welding between steel parts in the vacuum of space. The PEEK plastic in question is the Victrex® PEEK 450G.

4.2.2 Glue up

The glue used for this project is the Master bond EP29LPSP that is certified for use in space application. The preparation of the contact surfaces is light sanding to scuff up the surfaces for better bond between the parts and the adhesive agent. The mixing and application of the adhesive is done under room temperature and the working window is 4-5 hours. The curing process of this adhesive for this application is a cycle of 8-10 hours of elevated temperature to 140 °F (approx. 60 °C) and then cooling under room temperature. After this cycle the adhesive should be fully bonded with the components.

Sleeve application

The glue up of the sleeve sub-assemble would be the first of the glue ups of the final assembly of the CubeSat. The support and rail panels would be glued up via the contact surfaces and the indexing indents and groves in the rail part with its counter parts.

Figure 22 Sleeve glue up contact surfaces (red)

Next order of operation would be the glue up of the kill switch plunger and action piece of the kill switch assembly inside of the pocket for the assembly as its two-piece part. After that is done, then the kill switches would be pinned in place with the pins with overlap on both the switches and the holes of the rail panel.

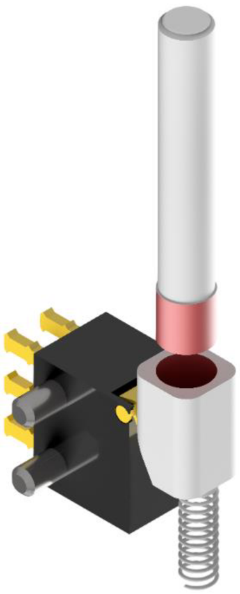


Figure 23 Kill switch assembly glue up contact surfaces (red)

After these operations are done the curing process may comments for this sub-assembly to finish the sleeve.

Final assembly

In the case the end user doesn't wish to glue up the whole CubeSat at once and wishes to conduct some tests on the CubeSat that are not possible in the "flatsat" form the PCB stack sub-assembly may be slid in and out of the sleeve.

After these tests would be conducted and the final assembly is required, then the PCB stack would be glue up via the indents, protrusion counter parts and the contact surfaces between the Z+/- panels and the sleeve. Connecting all the electronics would be advised before this step.

The curing process may by the same as for the sleeve application.

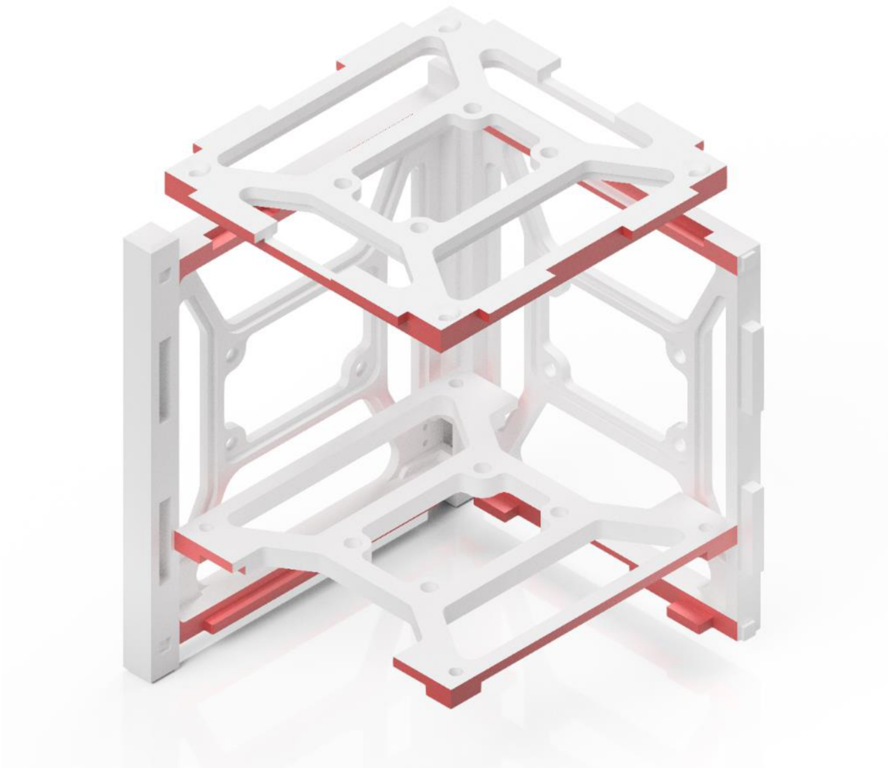


Figure 24 Glue up contact surfaces of the final assembly (red)

4.3 3D Printing

The preparation for the 3D printing process was done in the PrusaSlicer-2.4.1 software that allows wide range of control of the printing speeds, materials and other variables that are important to achieve high quality prints. The parameters in this part are of the recommended nature derived from the strength testing of PEEK material mentioned in the paper from chapter 2.3.2.

4.3.1 Printing parameters

In the table 4-1 are listed the parameters used for printing. The nozzle used has 0,4 mm diameter outlet for all prints. These parameters were chosen as close to the parameters used in paper mentioned in chapter 2.3.2 to achieve the same mechanical properties.

Parameter	First layer	Other layers	Unit
Nozzle movement speed	10	14	mm/s
Nozzle temperature	390	410	°C
Bed temperature	100		°C
Layer hight	0,18	0,1	mm
Extrusion width	0,48		mm
Infill pattern	Grid		-
Infill density	80		%
Perimeter thickness	3		-
Top/bottom solid layers	20		-

Tab. 4-1 Printing parameters

The Printing of the frame is divided into four separate operations to allow parallel printing and to also ensure proper adhesion between layers.

Rail panels

The first parts to be printed are the rail panels that come to contact with the rails of the dispenser, so the printing must be precise. Total printing time for these panels is 1 day 3 hours and 38 minutes from which the first layer takes 1 hour and 20 minutes with the parameters described above. For this print there are no supports used as they are nit necessary. Total length and weight of the filament used are 25,26 m and 75,35 g respectively. Total printing area used for this print is 232,45x100,28x11 mm of the total printing bed. The layout cane be seen in figure 24 and the total distribution of time and filament can be seen in figure 25.

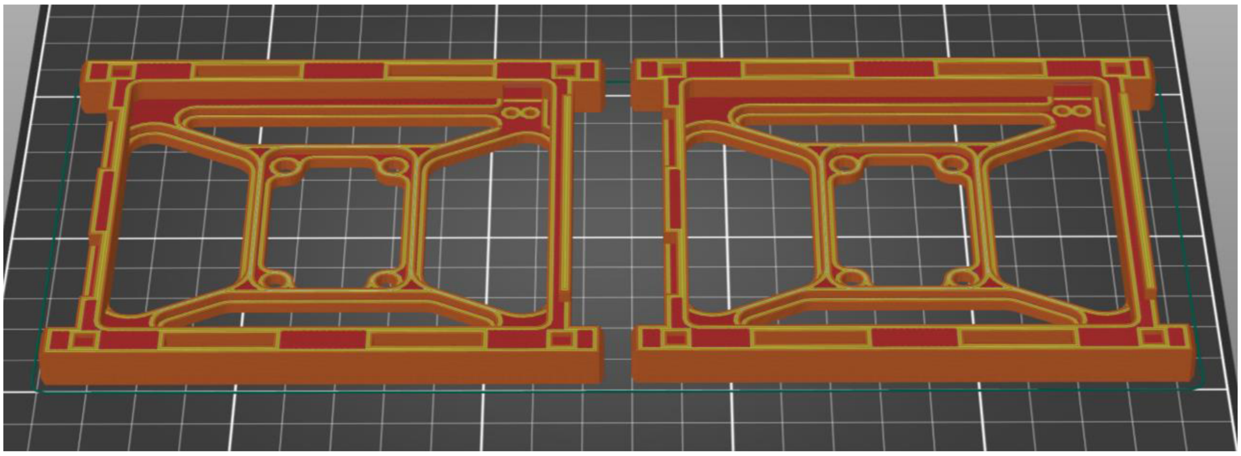


Figure 25 Rail panel printing layout

Feature type	Time	Percentage	Used filament	
Perimeter	7h51m	28.4%	7.36 m	21.96 g
External perimeter	4h11m	15.2%	3.76 m	11.21 g
Overhang perimeter	8s	0.0%	0.00 m	0.01 g
Internal infill	2h19m	8.4%	2.06 m	6.14 g
Solid infill	12h28m	45.1%	11.42 m	34.07 g
Top solid infill	26m	1.6%	0.41 m	1.22 g
Bridge infill	6m	0.4%	0.11 m	0.33 g
Gap fill	13m	0.8%	0.07 m	0.21 g
Skirt/Brim	3m	0.2%	0.05 m	0.14 g
Custom	12s	0.0%	0.02 m	0.06 g

Estimated printing times:

First layer: 1h20m

Total: 1d3h38m

Figure 26 Rail panel time and filament distribution

Support panels

The second printing operation are the support panels that connect the two rail panels. To ensure the proper spacing of the two rail panels the printing must be also precise. Total printing time for these panels is 16 hours and 1 minute from which the first layer takes 51 minutes with the parameters described above. For this print there are no supports used as they are not necessary. The printing area used for this print is 185,93x100,6x11 mm. Total length and weight of filament used is 14,5 m and 43,23 g respectively. The layout can be seen in figure 26 and the distribution of time and filament can be seen in figure 27.

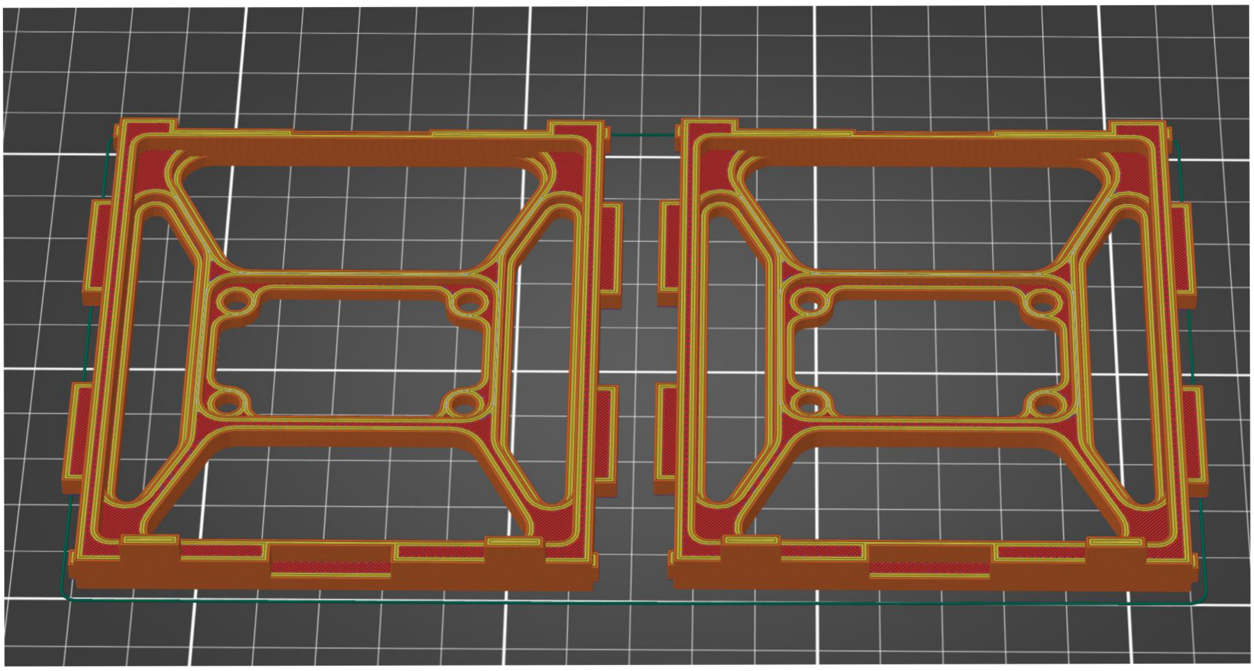
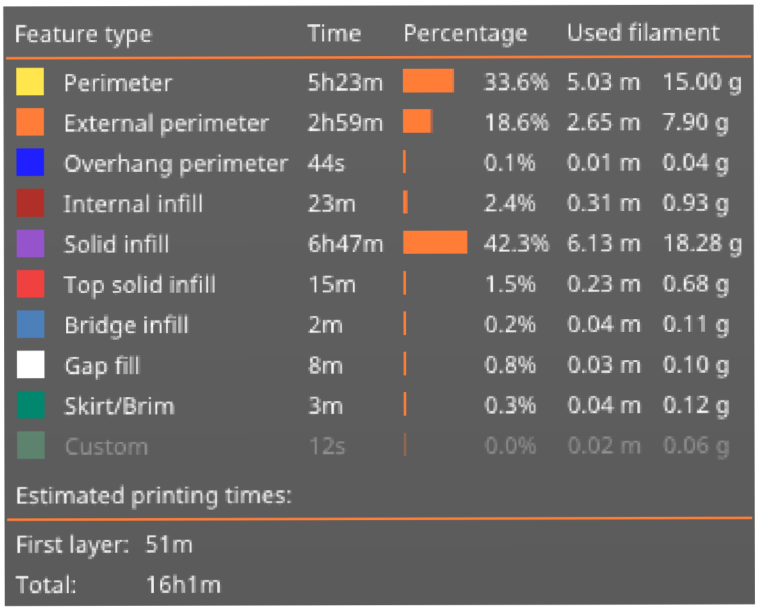


Figure 27 Support panel layout



Feature type	Time	Percentage	Used filament	
Perimeter	5h23m	33.6%	5.03 m	15.00 g
External perimeter	2h59m	18.6%	2.65 m	7.90 g
Overhang perimeter	44s	0.1%	0.01 m	0.04 g
Internal infill	23m	2.4%	0.31 m	0.93 g
Solid infill	6h47m	42.3%	6.13 m	18.28 g
Top solid infill	15m	1.5%	0.23 m	0.68 g
Bridge infill	2m	0.2%	0.04 m	0.11 g
Gap fill	8m	0.8%	0.03 m	0.10 g
Skirt/Brim	3m	0.3%	0.04 m	0.12 g
Custom	12s	0.0%	0.02 m	0.06 g

Estimated printing times:

First layer: 51m

Total: 16h1m

Figure 28 Time and filament distribution of the support panels

Top and bottom panels

The third printing operation is the printing of the top and bottom panels of the frame. Total printing time of these panels is 12 hours and 10 minutes from which the first layer takes 46 minutes with the parameters as described above. There are supports necessary for the bridge on the top panel. The printing area used is 187,08x89x6 mm of the printing bed. Total length and weight of the filament used is 10,73 m and 32 g respectively. The layout of the print can be seen in figure 28 and the time and distribution of filament can be seen in figure 29.

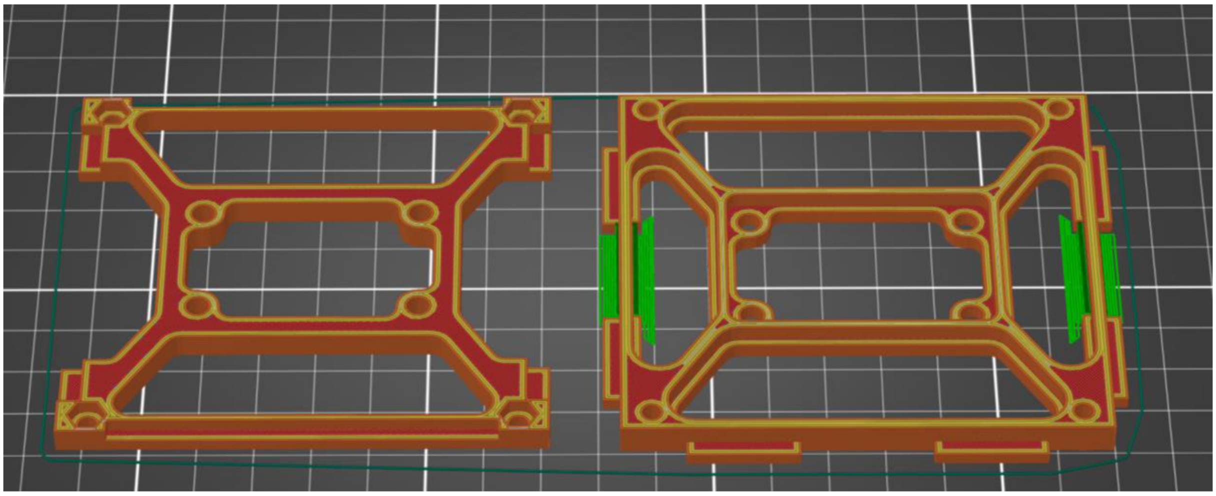
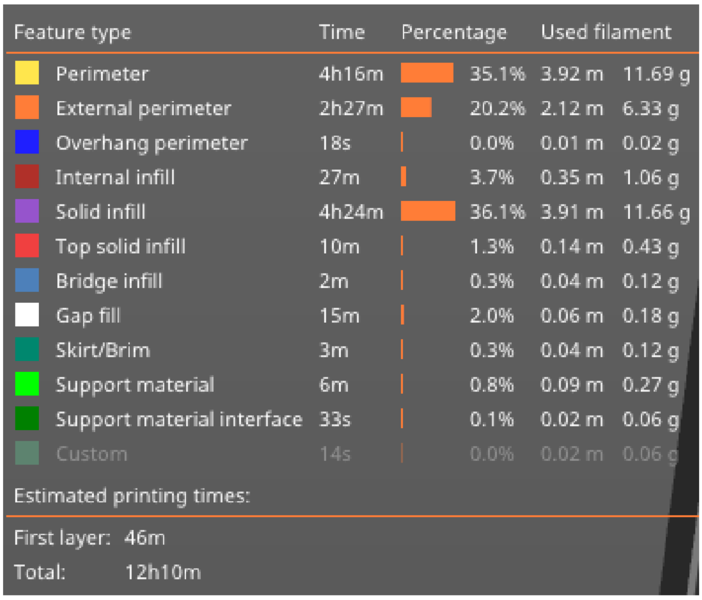


Figure 29 Top and bottom panel layout



Feature type	Time	Percentage	Used filament	
Perimeter	4h16m	35.1%	3.92 m	11.69 g
External perimeter	2h27m	20.2%	2.12 m	6.33 g
Overhang perimeter	18s	0.0%	0.01 m	0.02 g
Internal infill	27m	3.7%	0.35 m	1.06 g
Solid infill	4h24m	36.1%	3.91 m	11.66 g
Top solid infill	10m	1.3%	0.14 m	0.43 g
Bridge infill	2m	0.3%	0.04 m	0.12 g
Gap fill	15m	2.0%	0.06 m	0.18 g
Skirt/Brim	3m	0.3%	0.04 m	0.12 g
Support material	6m	0.8%	0.09 m	0.27 g
Support material interface	33s	0.1%	0.02 m	0.06 g
Custom	14s	0.0%	0.02 m	0.06 g

Estimated printing times:

First layer: 46m

Total: 12h10m

Figure 30 time and filament distribution of the print

Miscellaneous components

In the last print there are the rest of the components such as the spacers for the PCBs, camera adapter, plunger and action for the kill switch. Total print time of this print is 8 hours and 4 minutes from which the first layer takes 16 minutes with the printing parameters described above. Total printing area used is 102,04x92,75x25 mm of the printing bed. Total length and weight of the filament used is 6,08 m and 18,14 g respectively. The layout of the print can be seen in figure 30 and the time and filament distribution can be seen in figure 31.

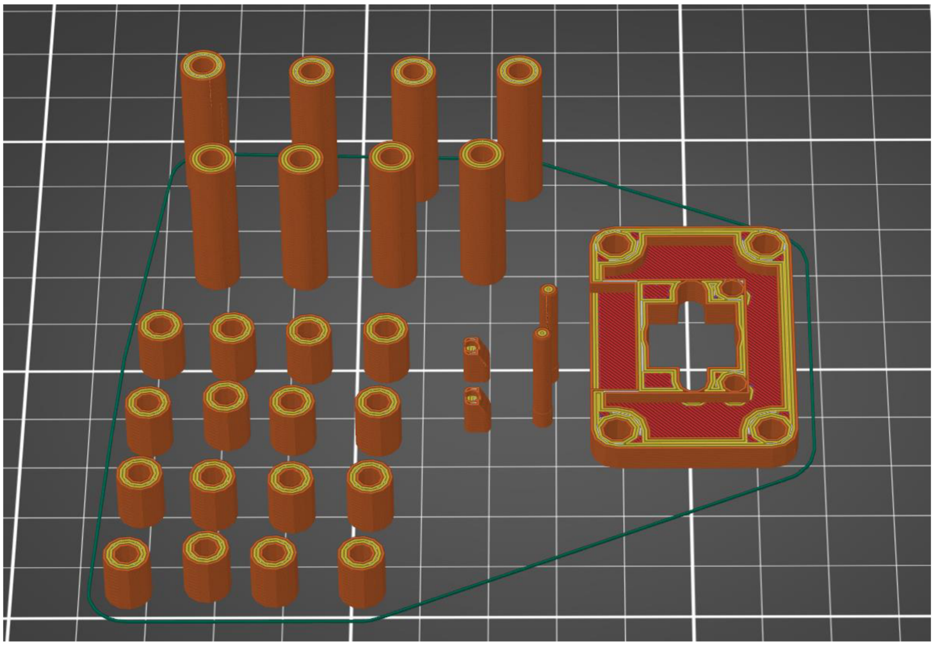


Figure 31 Miscellaneous components print layout

Feature type	Time	Percentage	Used filament	
Perimeter	2h53m	35.7%	2.63 m	7.85 g
External perimeter	3h8m	39.0%	2.44 m	7.27 g
Overhang perimeter	1s	0.0%	0.00 m	0.00 g
Internal infill	6s	0.0%	0.00 m	0.00 g
Solid infill	56m	11.5%	0.82 m	2.43 g
Top solid infill	2m	0.5%	0.03 m	0.10 g
Bridge infill	1s	0.0%	0.00 m	0.00 g
Gap fill	1h3m	13.0%	0.12 m	0.35 g
Skirt/Brim	2m	0.3%	0.03 m	0.08 g
Custom	11s	0.0%	0.02 m	0.06 g

Estimated printing times:

First layer: 16m
Total: 8h4m

Figure 32 Time and filament distribution of the print

5. FEM Analysis

The Fem analysis is conducted with the MSC Patran and MSC Nastran software. The model used to create the necessary models for the analysis via the Autodesk Inventor software. The philosophy of approach to the topic is that the loads are applied to the centres of gravity of the equipment and the connection between the rails on the CubeSat and the rails of the dispenser as the base body of the load case.

5.1 Definition of inputs

5.1.1 Imported geometry

The geometry of the CubeSat imported into the MSC Patran are done via the STEP model format from the Autodesk Inventor. The import is done as an assembly of all the components of the frame that include the rail panel, support panel, top panel and the bottom panel. The other components and equipment of the CubeSat are not physically simulated.

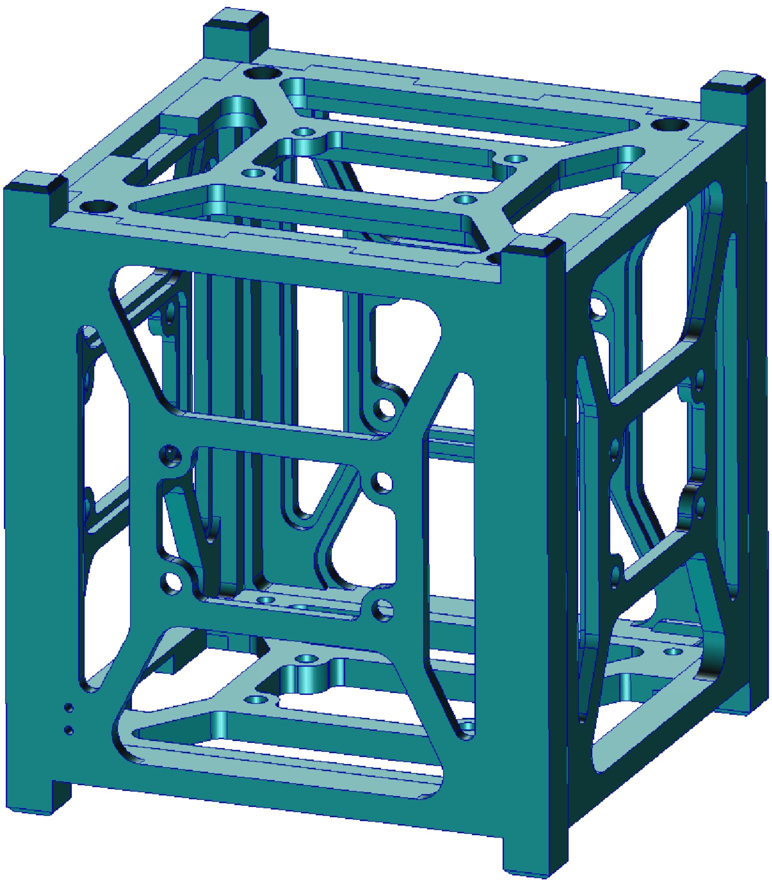


Figure 33 Imported geometry of the CubeSat into MSC Patran

5.1.2 FEM elements

All the components are simulated in the general areas of the models as Tet4 mesh elements with the maximal edge length of 7 mm. The key areas, such as the mounting holes, indexing and connecting groves and its counterparts, have smaller edge length to ensure the necessary accuracy of the simulations. The meshes of the frame are connected vie equivalent elements on the glue up faces to simulate the connection between the panels as a single straight face. Number of total elements is 87367.

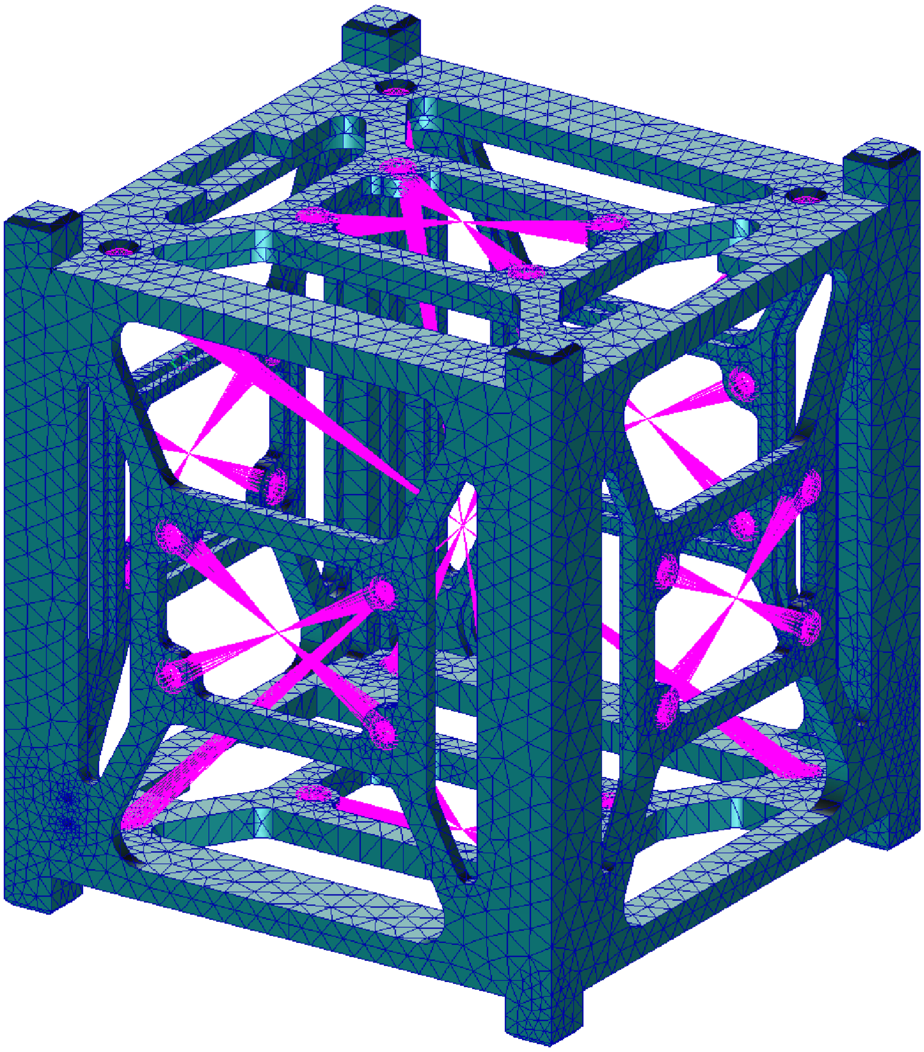


Figure 34 FEM mesh elements (blue) and MPC elements (pink)

The other components and equipment are simulated as FEM nodes in the centres of gravity of the components and equipment which are connected to the appropriate mounting locations on the frame of the CubeSat via the MPC RBE2 elements. The loads are connected to these nodes which are tied to the MPC elements.

5.1.3 Material simulations

The nature of the 3D printed PEEK material is that its much weaker in one direction than the other two, and that is the direction of the stacking of the layers as its printed as can be seen in the Figure 2. The directions along the layers can be considered as vary similar as the break and the yield in the respective directions is equally undesirable. Then the limits of the materials are the lower of the two directions along the layers in tensile strength, yang modulus, and poison number as the printing is not one directional and the layers have in the infill 90° from each other. The perpendicular direction to these layers is taken as stated in the table 2-2 in these simulations.

The directions of the parameters simulated for each panel in the same orientation as they are printed to be able to determine if the frame can withstand the loads.

5.2 Static loading

The static loading simulation is done to determine, if the frame is strong enough, to withstand the loads put on the frame while its being launched into orbit. The loads are generated by the inertial forces from the weight of the mounted components and equipment on the frame and are transferred via the frame into the rails of the CubeSat and by extension to the rails of the dispenser.

5.2.1 Boundary conditions

The boundary conditions are situated located at the contact surfaces of the rails. Each face of the rails takes away their respective degree of freedom in one direction. This is achieved via the displacement load set to 0 in the respective axis. So, the top and bottom surfaces of the CubeSat take away degree of freedom in the Z direction and the X and Y faces of the rails take away the degrees of freedom in their respective directions. Also, the boundary conditions are made so they act against the loads presented to them and don’t influence the opposite sides of the frame. Each of the setups can be seen in the figure below.

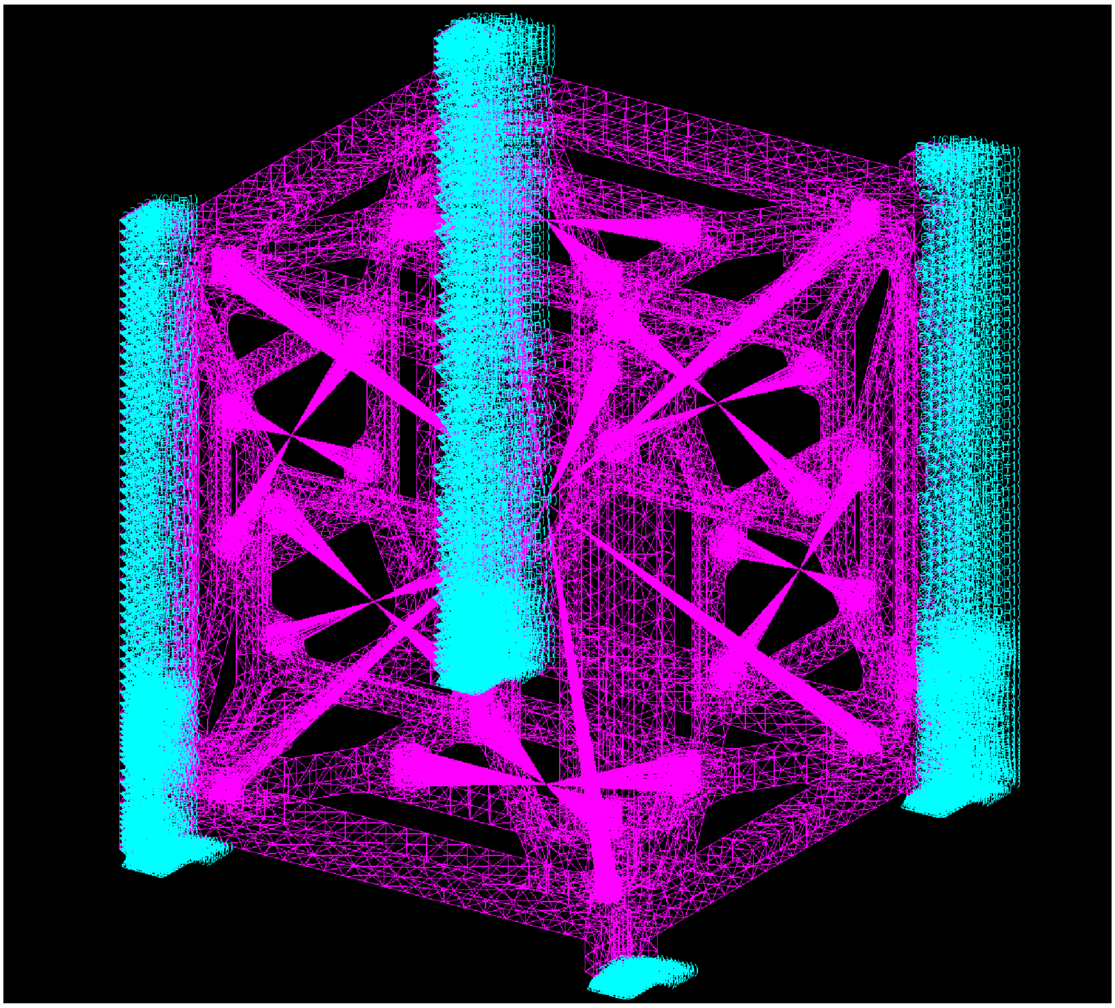


Figure 35 Boundary conditions (blue) in FEM

5.2.2 Loads

The loads for the simulation are done via forces located in centres of gravity of the equipment used. This is achieved via the MPC elements that connect the mounting points of the equipment and their respective load points. The forces are calculated from the weight of the equipment and the acceleration of the rocket. For the simulation purposes is used the acceleration of 6g at ground level which is standard maximal acceleration for non-organic launches into the earths orbits (such as the Falcon 9).

Thanks to the high level of symmetry of the frame and the CubeSat as a whole, the simulation can be done in only 7 directions of loading to test all of the major directions of loading and those are the X, Y, Z, XY, XZ, YZ and XYZ directions. The loads in each direction for all equipment assemblies can be seen in the table 5-1. The weight of the PCB stack is simulated as the rest of the available weight to the maximal weight to the maximal weight of the CubeSat.

Load points	X	Y	Z	XY	XZ	YZ	XYZ	Units
PCS Stack	(95,46;0;0)	(0;95,46;0)	(0;0;95,46)	(67,5;67,5;0)	(67,5;0;67,5)	(0;67,5;67,5)	(55,12;55,15;55,15)	N
X+	(2,12;0;0)	(0;2,12;0)	(0;0;2,12)	(1,5;1,5;0)	(1,5;0;1,5)	(0;1,5;1,5)	(1,22;1,22;1,22)	N
X-	(2,12;0;0)	(0;2,12;0)	(0;0;2,12)	(1,5;1,5;0)	(1,5;0;1,5)	(0;1,5;1,5)	(1,22;1,22;1,22)	N
Y+	(2,24;0;0)	(0;2,24;0)	(0;0;2,24)	(1,58;1,58;0)	(1,58;0;1,58)	(0;1,58;1,58)	(1,29;1,29;1,29)	N
Y-	(2,12;0;0)	(0;2,12;0)	(0;0;2,12)	(1,5;1,5;0)	(1,5;0;1,5)	(0;1,5;1,5)	(1,22;1,22;1,22)	N
Z+	(2,15;0;0)	(0;2,15;0)	(0;0;2,15)	(1,52;1,52;0)	(1,52;0;1,52)	(0;1,52;1,52)	(1,24;1,24;1,24)	N
Z-	(2,24;0;0)	(0;2,24;0)	(0;0;2,24)	(1,58;1,58;0)	(1,58;0;1,58)	(0;1,58;1,58)	(1,29;1,29;1,29)	N

Tab. 5-1 Vectorization of loads of each load point in the corelation to the directions in figure 36

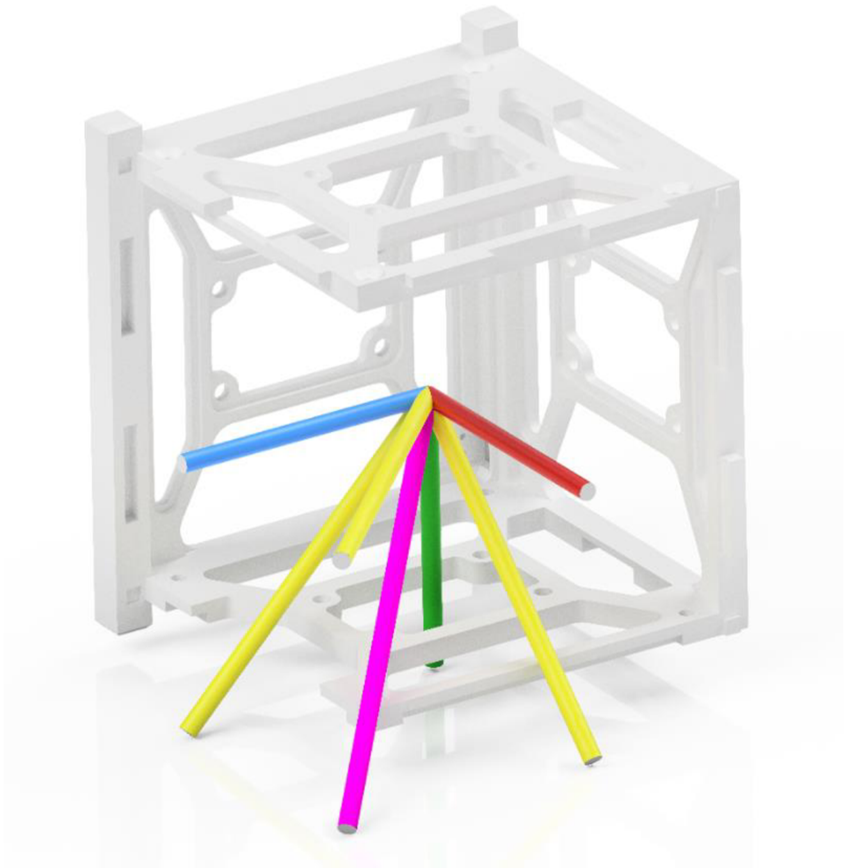


Figure 36 Load directions of the simulation X (blue), Y (red), -Z (green), 2D combinations (yellow), 3D combination (purple)

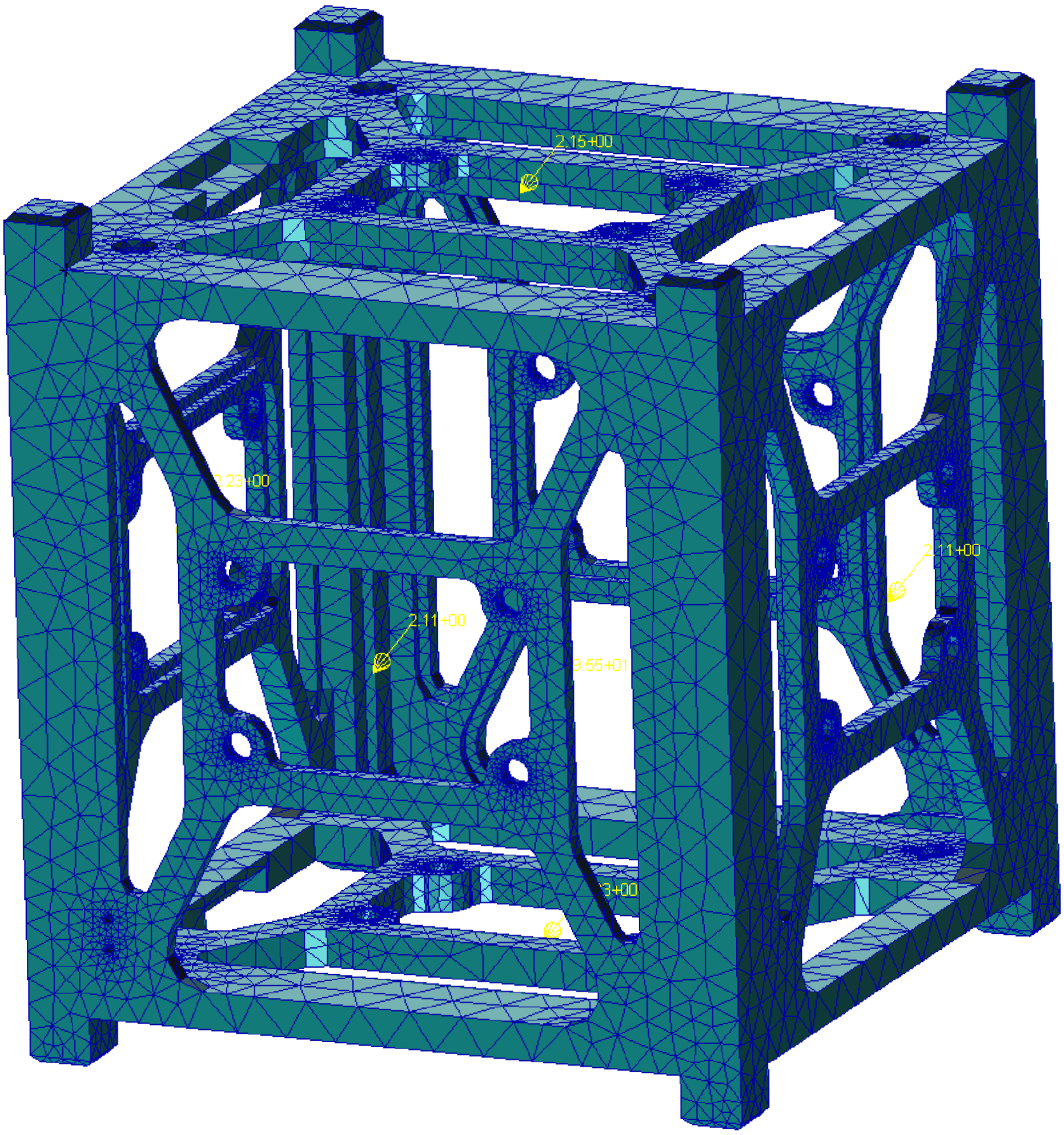


Figure 37 Example of loads (yellow) for the loading in X direction

5.2.3 Results

All the results for each of the load subcases are displayed in MPa for stresses and mm for the displacements. As all the results are within the maximal values for all the directions, even for the σ_3 direction (direction of layers), it can be stated that the frame can withstand the loads that were put forward for analysis. Also, for all the cases, all of the maximal loads are located in the mounting holes for the PCB stack as to be expected in this particular case.

X load direction subcase

For this subcase the maximal load is 6,07 MPa and is located in the mounting holes for the PCB stack. Other than that, we can see around the mounting points for the equipment on the outsides of the panels and the struts to these locations there is maximal load around 1,8 MPa. The maximal displacement is on the rail panels (X+- panels) under the mounting points for the panel mounted equipment and that is only $3{,}65 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

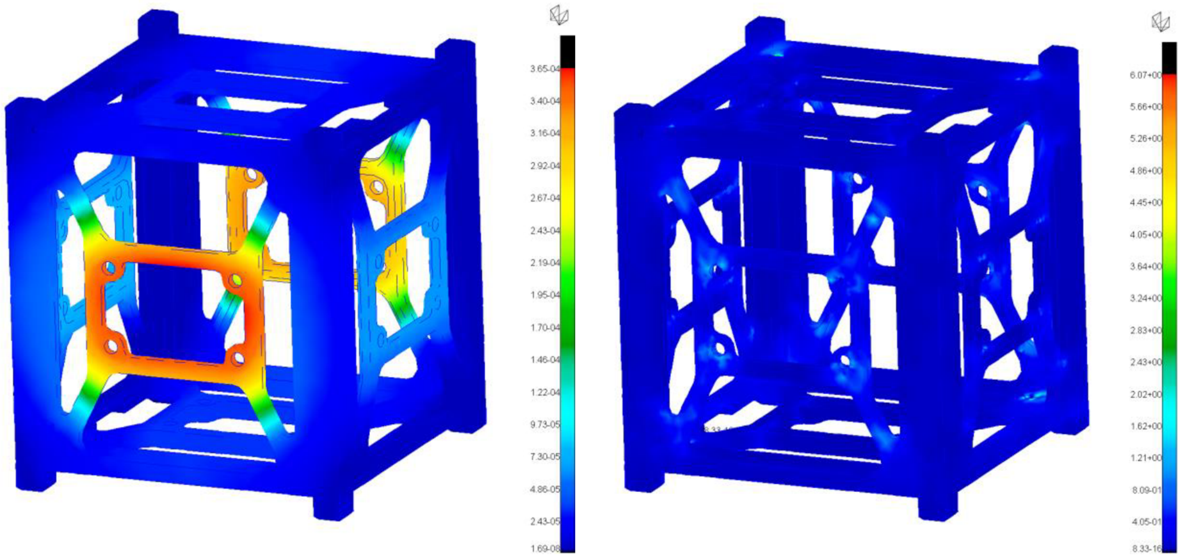


Figure 38 Visualization of the displacement (left) and the stresses (right) of the X loads

Y load direction subcase

The maximal load for this subcase is also located in the mounting holes for the PCB stack and it's 8,56 MPa which is also the maximal load for the whole CubeSat frame. Around the other mounting holes, the load is Around 2,3 MPa. The maximal displacement is on the support panel with the central interface panel (Y+ panel) as to be expected and the value is $3{,}66 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

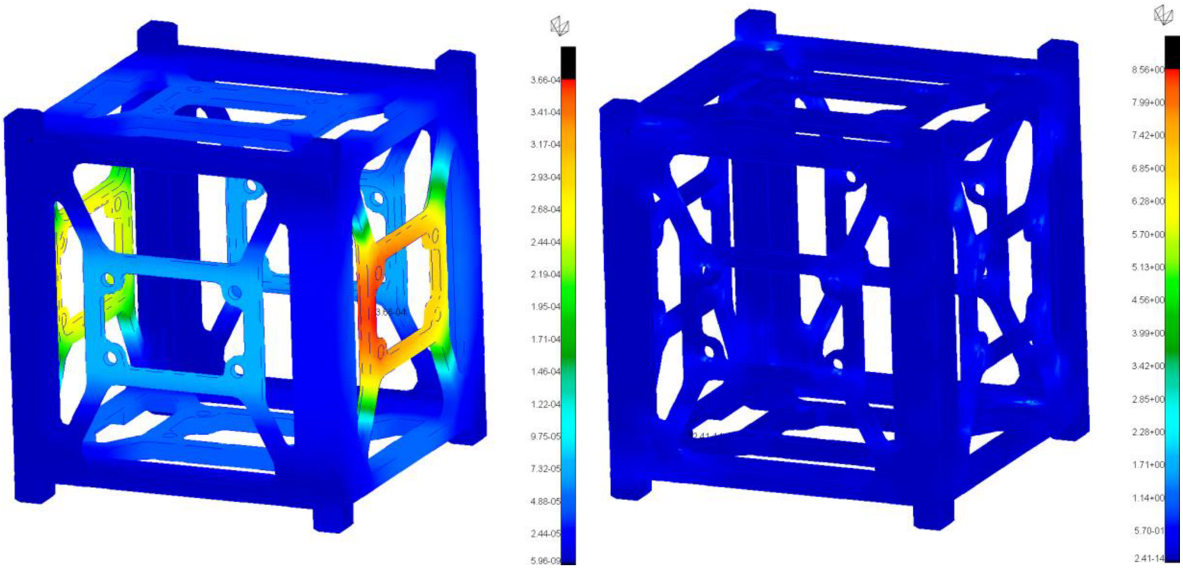


Figure 39 Visualization of the displacement (left) and the stresses (right) of the Y loads

Z load direction subcase

The maximal load in this subcase is on the Z- faces of the rails on the rail panel and the value is 5,98 MPa. The loads around the mounting points of the other equipment are around 2 MPa. The maximal displacement is on the top panel where the camera assembly is located, and the value is $2{,}51 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

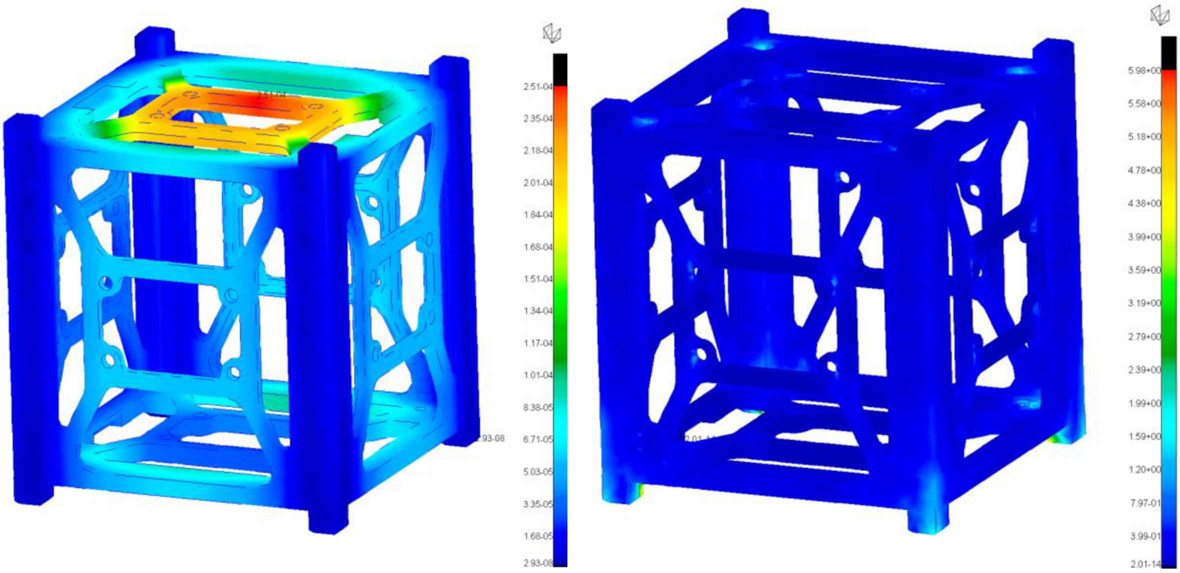


Figure 40 Visualization of the displacement (left) and the stresses (right) of the Z loads

XY load direction subcase

The maximal load for this subcase is again in the mounting holes for the PCB stack and the value is 6,78 MPa. The loads around the other mounting holes are around 2,25 MPa. The displacement is mostly prominent on the rail and support panels (X and Y panels). The maximal displacement is on the support panel with the central interface panel and the value is $2{,}6 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

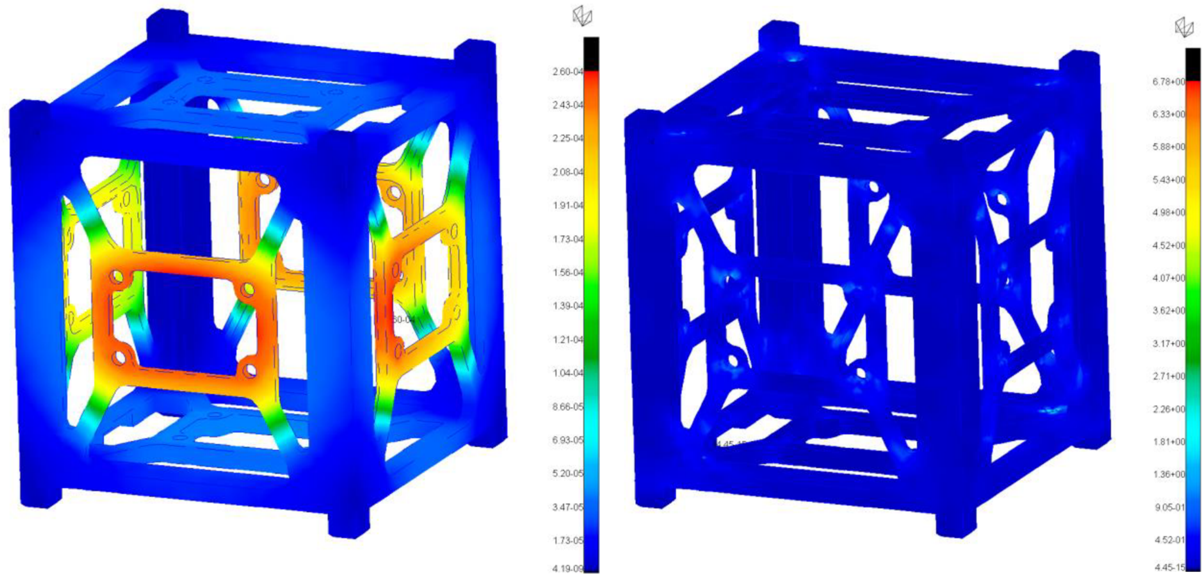


Figure 41 Visualization of the displacement (left) and the stresses (right) of the XY loads

XZ load direction subcase

The maximal load in this subcase is also in the mounting holes for the PCB stack and it's 7,4 MPa. Another substantial load is on the Z- side of the rails on the rail panel and it's 3,45 MPa. The loads on the other mounting holes are around 2,45 MPa. The displacement manifested on the rail panels and the top and bottom panels (X and Z panels), but the maximal displacement is on the rail panels (X+- panels) and it's $2{,}796 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

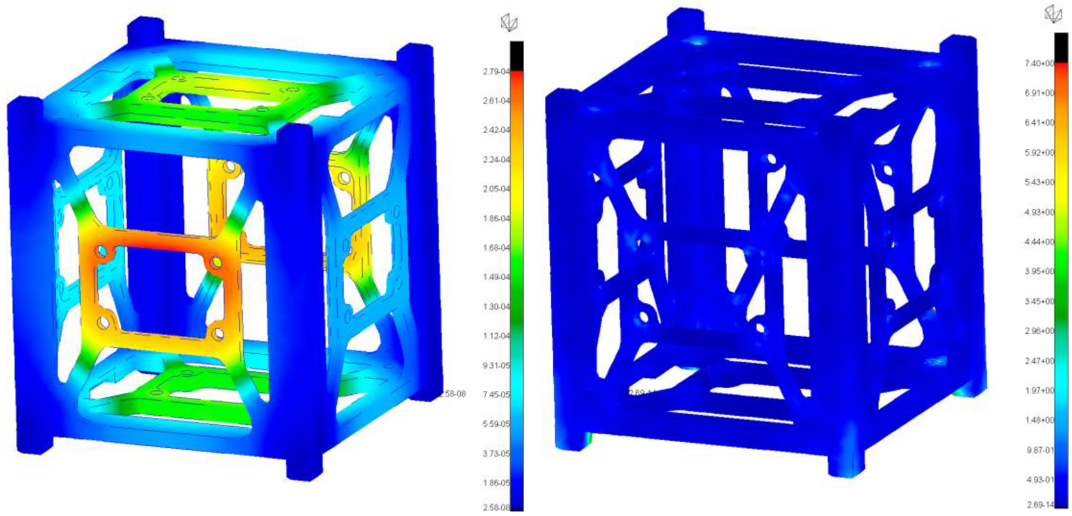


Figure 42 Visualization of the displacement (left) and the stresses (right) of the XZ loads

YZ load direction subcase

This load case is the second highest where the maximal load is 8,25 MPa and it's located in the mounting holes of the PCB stack. As in the previous load case there is also substantial load on the Z- face of the rail on the rail panel and the value of this load is 4,8 MPa. The other loads on the other mounting holes are around 2,75 MPa. The displacement is most prominent on the support and the top and bottom panels (Y and Z panels), and the maximal displacement is located under the central interface panel on the support panel with the value of $2{,}68 \cdot 10^{-4}$ mm. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

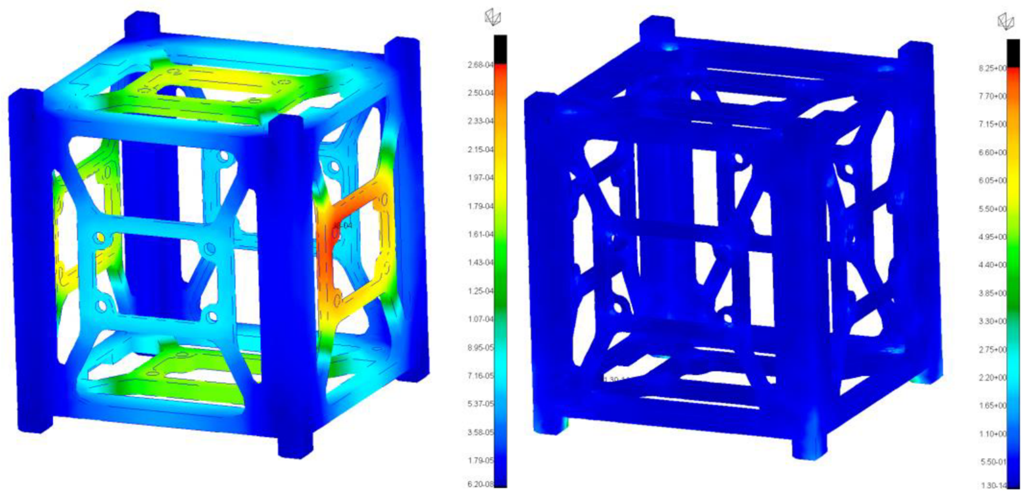


Figure 43 Visualization of the displacement (left) and the stresses (right) of the YZ loads

XYZ load direction subcase

In the last case the maximal load is located in the mounting holes for the PCB stack and the value is 7,37 MPa. Other major load is on the Z- faces of the rails on the rail panel ant there the value is 2,5 MPa and the load on the other mounting holes is only around 1,4 MPa. The maximal values are nearly identical on the support and rail panels and the value is $2{,}16 \cdot 10^{-4}$ mm in both cases. The maximal stress is under the maximal stress limit, even for the σ_3 direction.

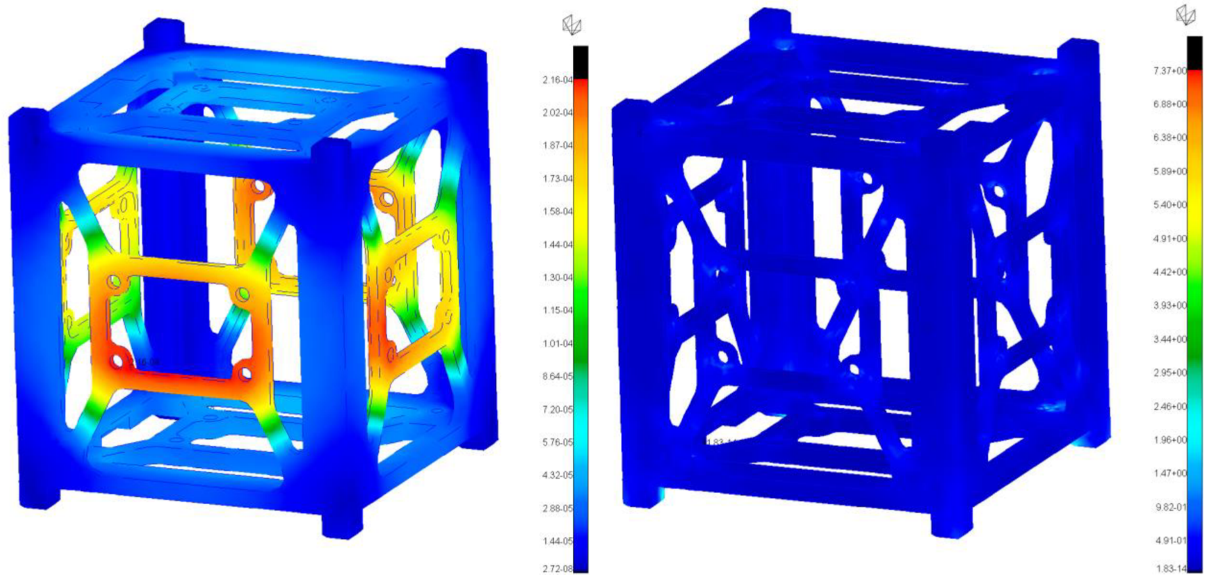


Figure 44 Visualization of the displacement (left) and the stresses (right) of the XYZ loads

6. Conclusion

The main goal for this thesis was to document the process of design and subsequent load analysis of a CubeSat frame with set parameters for internal and external equipment onboard. The frame was designed with non-standard approach in material choice and the final assembly interface, which was the use of high temperature 3D printed plastics and the use of adhesives.

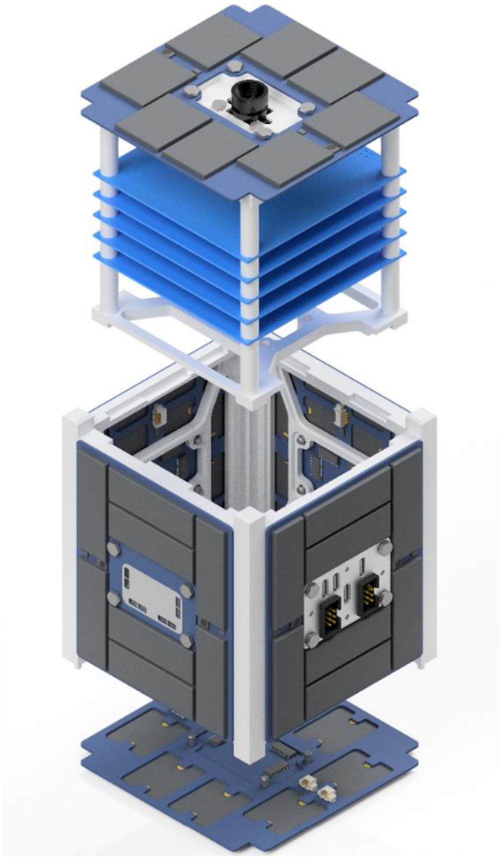


Figure 45 View of the CubeSat

The design was approached with ease of assembly and high rigidity in mind as the plastics are not that rigid by them self. This was achieved with the clever use of shaped elements in the design. The core of the frame consists out of 6 panels. On these panels is mounted the necessary equipment such as the PCB stack, solar packs, interface panel, kill swich assemblies and separation springs.

As for the analysis the frame is satisfactory for the conditions presented where the maximal load on the frame is 8,56 MPa and the maximal displacement $3{,}6616 \cdot 10^{-4}$ mm. As those values don not exceed the maximal stress loads of the material in any direction then we can conclude that the design is successful.

7. Bibliography

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8. Figure list

9. Table list

10. List of attachments

1. Assembly.3mf
2. Assembly_2.3mf
3. Assembly_3.3mf
4. Assembly_4.3mf
5. Bottom_part.stl
6. Camera_adapter.stl
7. Celek.stl
8. Rail_part.stl
9. Standoff_20.stl
10. Standoff_25.stl
11. Standoff_851.stl
12. Support_part.stl
13. Switch_actuator.stl
14. Switch_plunger.stl
15. Top_part.stl