

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**A NEW CONCEPTUAL STRUCTURE
DESIGN FOR NANOSATELLITES**

**M.Sc. Thesis by
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FOREWORD

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ABBREVIATIONS

ADCS	: Attitude Determination and Control System
CAD	: Computer Aided Design
CAN	: Controller Area Network
CNC	: Computer Numerical Control
COMM	: Communication
EPS	: Electronic Power System
FEA	: Finite Element Analysis
GEO	: Geostationary Earth Orbit
GPS	: Global Positioning System
IMU	: Inertial Measurement Unit
ITU	: Istanbul Technical University
ISRO	: Indian Space Research Organization
LEO	: Low Earth Orbit
NASA	: National Aeronautics and Space Administration
OBC	: Onboard Computer
PCB	: Printed Circuit Board
PPOD	: Poly Picosatellite Orbital Deployer
PSLV	: Polar Satellite Launch Vehicle
RQ	: Requirements
SPL	: Single Picosatellite Launcher
UHF	: Ultra High Frequency
VGA	: Video Graphics Array
VHF	: Very High Frequency
XPOD	: Requirements

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A NEW CONCEPTUAL STRUCTURE DESIGN FOR NANOSATELLITES

SUMMARY

This thesis is about the structure and mechanism subsystem of the ITU pSAT II satellite project of Control and Avionics Laboratory of Istanbul Technical University Aeronautics & Astronautics Faculty and supported by TUBITAK.

This thesis will start by giving a brief history of cubesats in general, and then describes the specifically ITUpSAT I. Second chapter gives information about several subsystems of the second cubesat project in Turkey, ITU pSAT II.

Third chapter is about specifically structural subsystem of the project ITUpSAT II. In this chapter, brief information is given for design philosophy of a satellite, launch vehicle, and deployment system, cubesat standardization, structural and physical requirements of the satellite and material and launch loads.

Fourth and fifth chapters describes these two different concept design that built for cubesats and specifically ITU pSAT II. Modeling, analyzing and results are discussed for both of them and one is selected finally.

NANO UYDULAR İÇİN YENİ BİR KONSEPT YAPI TASARIMI

ÖZET

Bu tezin konusu İstanbul Teknik Üniversitesi Kontrol ve Aviyonik Laboratuvarı tarafından yürütülen ve TUBİTAK tarafından desteklenen ITU pSAT II uydu projesinin yapısal altsistemiyle alakalıdır.

Bu tez, genel olarak küp uydular hakkında kısa bir tarihçe vererek başlıyor ve sonra özel olarak ITUpSAT I'ı tanımlıyor. İkinci bölüm Türkiye'nin ikinci küp uydusu olan ITU pSAT II'nin pek çok alt sistemi hakkında bilgi veriyor.

Üçüncü bölüm özel olarak ITU pSAT II projesinin yapısal alt sistemi üzerinedir. Bu bölümde, uyduların tasarım felsefesi, fırlatma aracı, ayrılma sistemi, küp uydu standartları, uydunun yapısal ve fiziksel gereksinimleri ve malzeme ve fırlatma yükleri hakkında bilgi verilmiştir.

Dördüncü ve beşinci bölümler küp uydular ve özellikle de ITU pSAT II yapısı için düşünülen iki farklı konsept tasarımı hakkındadır. Her ikisi içinde modelleme analizler ve sonuçlar tartışılmış ve sonuç olarak bunlardan biri seçilmiştir.

1. INTRODUCTION

Cubesats are nano and pico size satellites that are standardized in cubic sizes. The main goal of cubesats has been to make hard-earned space science and technology [1-4] readily accessible for students, engineers and even for some governments at a fraction of design/build/launch costs in comparison to standard satellite projects.

The most distinct properties of cubesats are weight and size. A standard cube shaped satellites must be less than 1 kg and its size must be approximately 10 cm per size that is called one unit -1U- cubesat. Correspondingly, 2U cubesats have 20*10*10 cm size and 3U's have 30*10*10 cm size, and also their weights increase respectively. This standardization makes easy compatibility between developers. Towards this end, in this paper we present the design and analysis of a modular 3U structure that gives provides the much needed flexibility to the satellite designers during the system integration phase. This modular structure is first tailored towards ITU pSAT II nanosatellite. ITU-PSAT II is the second student satellite project of ITU Controls and Avionics Laboratory, and the project aims to demonstrate on-orbit an advanced ADCS for nano-satellites (1-10 kg) with high precision three axis control needs.

Cubesat initiative that was started in beginning as an educational purpose. However, nowadays this initiative has been a sector for space missions. Universities, governments, private firms, even high schools are attempting to design their own cubesats with different mission and goals. Also big firms work cooperative with universities to test their subsystem or payload to reduce cost and risk of their big satellite launch. Not just organizations that develop cubesat also sub-sectors become have a say in this field. Several private firms develop and design satellite subsystems, bus systems, and various kits for these organizations. Until now, over 100 cubesats are developed and some of them are launched. Moreover, 17 cubesats are still active on orbit [5-6].

Furthermore, various adaptors that are single or multiple, are used cubesats to launch cubesats from launch vehicle to orbit. Poly-Picosatellite Orbital Deployer (PPOD) or Single Picosatellite Launcher (SPL) can be indicated as two of them [7-8].

Big satellite missions to LEO or GEO are pretty costly. For these kinds of satellites governments and big companies, expend millions of dollars to launch. In such a medium, for universities or small companies to design, build, and launch a satellite is not an easy affordable budget. Cubesat developers that design and built the satellite low cost, cannot afford this huge budget to launch. For this reason, cubesats usually launch as an auxiliary/secondary payload for launch site. Due to the fact that their lower weight and small size relative to the big LEO satellites, cubesats are allocated to small space in the rest of launch vehicle. In addition, they must be low risky for major satellite. In the past, a launch mission occurred that the launch vehicle was full of cubesats, but this mission unfortunately failed. In that case, to launch cubesat as an auxiliary payload seems the optimal way to launch due to the risk and cost.

1.1 Framework

Since 2003 when the first cubesat launch occurred, quite a lot of cubesats have been developed for various purposes. Over 50 cubesats have been mounted launch vehicles in order to put into the orbit among designed over 100 projects of cubesats [5]. Although some launch mission was concluded failure, several cubesats orbited successfully and there are still active satellites on orbit. Although primary mission of cubesats are generally to get telemetry and voice data, photograph or to actuate active control systems, some nano-pico satellites are launched for different private scientific missions such as biological experiment, earthquake detection, radiation measurement, cosmic dust detection, tether satellite experiments.

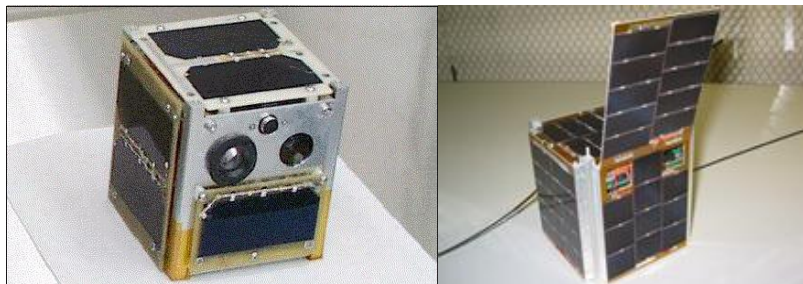


Figure 1.1 : CANX-1 [9], and CUTE-1 [10]

In the first cubesat launch mission, in 2003, Japanese CUTE-1, Canadian CAN X-1, Danish AAU Cubesat and DTUSat-1, XI-IV and American QuakeSat was launched

from Russia. In October 2005, three cubesats; NCube2, UAE-1, and XI-V was carried by Kosmos-3M Launch Vehicle. In addition, in 2006 CUTE1.7 and Genesat-1 was launched with different mission. In addition to these, a launch was aborted with 14 cubesats in Russia. The first stage engine shut down and the Dnepr Rocket was destroyed. Therefore, the board participation cubesat mission was unfortunately failure. After this rocket failure again Dnepr was appealed in 2007 in Baikonur, Kazakhstan and this launch mission ended in success and 7 cubesats were orbited. In the year of 2008, two launch missions occurred and the second one was failed. The first launch vehicle carried AAUSat-2, CAN X-2, Compass One, CUTE1.7, Delfi C3, and SEEDS (2). All of them except CAN X-2 are still active [11].

On 3 August 2008, the Falcon -1 rocket was destroyed with two NASA cubesats. PRESat and NanoSail-D were lost due to launch failure. There were three launches in 2009 in May, July, and September and total 10 cubesat launched respectively by Minotaur-1, Space Shuttle Payload Launcher (SSPL), and Polar Satellite Launch Vehicle (PSLV). In the third mission of 2009, Turkish ITUpSAT-1, Swiss Swisscube, and German BEESAT and UAE-2 were launched from India and all these cubesats are still active. Two more missions occur in 2010 from India and Japan and total six satellites were launched. Lastly, in 2011, KySat-1, Hermes, and Explorer-1 were launched by Taurus-XL rocket from United States and the unfortunately this mission was failure [5-6].

Some of the first cubesats were designed as a test platform. They just have basic spacecraft bus systems such as structure and mechanism, power system, onboard computer system, communication, and attitude control system. For this type of mission, CANX-1, AAU Cubesat, Cubesat XI-IV and CUTE-1 from the first launch can be given as an example that are all 1 U cubesats. While AAU Cubesats just sent beacon signals, Cubesat XI-IV sent image from the space and the camera of CUTE-1 used as a sun sensor.

On the other hand, a few cubesats developed to focus science mission objective. For example, QuakeSat was developed by students of Stanford University and launched in 2003. Even though there is not any accurate forecasting for earthquake, they are tried to change this by using a new method. They searched emission of Extremely Low Frequency magnetic signals. The mission is to detect, record, and downlink

these data. After launch, they achieved the mission target for months and downloaded over a gigabyte of data.

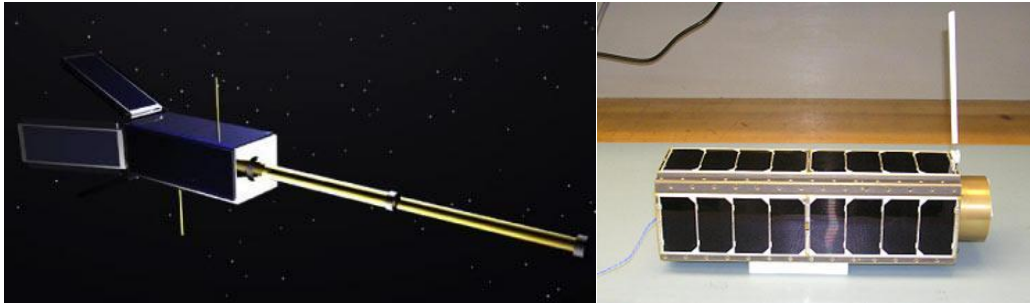


Figure 1.2 : QuakeSat-1 [12] and GeneSat-1 [13]

Also, another example of scientific cubesats is GeneSat-1 launched in 2006. This project was a collaboration of organizations that are between NASA Ames, industry partners, and universities. This satellite consists of 1U bus system and 2U payload. The goal was to develop the miniature life support system. Researchers noted that information gained from GeneSat-1 would help them realize how spaceflight affects the human body. Onboard micro-laboratory of GeneSat-1 can detect proteins that are the products of specific genetic activity. Almost two days after launch experiments of the biologic mission was complete and all of the data had been downloaded.

1.2 ITUpSAT-1

ITUpSAT-1 is the first Turkish student satellite and the first cubesat project of Turkey. The project was carried at Astronautical Department of İstanbul Technical University and manufactured and integrated at ITU Controls and Avionics Laboratory. ITUpSAT-1 was launched on 23 of September 2009 by the Polar Satellite Launch Vehicle from the Sriharikota city in India. The first goal of this project was education in space engineering. Students that work at Controls and Avionics Laboratory gained an educational, experimental heritage from this project. Besides, technically mission objective is to capture an image from space and download it [14].

ITUpSAT-1's main structure and all fasteners bought from Pumpkin Inc. Company. In addition, on board computer bought from Pumpkin, too. Electronic Power System, batteries, and solar panels are designed by our laboratory and produced by Clyde Space Company. Besides, passive control system is used in the satellite by orienting a magnet. As a payload, a VGA camera, three axes accelerometer, gyro and 'hayati'

board. Therefore, technically ITUpSAT-1 has to capture low definition image and to get beacon (voice) signal from 'hayati' board and telemetry data from sensors in order to reach target.

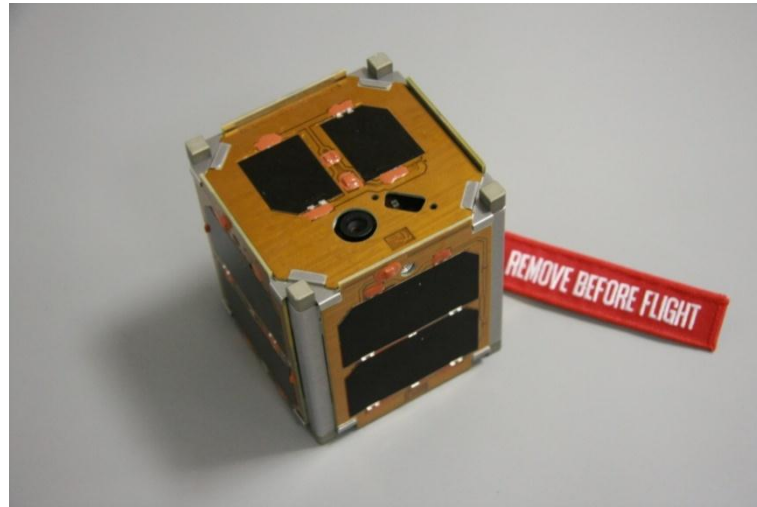


Figure 1.3 : ITUpSAT-1

After launch of ITUpSAT-1, in three hours the first beacon signals are taken by ground station in Satellite Telecommunication Lab. in ITU. In the first day, reports of signal received from other stations and civil those have amateur radio all over the world. Moreover, the first telemetry data and a half of photograph data are received from ground station in the first night. Finally, technical and educational missions of ITUpSAT-1 have accomplished.

2. ITU pSAT II PROJECT

This project aims to create a platform sized about a pico and nano satellite dimension (1-10 kg) that can be attached to different jobs, and while doing that, aims to make some key technologic advancement. The remaining of the project is about manufacturing the first sample of the platform, testing and enabling it for flight.

While pSAT I, which is sponsored by TUBITAK and is first satellite project of ITU, a lot of ability about academic know-how and engineering experience was gained. These abilities enclose analyzing, design, development, manufacturing, test, and operation phases for whole satellite. In this development phase, many deficiencies and many areas that are open to development in whole Turkey and world about pico and nano satellites are discovered. The aim of this project is filling a gap about pico and nano satellites' high performance orientation control, structure and mechanics in Turkey and whole world.

This defined key techs, and scope of our project can be summed in two headings. These are high performance nano satellite orientation determination and control systems with structure and mechanisms respectively. In this project scope, a low cost star-tracker and high performance orientation control computer and determination sensor for nano satellites will be developed. A complete set of micro reaction wheel control system will be tried in nano satellites for the first time. In development of structures and mechanism techs, composite structure application and highly risky mass constraints will be developed. Nano satellite platform will have the capabilities to carry scientific experiments. So, physics, astronomy, meteorology, and such sciences can access to space based platform.

The impact of this project is:

- Decreasing deficiency of our country in this field, pico and nano design in university, test and manufacturing in institutional and practical areas, increasing the knowledge and improving the techs.
- Bigger and better satellites' design and manufacturing, increasing the experience of engineers about this field.

- High technologies can be sold for cheap prices in the future in our country.
- Satellite design and manufacturing number of people will increase.

2.1 Sub- Systems of ITU pSAT II

Up to now, the concept design of ITU pSAT II is completed. All equipment's are ordered and some of them are reached. Weight, power and link budgets are approximately calculated. Subsystems excluding structure subsystem will be mentioned in this section elaborately.

Table 2.1 : Weight and Power Budgets of ITU pSAT II

Components		Number	Weight (gr)	Total Weight (gr)	Power (Min) (mW)	Power (Max) (mW)
Structure						
	Top and bottom surface	2	35	70		
	Lateral surface	2	170	340		
	Fasteners	1	50	50		
	Cabling	1	100	100		
Solar Panel					0	0
	1U (bottom) Panel	1	60	60		
	1U Standard Panel	1	55	55		
	3U Panel	3	180	540		
EPS						
	EPS Board	1	105	105	250	250
	Battery Board (w/ four batteries)	1	213	213		
OBC	PCB Board	1	70	70	250	250
COMM						
	VHF Transceiver Li-1 UHF/VHF Radio	1	52	52	200	10000
	S-Band Transmitter with patch antenna	1	92	92	0	4000
	Deployable Antenna	2	10	20		

Table 2.1 : Weight and Power Budgets of ITU pSAT II (continue)

Components		Number	Weight (gr)	Total Weight (gr)	Power (Min) (mW)	Power (Max) (mW)
ADCS						
	ADCS Computer	1	70	70	0	1500
	Sensors					
	IMU(Gyro+Acc+Magnetometer+Temp)	1	70	70	0	367,5
	Magnetometer	1	7,5	7,5	0	120
	Gyro	4			0	4x220=880
	Sun sensor	5(4)			0	0
	Temperature	4			0	4x1,6=6,4
	Actuators					
	Magnetorquer	4(3)			0	3X330
	Reaction wheel (with aluminium box)	3	60	180	0	3000 x 3 = 9000
	Magnetoboom					
	Mechanism + arm + housing	1	40	40		
	GPS				0	1000
	PCB Board	1	70	70		
	GPS Receiver	1	60	60		
	GPS Patch Antenna	1	50	50		
Payload						
	Payload	1	1200	1200	0	5000
	Voltage Converter	1	12	12		
	Patch Antenna	1	100	100		
Camera						
	Camera sd card interface board	1	70	70	0	100
	Housing	1	40	40		
	Nex-5 Camera module	1	230	230	0	500
	Lens (16mm)	1	67	67		
				4033,5		

2.1.1 Attitude Determination and Control

ADCS of ITU pSAT II consists of three distinct hardware layers integrating sensors, actuators, and ADCS computer over the CAN bus [15]. The sensor layer embeds a set of low-cost inertial and magnetic sensors, sun sensors, a GPS receiver and an in-house developed multifunctional camera/star-tracker. The actuator layer includes a redundant assembly of reaction wheels, magnetic torquer coils and an experimental set of uPPTs(micro pulse-plasma thrusters). The ADCS computer system design embeds a Blackfin processor and interfaces to the dual data bus system. In addition the magnetotorquer drivers and the reaction wheel drivers are implemented on this compact unit. The ADCS computer provides analog and digital data interfaces to the sensor board and the external magnetometer which is located at the end of the boom mechanism. In addition to the GPS unit which is embedded to the bus system, the ADCS houses the following attitude determination sensors :

External Magnetic Field Sensor : Honeywell HMR 3300

Inertial Sensor and Internal Magnetic Field Sensor : Analog Devices ADIS 16405

Sun Sensors : Silonex SLCD-61N8 photodiodes

The complete set of sensors provide acceleration, angular velocity, internal and external magnetic field strengths on the three body axes. In addition, using the photodiodes on each panel, the panel illuminations and thus coarse sun sensing data(i.e. the sun vector) is obtained after filtering. Current actuator assembly for ADCS system consists of four magnetic torque generators and four reaction wheels completing a fully redundant set. An inhouse developed uPPT system is also included only for experimental purposes including additional momentum dumping capability.

2.1.2 Electrical Power System

ITU pSAT II is a 3U cubesat have approximately 0.14 m² surface area. With solar panels on each side, excluding the areas that are occupied with communication and magnetic boom, peak power produced by the satellites will be about 11 Watts by using 28% efficient solar cells. Electrical Power System (EPS) prototype circuit includes CAN BUS interface, microcontroller, current measurement module, regulator module and battery charger module. The EPS and the battery board of the

bus are customized Gomspace P31U-S and BP4-S units respectively. As configured the EPS can provide two regulated power buses: 3.3V@5A and 5V@4A. The battery board embeds 10.4 Ah and approximately 39Wh capacity.

2.1.3 Communication

On-Board Computer (OBC) unit of ITU pSAT II includes an AstroDev Li-1 UHF Transceiver module for communication purpose with ground station. Depending on the satellite power, the transceiver module can be configured to transmit across 250mW to 4Ws at 9.6kps. This UHF uplink/downlink provides the main T&TC functionality on the ITU pSATII.

2.1.4 Payload

ITU pSAT II embeds two experimental payload units excluding the ADCS system. These units are Camera/Star Tracker: Aerocon customized Sony Nex-5 camera unit, and S-Band Transmitter: Aerocon customized AstroDev Be-1 S-band transmitter with cap antenna.

The camera system is a customized and space environment modified Sony NEX-5 unit. This compact unit embeds a 14.2 megapixel image sensor with photograph and video recording capability. The images taken by this unit are not only used for earth imaging but also star tracking and thus absolute attitude determination.

The S-Band transmitter unit is a customized AstroDev Be-1 S-Band transmitter which allows us to downlink precious science and image data at speeds up to 600 kbps. This unit can be configured to transmit up to 2 Watts.

2.2 Structure & Mechanic Systems of ITU pSAT II

Structure and mechanism system of ITU pSAT II is the main subject of this thesis. Within the scope of the project,

- The lightest configuration of the structure that subject to loads come from launch vehicle will be provided with structural shape optimization. The best-optimized and convenient structure among 3U cubesats in market is targeted.
- Deployable solar panel will be allocated to structure if the system needs more energy for other mission to increase the energy opportunity. By considering,

the energy need and weight factor extra two or four solar panels will be deployed.

- To provide a lighter structure according to aluminum frame, usage of composite material is targeted. In satellite technologies, weightiness is one of the best important things due to the fact that the launch cost is directly depend on the mass. Since to use of composite material in big satellites have risk factor, to try experiment of composite material in cubesat is more sensible. This will be one of the first examples all around the world.
- Mechanism of deployable dipole antenna and magneto boom will be designed. Magnetometer must be far away from the satellite not to change magnetic field and so a boom is needed.

3. ITU pSAT II STRUCTURE

3.1 Design Philosophy

Satellite structure has gone through several phase from concept design to final model [16-17]. After every phase, requirement and constraints are checked whether were fulfilled. A design flowchart is composed to show all phases in Figure 3.1. For example, if the structure design cannot fulfill the launch requirements after Finite Element Analysis, we should turn back to design phase. While for some designs, just modeling was sufficient, for some special designs even prototyping were done to visual design concepts. On the other hand, computer programs were used to simulate space and launch environment. Besides, designs that are manufactured should be tested to verify simulation programs.

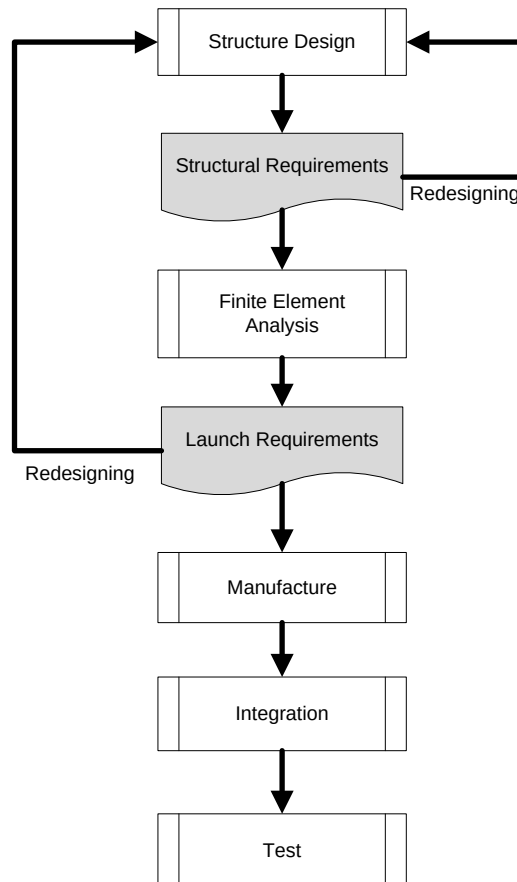


Figure 3.1 : Design Flowchart

3.1.1 Modeling

Modeling is the first and important step to design a satellite, because it simplifies the whole process. Computer Aided Design (CAD) Programs are used to model structures. The major advantage of use of CAD is reduction of time. In addition, it provides to reduce to use of physical models and prototyping. It is a quick and easy way to focus details and visualize physical changes when needed. By means of CAD modeling, deficiencies in some parts or incompatibility between equipments can be seen in the phase of modeling without pass to analysis phase.

In this project, CATIA V5R18 is used to model as CAD Programming.

3.1.2 Analyzing

Finite Element Analysis (FEA) is the second step of the design process. FEA is extremely useful to check strength of components and main structure for various loading conditions. Modeled structure in CAD program is imported to FEA program to simulate launch and space environment, especially for structural and thermal loading. The selected structure is meshed on FEA Program. Boundary conditions and loading are defined. Finally, static and dynamic analyses are completed for cubesat to define maximum stress distribution and natural frequencies. If the satellite structure cannot resist stressing under structural loading, after analyzing, modeling phase should be repeated. For the ITU pSAT II, every modeled structure in CAD to try concept design was analyzed in FEA Program. All analyses were performed often that served to quick feedback in design step.

In this project, ANSYS Workbench 11 is used as FEA Programming for simulation.

3.1.3 Manufacturing

Prototyping/Manufacturing is generally costly and time losing step for design process. Nevertheless, some components or main structure parts should be prototyped to visualize deficiencies and coincidences [18]. Although there are no problems about CAD or FEA, real models can be different for some cases. On the other hand, sometimes for moving particles such as solar panel or boom mechanisms should be needed to manufacture. For this kind of situations, rapid prototyping can be more beneficial.

For example, for our project a real model including all components and main structure parts is manufactured in Laser CNC Machine to see face-to-face contact. One mm Plexiglas is used to manufacture it. In addition, a designed deployment boom mechanism is prototyping by using aluminum.

3.1.4 Integration

After all components completed, integration should be performed. Especially to see the assembly sequence and compatibility between main structure, components, and deployment systems is very important. Ease of integration is a selection criterion for designed structure. If a structure has ease of integration and less number of fasteners, it can be more usable and selected in the case of having similar properties such as cost and stress distribution.

3.1.5 Testing

Testing is the most important and inalienable part of design process [2-19]. The vibration test and thermal vacuum test should be completed to simulate real launch and space environment. According to testing requirements in CDS, random vibration, thermal vacuum bake-out, qualification, and acceptance tests should be performed as defined by launch vehicle provider. In addition, functionality tests for satellite should be carried out for after every test process.

Testing is also the longest and most painful step of the cubesat design process. To have available infrastructure systems such as testing facilities is the one of the important step to accelerate the process. If you have testing facilities in your lab, you can start the process whenever you need. Istanbul Technical University has a Thermal Vacuum Chamber in Space Systems Design and Test Lab and a Shaker Table in Vibration and Acoustic Lab in Mechanical Faculty.

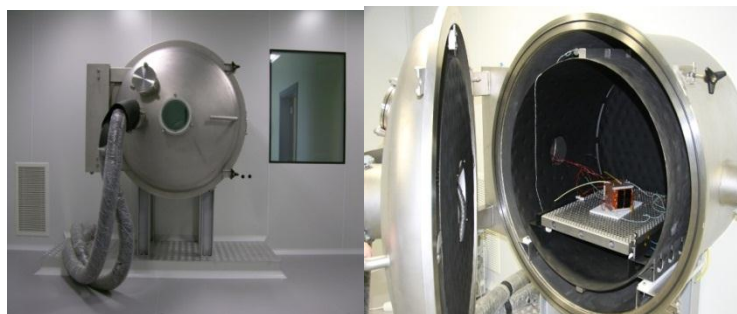


Figure 3.2 : Thermal Vacuum Chamber of ITU

3.2 Launch Vehicle

In the beginning of the project, the launch vehicle should be defined according to the mission. The satellite's polar orbit will be approximately 700 km. In the scope of that, for the mission of ITU p SAT II, The Polar Satellite Launch Vehicle is the best compatible launch vehicle when consider cost and orbit computation. Characteristic properties of PSLV will be discussed in following parts such as loads.

The PSLV is the first operational launch vehicle of Indian Space Research Organization (ISRO). 1600 kg satellites in 620 km sun-synchronous polar orbit and 1050 kg satellite in geo-synchronous transfer orbit are able to launch via PSLV. It measures 44.4 m tall, with a lift off weight of 295 tones in general configuration. It uses solid and liquid propulsion systems in four stages by turns [20].

Until April 2011, there had been 17 continuously successful flights of PSLV, and it has the reliability rate. With its variant configurations, PSLV has proved its multi-payload, multi-mission capability in a single launch and its geosynchronous launch capability [20]. Besides, PSLV had carried several cubesats to orbit. For example, on September 2009, PSLV C14 launched with OceanSAT2 and two nanosatellites and four picosatellites into 720 km. intended Sun Synchronous Polar Orbit. The first satellite of ITU is one of them. Therefore, after this successful mission, ITU p SAT II is decided to launch via PSLV. In Figure 3.3, lifting off PSLV C14 is shown [21].



Figure 3.3 : PSLV-C14

For safety launch of satellite, there are some requirements to do during and after launch. Cubesats should be powered off during launch, and should be activated after

deployment. Deployment of antennas or radio transmission is not allowed during the first 15 minutes after separation from the deployable system. In addition, large deployables such as solar panels can be deployed 30 minutes after separation, and high power radio transmission is allowed [7].

3.3 Deployment System

Deployment System is an important step to provide reliable and cost-effective launch. The adaptor is the interface structure between the satellite and launch vehicle. Cubesats should be well suited with the deployment mechanism to ensure safety and success of the mission. Generally, there are a rectangular aluminum box, a door and a spring mechanism inside the system.

To design and provide deployment systems become widespread between cubesat developers. There are various interface structures for 1U or 3U cubesats. The standardized by Cal Poly and best-known cubesat deployment system is the PPOD [7]. PPOD have ability to carry three 1U cubesats or one 3U cubesat. Several successful flight missions were carried by PPOD in the past. The eXperimental Push Out Deployer (X-POD) was developed by Space Flight Laboratory University of Toronto. Besides, ISIPOD is developed by Innovative Solutions In Space (ISIS) Company. In addition to these 3U cubesat deployers, Astro-Fein has developed a 1U cubesat deployment mechanism that the name is Single Picosatellite Launcher (SPL). ITUpSAT-1 was launched by using SPL [8].

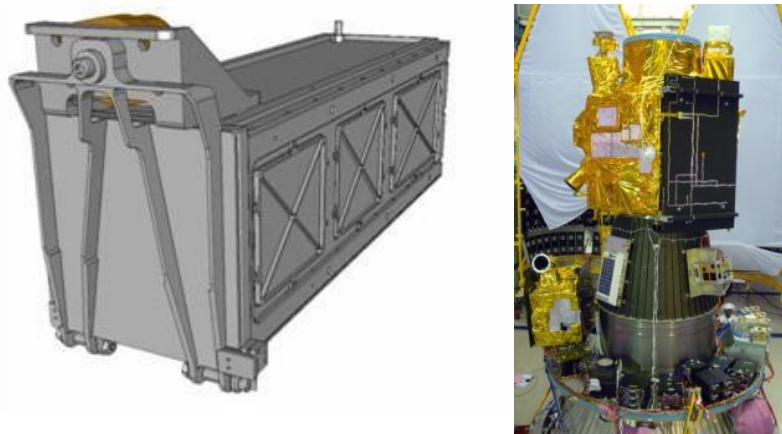


Figure 3.4 : PPOD and Its Allocation in Launch Vehicle

3.4 Cubesat Standardization

Within the scope of the Cubesat Program, the Cal Poly determines “Cubesat Design Specifications” that is mentioned about constraint and requirements of the design [22]. Some rules about the structure design must be implemented to compatibility to interface adaptor. For example, all parts of satellite shall remain attached during launch, ejection, and operation. Risky materials shall not use on cubesat. Materials of cubesat must have low out-gassing property. Features and physical dimensions of design are showed in the Cubest Specification Drawing in Appendix A.1. Nevertheless, just mechanical requirements will be mentioned in this part.

- Each triple cubesat mass should be low in 4 kg.
- Center of gravity of the cubesat should be allocated within a sphere of 2 cm from its center of geometry.
- For cubesat main structure, AL 6061 or 7075 should be used. Since, the material of satellite should be similar properties with the material of adaptor.
- The cubesat’s contact areas with the adaptor should be hard anodized.
- The coordinate system of the cubesat should be the same with the CDS Drawing for compatibility with the adaptor.
- The cubesat’s wide should be 100 ± 0.1 mm for X and Y directions. In addition, a triple cubesat’s tall should be 340.5 ± 0.3 mm for Z direction.
- No components should exceed 6.5 mm normal to the surface of the 100 mm cube.
- Exterior surface of the cubesat should not contact with the interior surface of adaptor such as deployable panels and antennas.
- Rails should have a minimum width of 8.5 mm and at least 75% of rails should contact with the adaptor rails.

3.5 Mechanical Requirements and Objectives of the Project

There are some requirements and objectives specifically determined in the project. Those are mentioned elaborately below.

The sizing of the satellite in the main three dimensions, the design of rails in corners and solar panels, and protrusions for the six sides of the satellite are decided according to the “Cubesat Design Specifications” constraints.

In addition to structural requirements that are given in the “Cubesat Design Specifications”, the following requirements are underlined for our design:

- The weight of satellite main structure (bearing frame) should be less than 450gr,
- The number of fasteners (such as screw, nut, spacers, and metal bar) that are used for connecting subsystems, solar panels and main structure should be minimized for operational ease,
- When the satellite change mission to mission, the cubesat structure should be fulfilled the new mission. A unique structure design should be respond for all payload changes,
- Internal volume of cubesat should be maximized, and external volume should be modular to add deployable solar panel when required. Besides ease of access to satellite internal volume should be provided during integration,
- Satellite main structure should be multi-functional. The structure should allow design modifications (such as subsystem size and position change) to be made without any changing the main structure of the satellite during the design, manufacture, and test,
- All carrier boards of satellite subsystems should be put into main structure as horizontally or vertically when it is required.

3.6 Design of ITU pSAT II Structure

In this thesis, the optimum structure design will carried out within the scope of requirements that mentioned above. To find the well-situated design for the cubesat many design solutions are studied. All constraints are reviewed and requirements that determined in the CDS and project draft are examined. According to both CDS and the project requirements, designed tens of structures are eliminated. While the selection of convenient structure is gone on, weight factor, internal volume, material

selection, and strength are considered. Finally, selected two designs are elaborately studied. Both of these two designs are detailed in next two chapters.

3.6.1 Material Selection

The selection of material is one of the significant steps on design of satellite structure. Since weightiness is an important factor for on-orbit object. Specially, for 4 kg cubesat, a little change of structure, so mass, makes valuable space for other subsystems, components. Not only weight factor, but also strength, stiffness, thermal conductivity, thermal expansion, manufacturability, and cost factor are considered while satellite designed [23]. Material requirements are given below;

- All materials that will use in satellite should be selected from list that NASA determined.
- Thermal expansion coefficient of the selected material should be similar with the material of deployment mechanism.
- Yield strength of the selected material should be bigger than max Von Mises stress.
- The material should be easy manufacturability.
- To minimize the mass the material that has low density should be selected.
- The material that has low out-gassing property should be selected.

Table 3.1 : Material Properties

Material	Density (g/cm ³)	Elastic Modulus (GPa)	Tensile Yield Strength (MPa)	Thermal Conductivity (W/m-K)	Manufacturability
Aluminum 6061 T6	2.7	68.9	276	167	Easy
Aluminum 7075 T6	2.81	71.7	503	130	Easy
Titanium	4.5	116	140	17	Hard
Stainless Steel	8	195	275	15.9	Easy
Magnesium AZ31	1.77	45	200	96	Hard
Composites	-	-	-	-	Hard

The materials and their properties, that used in cubesats up to now listed in the below table. Aluminum and the magnesium are distinguished among the material both have high strength and light. In addition to above requirements, thermal conductivity of the selected material should be high. In this case, aluminum is preferred for main structure according to list. In addition to our selection, CDS just determined special aluminum for cubesat's structure. Those are AL 6061 and AL 7075.

By considering weight, strength, coefficient of thermal expansion, manufacturability, and the cost criteria, AL-7075 is selected for the material selection of the ITU pSAT II structure. Even though AL 6061 T6 is lighter than AL 7075, we selected AL 7075 because of the fact that it has easier manufacturability. This is in compliance since the major material of the launch PODs is usually AL-7073-T73.

Besides, according to project requirements, composite material should be used in structure to try this kind of materials on cubesats. In that case, on condition that not used in main structure, it will try on secondary structures such as panel or board.

3.6.2 Loads

Predicting suitable loads is one of the hardest steps of designing a spacecraft. Because of the complexity and high variety of mission environments, little inaccuracies in the finite element models are capable of causing large errors [24-25]. During its launch, a satellite is subject to various external loads resulting from steady-state booster acceleration, vibro-acoustic noise, air turbulence, gusts, propulsion system engine vibrations, booster ignition and burn-out, stage separations, vehicle maneuvers, propellant slosh, payload fairing separation and ejection. These sources' characteristic feature is being random and independent [26].

Every event generates structural loads in the life of a spacecraft from launch to put on orbit. Even though launch causes the highest value loads for most spacecraft structures, any other event can be critical and significant for some parts of the structure, such as manufacturing, ground handling- testing, pre-launch preparations, payload separation, on-orbit operations, landing [27].

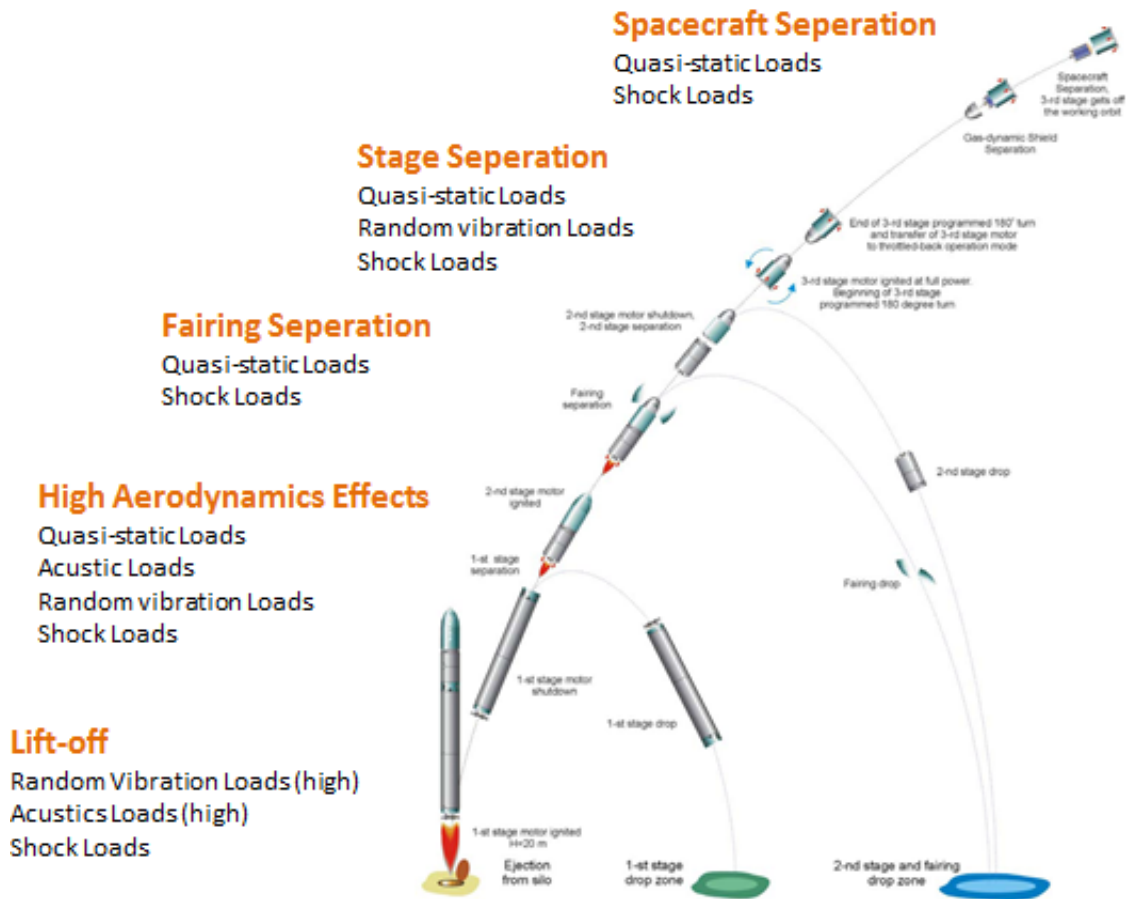


Figure 3.5: Launch of Launch Vehicle [28]

Launch contains a sequence of actions, and these events have some independent source of load which is related to the launch vehicle and payload. Some of the loads are comparatively steady-state or constant over time, such as thrust while a rocket engine burns while some of them are transient, such as thrust when rocket ignites or shuts down. Acoustic loads are sound pressure waves. As the majority of the acoustics consist of waves with various frequencies, they cause the random vibration of the structures. Pyrotechnic shock is high-intensity, high-frequency vibration ($>1000\text{Hz}$) caused by the explosive commonly used to separate stages.

Lift-off is definitely the most visually remarkable part of launch [29]. Furthermore, it causes complex and harsh dynamic atmosphere. After the main engines are ignited at lift-off, pressure grows quickly in the launch-pad's exhaust ducts. The air in the environment causes transient air pressure, or overpressure forces, which in turn affect the vehicle. These forces are important since they are asymmetrical about the vehicle. Design of the launch pad significantly has an influence on these forces.

At the transonic speeds where the vehicle come close to the speed of sound and passes through it, a complex loading environment forms again. Shock waves develop, changing the aerodynamic pressures, which affect the vehicle. The energy and positions of the shock waves alter very quickly and arbitrarily, and the location of them depends significantly on the space vehicle's structural configuration. Effects of these loads are vital; they come together with static air pressure, steady winds, wind shears and gusts, and the forces used for the booster stabilization and maneuvering.

Satellites also are exposed to acceleration during stage separation and payload fairing separation. "Any time a rocket engine ignites or shuts down, the launch vehicle and payload experience a transient force. Axial acceleration during any stage builds as propellant is used up, because there is less mass to lift. For some boosters, the slowly increasing axial acceleration before shutdown becomes so high that it alone can be a design driver, even if the transient loading of shutdown is insignificant [26]."

After launch vehicle gains adequate altitude, the air becomes sparse enough, and as a result, aerodynamic forces and thermal effects no longer affect the payload, and the fairing of the payload becomes unnecessary baggage. While the high energy of this occasion brings forces in all directions at the fairing's interface to the launch vehicle, the radial forces are self-contained within the fairing segments [26].

3.6.2.1 Quasi-Static Loads

As mentioned above, quasi-static loads are appeared during all launch period [30-31]. The launch period normally is dynamic however, we assume as a static. Therefore, load is called quasi-static. Using quasi-static loads, system can be simplified, and strength analysis can carried out. Because of the complexity of the system, FEA programming should be performed to find responds.

According to PSLV rocket, during launch, maximum static and dynamic accelerations occurring in spacecraft are given in Table 3.2 [28]. The design check should be carried out by applying a load factor of 1.25 to the below levels. The spacecraft should be able to endure a maximum static loading of 13.75 g in any direction for worst case loading. Here g shows the gravity and its value is 9.81 m/s².

Table 3.2 : Max. Acceleration of PSLV

	Longitudinal	Lateral
Max Static and Dynamic Acceleration (main satellite)	+7 g - 2.5 g	1.5 g
Max Static and Dynamic Acceleration (auxiliary satellite)	+11 g	+ - 6 g
+ Load Factor 1.25	+13.75 g	+7.5 g

3.6.2.2 Frequencies

To avoid dynamic coupling between low frequency modes of the vehicle and spacecraft, the Auxiliary Satellite should have frequencies bigger than 35 Hz in longitudinal axis and 20 Hz in lateral axis. These include the influence of the Satellite separation system [28]. Cubesats are determined as auxiliary satellites inside launch vehicle according to main spacecraft. Therefore, its' fundamental frequencies are not same with below that is shown in Table 3.3. In this case, fundamental frequencies of cubesats should be bigger than 90 Hz in longitudinal axis and 45 Hz in lateral axis.

Table 3.3 : Fundamental Frequencies of PSLV

Fundamental Frequencies	Longitudinal	Lateral
Main Satellite	≥ 35 Hz	≥ 20 Hz
Auxiliary Satellite	≥ 90 Hz	≥ 45 Hz

4. CONCEPT-A

Concept-A is the first structure design that is tried during design process for ITU pSAT II in the scope of Tubitak project. The aim of Concept-A design is to produce low cost and provide easy assembly. In Figure 4.1, the general view of satellite is demonstrated. This structure is designed according to requirements in CDS and project. The property of this structure is to compose faces. In this part, we explain in detail the design and the analysis phase of our design while step-by-step addressing deficiencies on the already developed and commercially available cubesat structures [32-35].

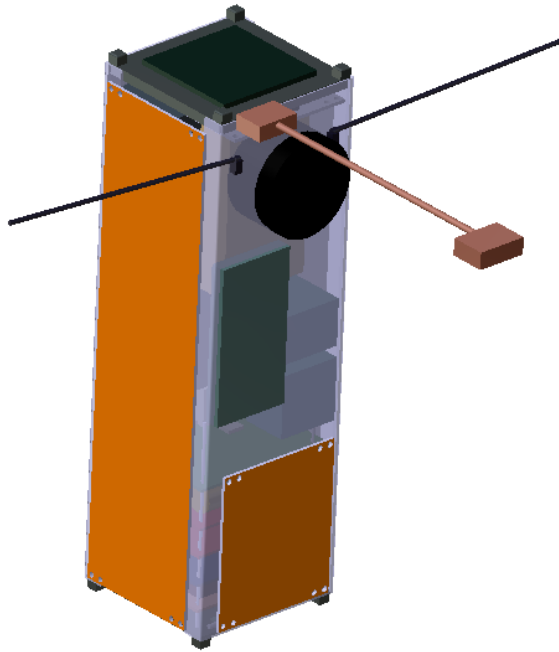


Figure 4.1 : General External Structures View

4.1 Modeling of Structure

In this design, the structure consists of faces. There are one bottom face, two side faces that are assembled with hinges reciprocally and one top face that is called as a hat. Specially, one of the main reasons of using faces is to increase internal volume of satellite. Moreover, in Concept-A, we designed internal allocations of satellite. the

material of ITU pSAT II is AL 7075. The total weight of the satellite structure is approximately 420 gr.

We need to put into satellite as much as possible equipment. Subsystems that are on the PCB104 boards such as EPS or OBC are connected to bottom faces via mile. Boards that are arranged in an order are connected each other electronically via connectors. This part is approximately 1U part of satellite. The 2U part, which is rest of satellite, components are allocated to reciprocal faces that are bigger than standard PCB104 boards. This reciprocal faces can be called as walls. The purpose is to allocate components to 10*34 cm size reciprocal walls without. There is no space in the top side of satellite when walls closed.

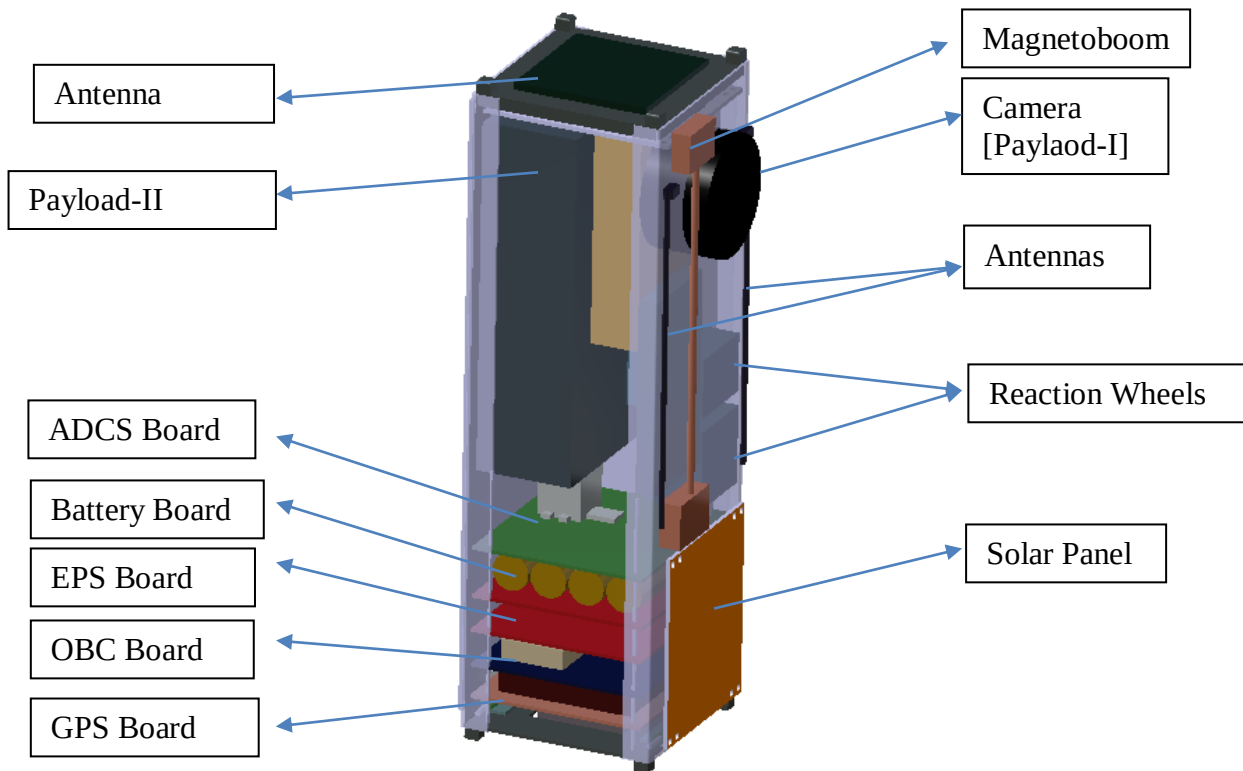


Figure 4.2 : General Internal Structure View

In this design, as mentioned above, reciprocal two hinges are used to connect side faces and bottom face at the bottom side of satellite. The aim of these hinges is to provide convenient usage of satellite during assembly and integration procedure. Satellite often is disassembled during functionality and physical tests. During these processes, satellite and all components should be kept from any damage. Work medium should be reliable and convenient. Satellite walls are opened when worked

on it and closed when needed. Opened structure and internal components can be seen in Figure 4.3.

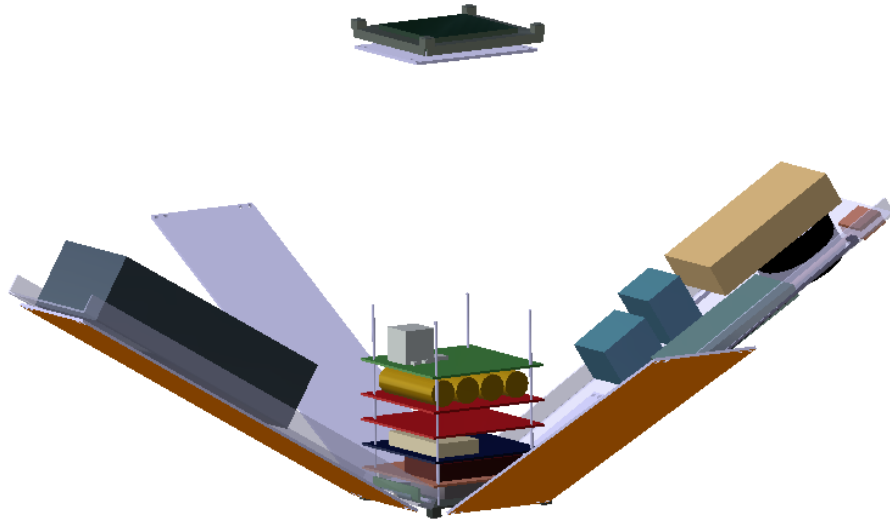


Figure 4.3 : Internal Structures

Subsystems boards' bottom to up respectively, GPS board, OBC Board, EPS Board, Battery Board, and ADCS Board that are arranged in an order to bottom face. As being standard cubesat bus, for PCB 104 Boards miles provide connection. Bottom face has a hole in the middle to put GPS receiver to it as seen in the Figure 4.4. In addition, there are spaces in the two edges of bottom face in order to freely open hinges. If we need, feet of satellite can be monoblock with bottom face. It can be caused hard producibility. On the other hand, feet can be used separately.

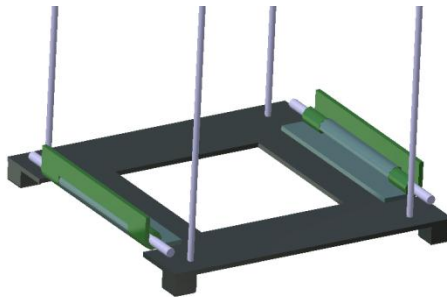


Figure 4.4 : Bottom Face

Walls in the (y) direction are used to hang these components. Some of them are connected to walls externally and the other internally. In this design, external structures such as antennas, solar panels, magnetoboom are connected to reciprocal walls externally. For example, in Concept-A payload box, which called black box,

reaction wheels, S band antenna, and camera are hung to walls internally. All these are demonstrated in the Figure 4.3.

1U parts of cubesat is used as a standard 1U cubesat bus system in Concept-A. In the rest of satellite, which 2U part, walls are full of components. In addition, camera, S band Patch Antenna, Magbeto-boom and deployable antennas and 1U solar panels should be external. In this case, (+y) wall is thought as an outward wall. Besides, 3U solar panels are allocated to (+x), (-x) and (-y) directions. There are not any solar panels or closed structure on top and bottom faces. Antennas should be directed to Earth or Space. For example, GPS antenna is directed to GPS satellites, so to space.

Two reciprocal sides are folded from two edges. Thickness of sidewalls is 1.5 mm. Solar panels in (x) direction are connected from these folded edges via screws. Because of the fact that there is not any mass in (x) sides, this method provides to minimize weight.

4.2 Advantages and Disadvantages

Design parameters that a satellite should have, are elaborately discussed in Section 5.2. Concept-A structure and Concept-B structure are compared not to each other, just commercial cubesat structures. Internal volume maximization of Concept-A is quite good. Because thickness of sidewalls is total 3 mm, 97 mm is available to allocate big components.

Besides, this structure is easy producible. It just consists of plates and is produced by cutting and folding in CNC machine. Because of that, cost of machinability is relatively low. Even though assembly and integration are easy because of hinges, they are also hard because of having too many parts.

4.3 Assembly

1. Firstly, bottom face is thought as a baseline. The assembly starts with this part.
2. Secondly, reciprocal walls are assembled to bottom faces via hinges. Hinges are connected to faces via screws or rivet. This procedure need not to repeat often.

3. Miles that determined length are assembled to bottom face from four corners and subsystems are arranged in order via spacer and connectors.
4. Then other subsystems are assembled to reciprocal walls via screws and nuts.
5. Then hinges are closed and top face that called hat is connected to walls.
6. After satellite become closed view, magnetboom, deployable antennas and solar panels are assembled externally.

4.4 Analysis

In this part of thesis, structure that modeled in drawing program will be analyzed by ANSYS Workbench FEA programming. The reason of using a computer program is complexity of CAD modeling. In this sense, quasi-static of Concept-A structure are performed. To simplify the analysis, some assumptions were made during the analyzing of the satellite structure.

Loads come from lanch vehicle and assumptions are discussed in Chapter 5.4 elaborately.

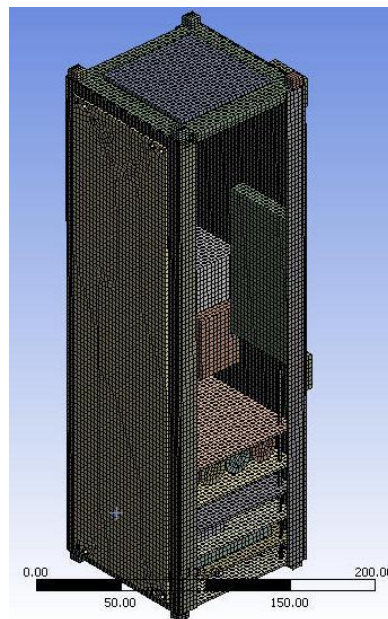


Figure 4.5 : Meshed Structure of Concept-A

In the modeling of the satellite, some equipment are entered the system as a mass in analyzing program. The material of the frame structure was determined as AL 7075. In addition, the material of boards and solar panels are FR-4 composites. Both properties of material are given in the Table 5.2.

Finite Element Method is used when analyzed structure in ANSYS. Solid elements type is used in analysis. Meshed structure can be seen in Figure 4.5. Quadrilateral elements are used in analysis. 68956 element and 360106 node point are used when performed analyses.

4.4.1 Static Analysis

In this study static analysis of the satellite structure is performed. In order to estimate the strength of the satellite structure, static analysis is critical. Tensile and compressive stress values are calculated using static analysis and compared with the yield strength of the materials used in construction of the structure.

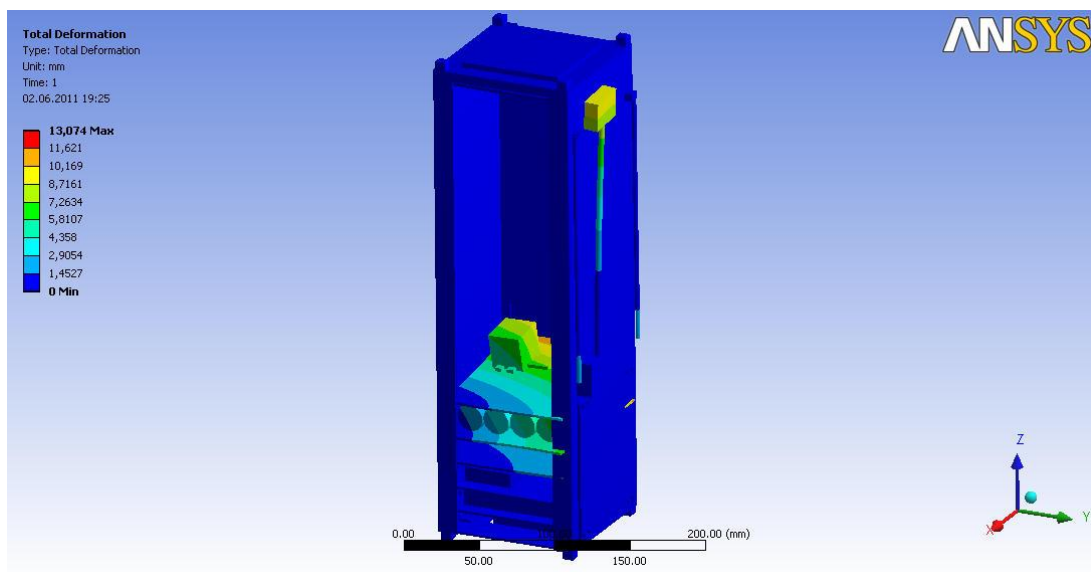


Figure 4.6 : Deformation of Concept-A

ITU pSAT II as an auxiliary satellite in launch vehicle, will subjected to 11 g in longitudinal axis and 6 g in lateral axis because of launch loads. With the load factor, we used 13.75 g and 7.5 g in longitudinal and lateral axis respectively for analyses to simulate the real launch environment. In this case maximum acceleration is 13.75 g and it is implemented all three direction to apply worst-case scenario.

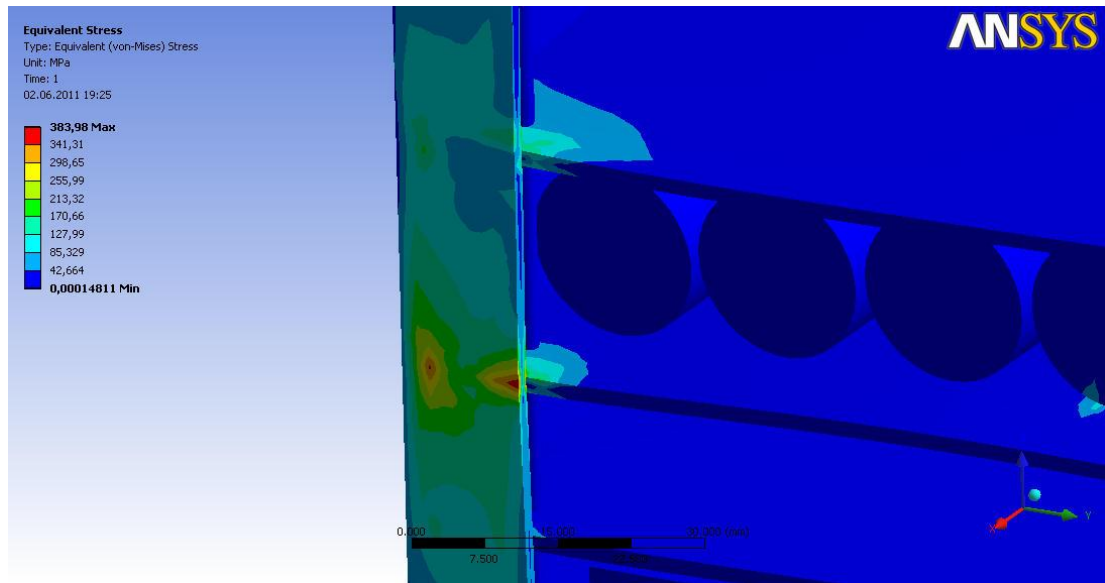


Figure 4.7 : Von Mises Stress of Concept-A

Total deformation and the stresses on the satellite are shown in Figure 4.6 and 4.7, respectively. The analysis indicates that the total deformation is 13 mm and it is very high in comparison to the satellite dimensions. In addition, maximum stress occurs in walls. The analysis indicates that Von Mises stress is observed as 383 MPa, and this value is within the specifications since AL-7075 yield strength is 300 MPa. Both of these results can not be reasonable. The reason of these results is modelling error. We did not use any fasteners to connect miles with walls. This case caused to big deformation and stress of 1U cubesat unit. These results can be adjusted by using fasteners between miles and walls.

5. CONCEPT-B

Concept-B is the second and selected structure design that is tried during design process.

The aim of this work is to develop a highly modular 3U main structure for cubesat satellites. Towards this goal, we have designed an innovative modular cubesat structure around structural columns, which support rack-like operation for our ITU-pSAT II nanosatellite. ITU-pSAT II aims to demonstrate on-orbit a standardized bus architecture and an indigenous in-house developed ADCS. The envisioned structure provides the much-needed flexibility to the satellite designers during the design, development and test cycle. Specifically, the structure allows the designers to change the location of subsystems or perform design modifications to the subsystems without the need and the necessity to re-design the main structure. This new modular structure is also in accordance with standards that are determined by Cal Poly State University for the cubesats and thus carries one-to-one compatibility with launch pods.

In this part, we explain in detail the design and the analysis phase of our design while step-by-step addressing deficiencies on the already developed and commercially available cubesat structures.

5.1 Modeling of Structure

In light of the above requirements, the designed structure is made up of a frame structure in which the columns in the corners are designed to carry main loads. The structural columns are planned as a rack system and subsystem boards are placed into the racks. Therefore, Concept-B is specialized and called as a rack system. In this conceptual design, boards that are subsystems are planned as a shelf, and the main structure of the cubesat is designed as a rack system. Many different options are designed to build rack system. Approximately 20 concepts are performed. Most of previous designs are planned as a monoblock. Those are generally considerably strength in the results of FEA phase. Nevertheless, those are not compatible because

of difficulty of manufacturing. Therefore, we decided to change the monoblock system to multi-partite system. Three of monoblock designs can be seen in the Figure 5.1.

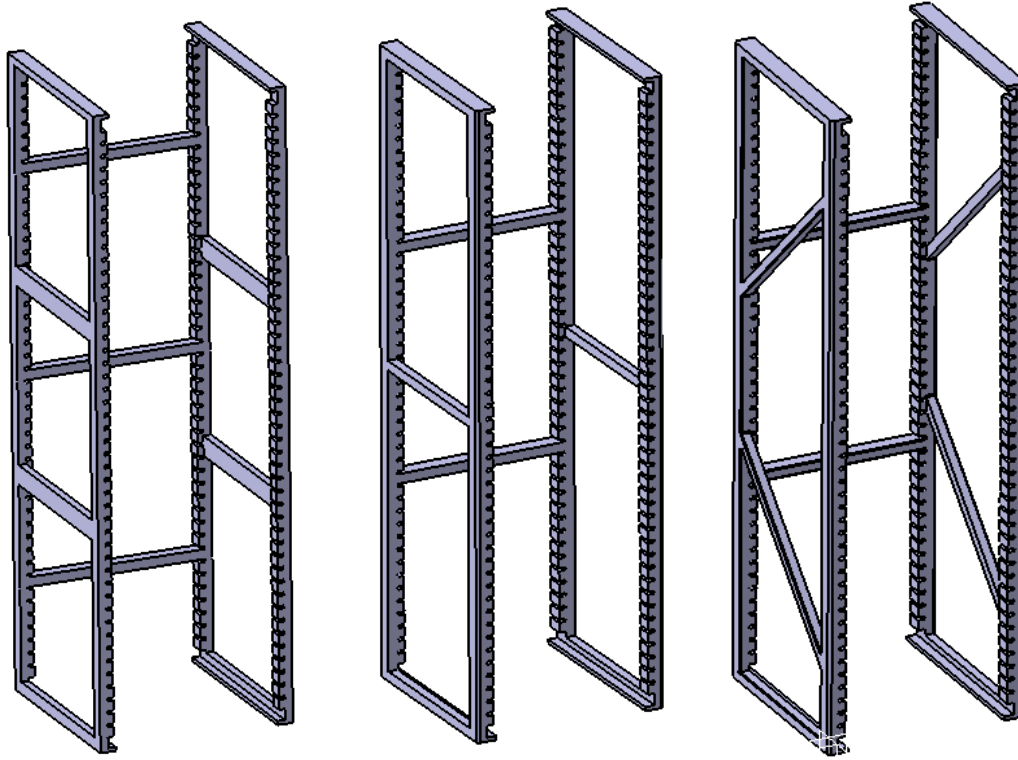


Figure 5.1 : Monoblock Conceptual Designs

The final design of Concept-B is consist of four carried frames. Two of them are side frames and two of them are top and bottom faces. Side frames and top and bottom faces are symmetric elements to each other.

White boxes that seen in all figures, are dummy loads to simulate components.

Side frames are designed in order to carry not only loads but also boards. Side frame's columns are used as rack. According to the CDS, rails should be minimum 8.5 mm. Therefore, columns are built 8.5*8.5 mm. Moreover, lateral elements that connect columns are used to attach solar panels to frame structure.

Spaces between every single rack in side frames are calculated accurately. Thicknesses of rack and spaces are determined according to board thickness, total length of cubesat, and connector thickness that will use to connect subsystems electronically. In total, there are 80 racks in order to put on boards when needed. The number shows that there are 80 different options for board place and these places can change when being necessary.

Top and bottom faces can change according to the necessity. For example, if we need a big space in top or bottom side of cubesat in order to put big component such as a camera or an antenna, we can design different option to put them. If camera has small dimensions, the first option for top face can be used as seen in the Figure 5.4. If camera or antenna have big dimensions the second option, which is used in ITU pSAT II, can be used as seen in the Figure 5.4.

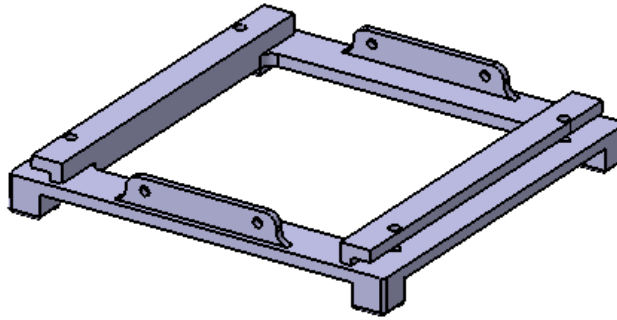


Figure 5.2 : Option for Top and Bottom Faces

Besides, in cubesats that designed by other organizations up to now, feet of satellite are designed as a different part from the main structure. Generally, 8 feet were used in them. We envisioned feet as a monoblock with top-bottom faces. By this way, ease of assembly and integration of cubesat are provided. Also, number of parts and time to assembly decrease. In addition to this, there are two parts of them to fix solar panels to main structure in the front and back sides of top-bottom faces.

All subsystems are designed on boards that are called Printed Circuit Board (PCB). PCBs are used also to prevent bending and buckling, because of their high strength capacity. In the case of cubesat put on the launch vehicle in horizontal direction, because of the fact that height of cubesat is bigger than width, buckling can be occurred. In that case, boards would be prevented buckling.

In Figure 5.3, components are:

- Dark and Light Greys - Main Frame,
- Greens - Boards,

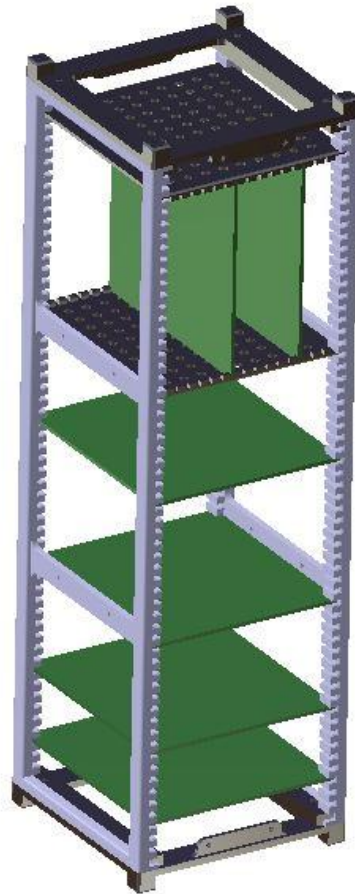


Figure 5.3 : Concept-B

In addition, the number of fasteners used in the design is almost %60 less in comparison to commercially available such structures. Because toy-block system is used, numbers of fasteners are reduced. For example, boards just connected with connectors. There is not any spacer or metal bar to connect boards to each other. First, we can connect them via connectors and after, shelve rack to the columns. Another example is reducing of the number of screws and nuts. Just four screws and nuts are used to connect side frames to top face. Totally, just eight screws and nut respond to need. In result, for whole satellite sixteen fasteners are used to attach cubesat structure.

The rack system provides a very modular structure in the way that it allows flexible placement of the subsystems. For example, boards, which are off from standard PC-104 dimensions, can be easily located in the vertical plane. In such case, 1U bus system can be put into upper side of structure as a unit block, and the rest of satellite can be used for bigger payloads such as camera, antenna deployable mechanism and magnetometer booms. Another example, big payloads, which can be seen in the

Figure 5.4 such as camera or black box, can be put into vertically upper or lower side. In addition, the rest of satellite can be used for 1U bus structure horizontally. Examples, which are conceptual design, can be seen in the Figure 5.4.

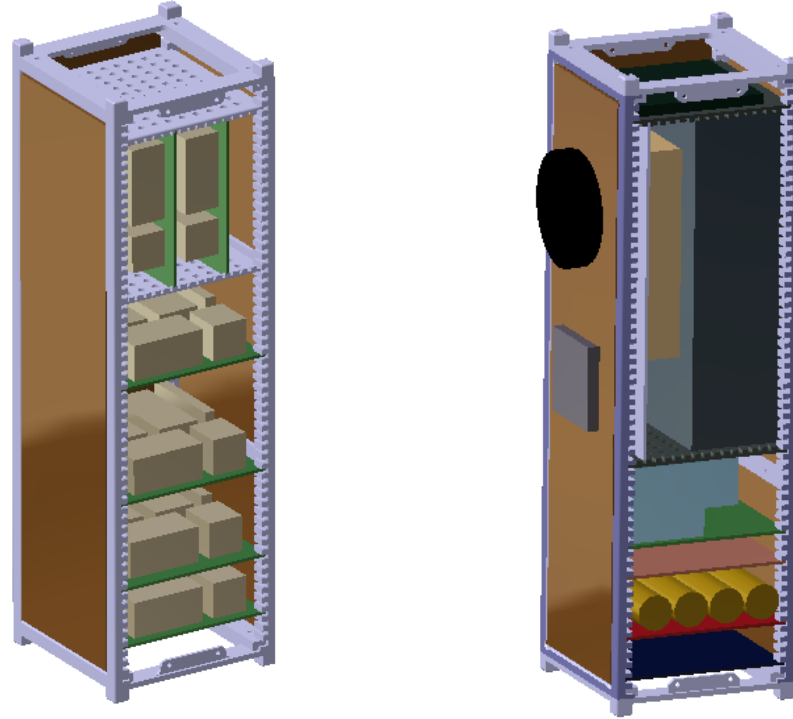


Figure 5.4 : Conceptual Designs of ITU pSAT II

In order to rack boards vertically, we design a new component that is called vertical rack. When we need some boards to use as a vertical, we can adjust length of boards as we need and then we can use vertical racks inside main rack system as seen in the Figure 5.4. Vertical rack design is shown in Figure 5.5. The material of vertical rack is AL 7075 that the same with main structure to avoid different thermal expansion. The reason of small holes is to minimize the total weight.

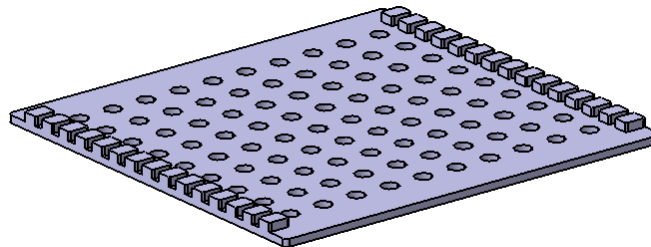


Figure 5.5 : Vertical Racks

Moreover, side solar panels are embedded into the main structure in order to make additional room for deployable solar panels in case of need for extra energy. There are two kinds of side solar panels. One of them is connected to side frame from two

points in (x) direction, another one is connected to top and bottom faces in (y) direction. If we need 1U solar panels for top and bottom in (z) direction, we can attach them top and bottom faces. There are extra spaces on top and bottom faces to attach them. The structure is flexible to make change in order to connect solar panel. If there are constraints about connect point on solar panel, the places of connection points can be change on structure.

In (y) direction, there is not any constraint to prevent moving of boards. The solar panels in (y) direction are designed in order to fix these boards. Because of the fact that boards are connected each other via connectors, the movement of them completely are quite small in (y) direction.

Internal volume maximization is an important criterion while making satellite design. Although in corners $8.5 \times 8.5 \text{ mm}^2$ area seems out of use, actually there are bigger area in internal volume for usage. While standard PCB 104 boards have $96 \times 90 \text{ mm}^2$ area of usage, we can produce bigger boards that have $98 \times 90 \text{ mm}^2$ area of usage in the case of need. Therefore, all boards, which have 90 mm width, can be produced, or used even if it is standard board.

5.2 Advantages and Disadvantages

There are many criteria to define side-by-side comparison for structural design. Weight factor, ease of access and integration, modularity, and low-cost are some of them. These criteria provide determining of some advantages for selected design.

Firstly, a satellite structure should be weightless. By this way, we can use extra mass for other documents and subsystems. In addition, flying objects should be as light as possible. Concept-B structure has 400 gr weight in total. This is quite good value in contrast with other satellite structure in market and our first design Concept-A. For example, Pumpkin standard 3U structure and ISIS structure are approximately 450 gr and 500 gr respectively.

In addition, size of internal volume should be as big as possible. This is another important criterion. Not only external panels (faces) or columns should be thin but also they have to carry loads. For this case, several trials should be done. Finally, optimum size was selected for carried elements and internal volume maximization was provided.

Table 5.1 : Design Parameter Checklist

Parameter	Concept-A	Concept-B
Weight Factor	H	H
Internal Volume Maximization	H	M
Ease of Access	M	H
Ease of Production	H	M
Low-cost	H	M
Modularity 1U-2U-3U	L	H
Provide RQ in CDS	H	H
Provide RQ in Project	M	H
Ease of Assembly	H	H
Ease of Integration	H	H
Accommodates Multiple Payload with Minimal Changes	M	H
Modularity for Deployable Solar Panels	M	H
Fewest Possible Parts	M	H

L- Low
M- Medium
H- High

Ease of production is an important selection criterion. Side frames and top-bottom faces of Concept-B structure will produce in CNC machining. This structure is not an easy machinable because of details in columns. 1.7, and 3.7 mm thickness of spaces and are racks very small and this make hardness the production. During design process, when a small change is needed production of structure should be repeated. Therefore, the structure should be re-producibility immediately. Concept-B is actually hard to re-produce because of its small dimensions.

In addition, access to satellite should be easy. Both during and after integration, accessibility to cubesat should be provided. Ease of access can be provided for example by placing big spaces to lateral faces. In Concept-B design, ease of access is provided with this process.

Being low cost is another criterion that a satellite should have. Especially satellite structure should be produce low costly to be able to repeat production process when needed. According to our research, even though cost of Concept-B structure is lower than other 3U cubesat structures in market, it is higher than cost of Concept-A structure. Because of it is difficult to produce.

Modularity that is an important criterion for satellite structure is provided for user that needs different size of satellite. Designed structure should be compatible for 1-2-

3 U cubesats. Therefore, we tried to design a modular structure. The satellite that consists of side frames and top-bottom faces has a modular structure. If we change the mission and decide to launch a 2U cubesat, just changing the measurement of length of side frames would be sufficient.

Ease of assembly and integration of the cubesat structure are two of the important criteria in design of satellite. For example, while especially functionality testing is continuing, several times assembly of satellite need. Therefore, time of assembly should be as short as possible. For Concept-B, not only lack of fasteners but also simplicity of components provides ease of assembly and integration.

In addition, Concept-B provides all requirements in CDS and project that mention about above.

Another property is to accommodate multiple payloads with minimal changes. For example, if we have a payload that has small dimensions such as a star tracker, we can accommodate it to a board and then to rack system. On the other hand, if our payload has big dimensions such as a big camera, we can use carrier board, which designed in order to put components to structure, seen in the Figure 5.4 then we can put them into rack system. In other words, small arrangements can respond to problem about dimension for Concept-B.

As we mention above, usage of additional solar panels are so flexible for Concept-B structure. Side solar panels are embedded into the main structure and deployable solar panels are not seen in the Figure 5.6. Nevertheless, there are enough places for deployable solar panels in order to make additional room in case of need for extra energy, according to requirements in CDS.

We should use fewest possible parts in design of structure. Our structure consists of four parts that are two side frames, top face and bottom face. If the structure consisted of monoblock, ease of assembly would not be possible. In Concept-B design, we use four main parts and total sixteen screws and nuts. This is quite satisfying number for a cubesat. As we mention above, the number of fasteners used in the design is approximately 60 % less in comparison to other cubesats.

5.3 Assembly

Assembly procedure of Concept-B structure is consisting of three main steps;

1. Subsystems are assembled together out of structure firstly,
2. Internal structures that are subsystems are assembled to the main structure,
3. External structures such as solar panels are mounted to the main structure directly.

To assemble electronic components outside main structure provide to keep them. Besides, functionality tests can be completed while satellite components are outside and working without fix them to mainframe. In addition to this, working without fix to main satellite keeps from broking that may be occurred because of using often.

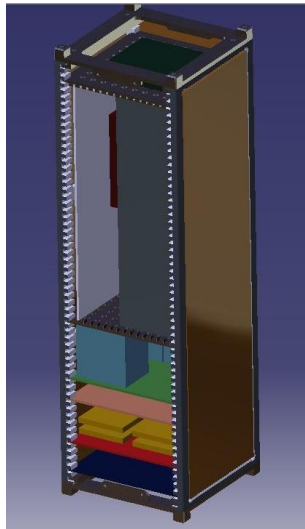


Figure 5.6 : Concept-B

Firstly, subsystems that consist of PCB and connectors are assembled together bottom to top respectively, On Board Computer (dark blue), Electronic Power System (red), Battery Board (red and yellow), Sensor Board and Reaction Wheels Board (green). Secondly, main structure is built by connecting side frames and top and bottom faces to each other. All steps of assembly are seen in APPENDIX A.2. Then first main block that is basic bus system is assembled to main structure. Thirdly, the second part of satellite, which consists of payload (black box), is assembled to vertical racks outside and then this system is mounted to main structure.

After internal assembly completed, external parts are fixed to main structure. First solar panels in x side are mounted and then solar panels in y are fixed to aluminum frame. Then deployable magnetoboom, antennas and solar panels, if need, are assembled on solar panels or main structure.

5.4 Analyses

In this part of thesis, structure that modeled in drawing program will be analyzed by ANSYS Workbench FEA programming. The reason of using a computer program is complexity of CAD modeling. In this sense, quasi-static and modal analyses of Concept-B structure are performed. To simplify the analysis, some assumptions were made during the analyzing of the satellite structure.

Actually, satellite is in the deployment system during launch period. In this period launch loads, which discussed above, will get in the satellite. Essentially loads do not directly come in satellite. We can consider satellite with deployment system. We consider the satellite while doing analyses without deployment system. Nevertheless, boundary conditions due to deployments system will be account. It does not decide yet which deployment system will be used when satellite launched. Therefore, although there is spring load in PPOD, we assume that feet are simply supported both bottom and top side in (z) direction. The boundary conditions are shown in Figure 5.7.

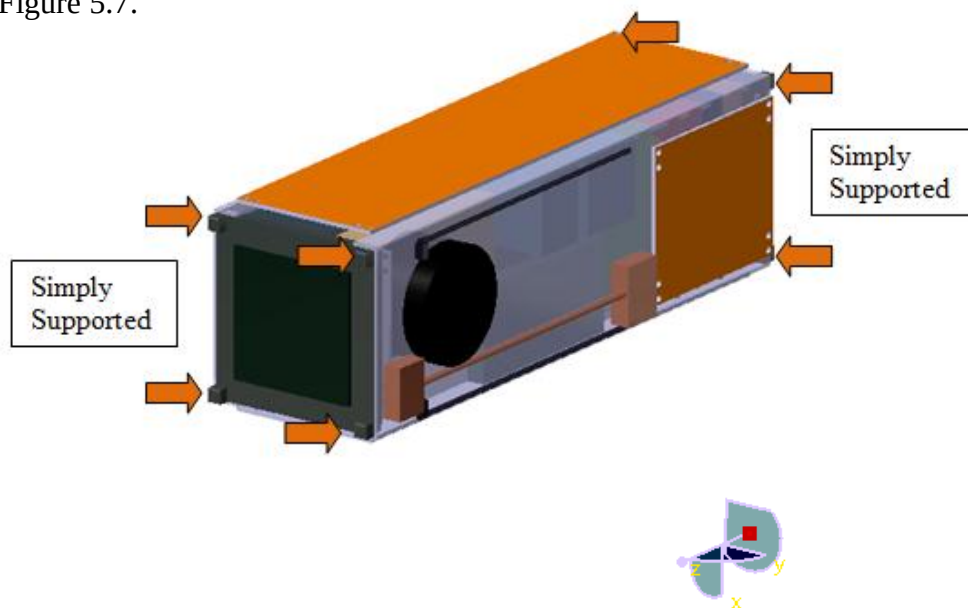


Figure 5.7 : Boundary Conditions

Besides, coordinate system of satellites is as shown in the Figure XX. Earthward side of satellite is determined as a (+z) direction. The side that has camera and antennas is the (+y) direction. Another side of satellite is (+x) direction according to right-hand rule. Although satellite and separation system coordinate system are determined certainly, we do not have any information about how deployment system will assembled to the launch vehicle. Therefore, we do not know satellite which axis will be coincides with the longitudinal axis of launch vehicle. By considering the worst case, we assume the maximum loads will get in all axes.

In the modeling of the satellite, dummy equipment are entered the system as a mass in analyzing program. The material of the frame structure was determined as AL 7075. In addition, the material of boards and solar panels are FR-4 composites. Both properties of material are given in the Table 5.2.

Finite Element Method is used when analyzed structure in ANSYS. Solid elements type is used in analysis. Meshed structure can be seen in Figure 5.8. Quadrilateral elements are used in analysis. 95570 element and 366485 node point are used when performed analyses.

Table 5.2 : Properties of Material

Properties	Materials	
	Frame Structure AL 7075	Boards/ Solar Panels PCB- FR4
Modulus of Elasticity (MPa)	68900	18615
Poisson Ratio	0,33	0.136
Density (kg/mm ³)	2.7 e-6	1.85 e-6
Yield Strength (MPa)	503	300

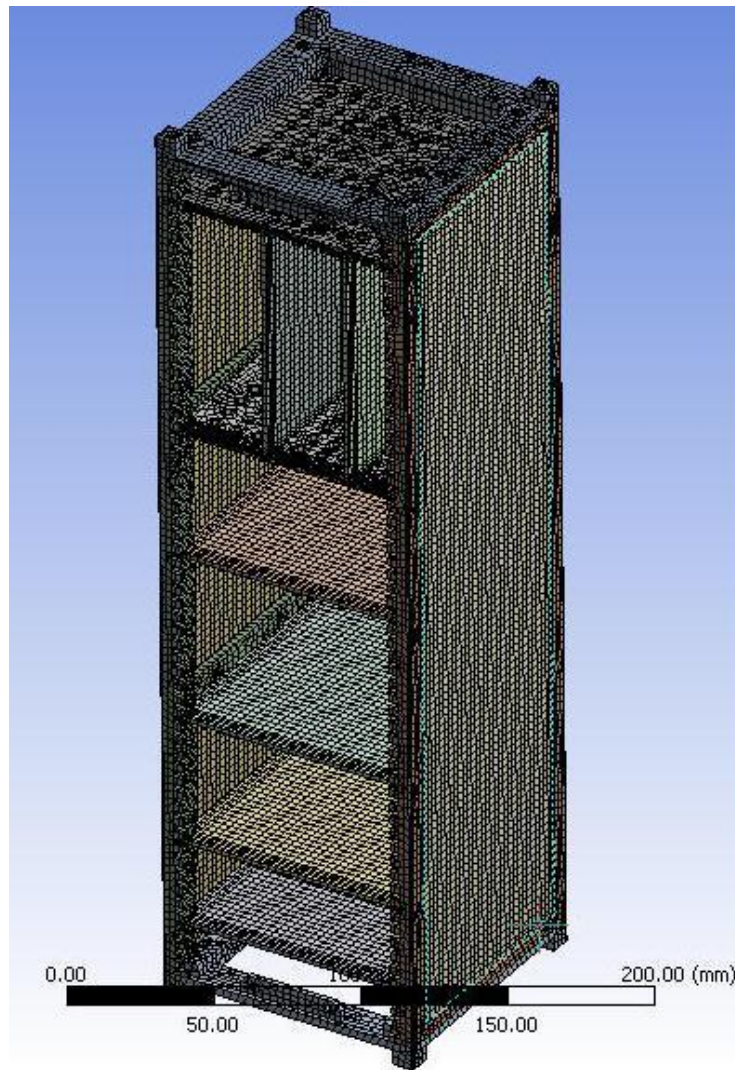


Figure 5.8 : Meshed Structure of ITU pSAT II

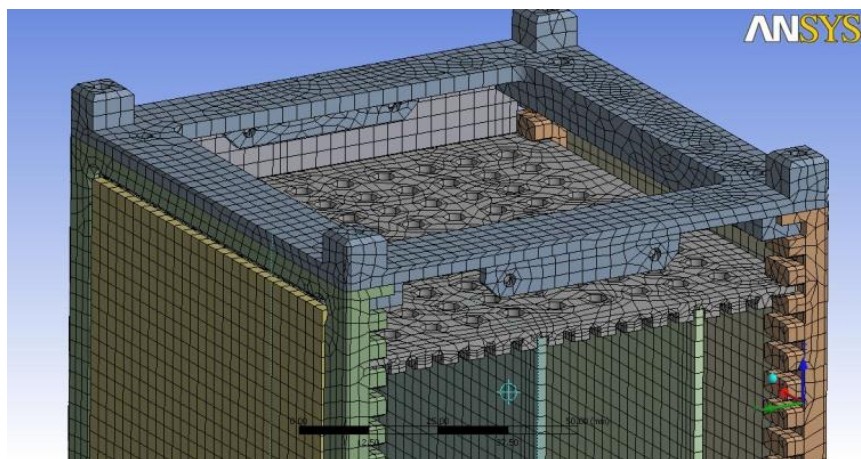


Figure 5.9 : Meshed Structure of ITU pSAT II (Detail)

5.4.1 Static Analysis

In this study static analysis of the satellite structure is performed. In order to estimate the strength of the satellite structure, static analysis is critical. Tensile and compressive stress values are calculated using static analysis and compared with the yield strength of the materials used in construction of the structure.

ITU pSAT II as an auxiliary satellite in launch vehicle, will subjected to 11 g in longitudinal axis and 6 g in lateral axis because of launch loads. With the load factor, we used 13.75 g and 7.5 g in longitudinal and lateral axis respectively for analyses to simulate the real launch environment. In this case maximum acceleration is 13.75 g and it is implemented all three direction to apply worst-case scenario.

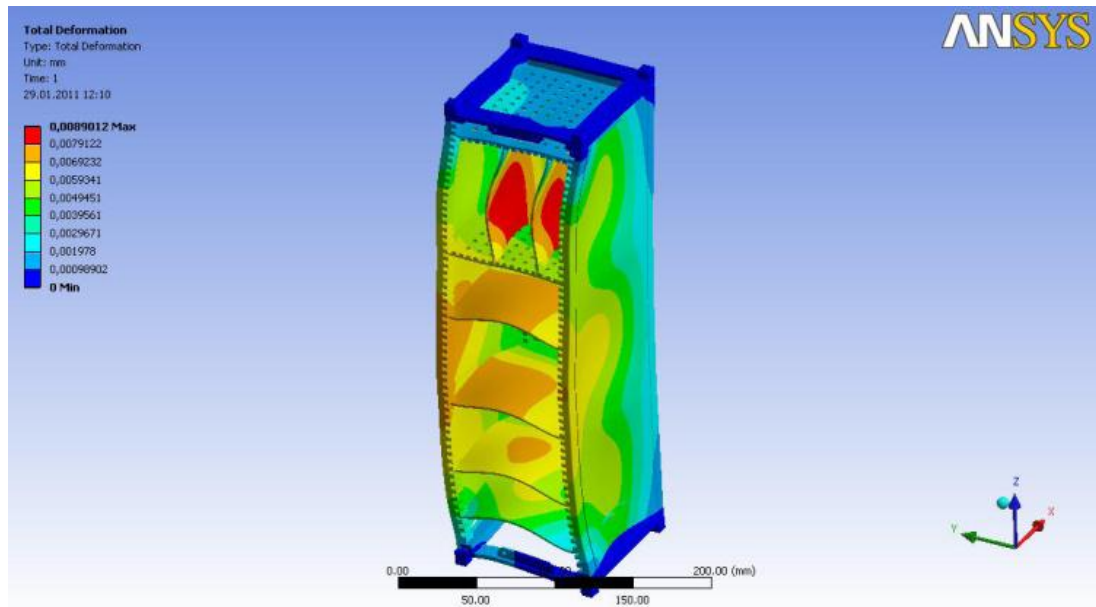


Figure 5.10 : Total deformation of Concept-B

Total deformation and the stresses on the satellite are shown in Figure 5.10 and 5.11, respectively. The analysis indicates that the total deformation is 0.009 mm and it is very small in comparison to the satellite dimensions. In addition, maximum stress occurs in side frame. The analysis indicates that Von Mises stress is observed as 63 MPa, and this value is within the specifications since AL-7075 yield strength is 503 MPa.

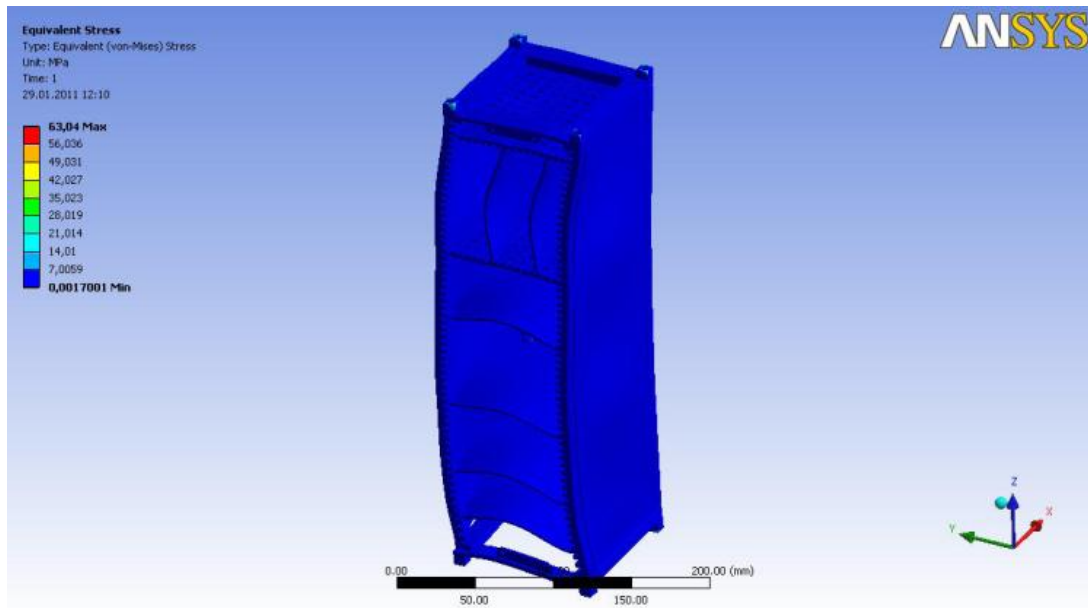


Figure 5.11 : Von Mises Stress of Concept-B

5.4.2 Modal Analysis

In order to find natural frequencies of Concept-B, the modal analysis of structure is performed. According to the user's guide of PSLV, the payload of launch vehicle has to be designed with a structural stiffness, which guarantees that the values of fundamental frequencies of the satellite at the launch vehicle interface are not less than 35 Hz in the longitudinal axis and 20 Hz in the lateral axis. For auxiliary satellites these values 90 Hz and 45 Hz, respectively. In order to prevent a resonance, the natural frequencies calculated by the analysis must be above these constraint values.

In the modal analysis, spectrum of frequency is determined from 0 to 2000 Hz according to PSLV user guide because of the given random vibration values in this range. The natural frequencies in the range of 0 to 2000Hz are found as a result of modal analysis and all 31 modes are shown in the Table 5.3. There are some similarities in the different modes of vibration due to the almost full symmetry in the geometry of the structure. The first natural frequency of ITUpSAT1 structure is found to be 216.25 Hz, which is well above the minimum fundamental frequency constraint of the launch vehicle, and the last one is 1917.6 Hz. First three mode of Concept-B structure can be seen in below figures.

Table 5.3 : Natural Frequencies of Concept-B

Modes	Natural Frequencies (Hz)	Modes	Natural Frequencies (Hz)
1	216,25	17	1317,7
2	730,57	18	1331,9
3	769,53	19	1338,1
4	775,01	20	1338,8
5	788,06	21	1359,1
6	802,12	22	1379,8
7	843,02	23	1386,9
8	1086,6	24	1439,4
9	1193,2	25	1538,9
10	1221	26	1596,3
11	1226,3	27	1610,7
12	1239,2	28	1630,7
13	1244,1	29	1807,9
14	1272,7	30	1820,6
15	1276	31	1917,6
16	1293,1		

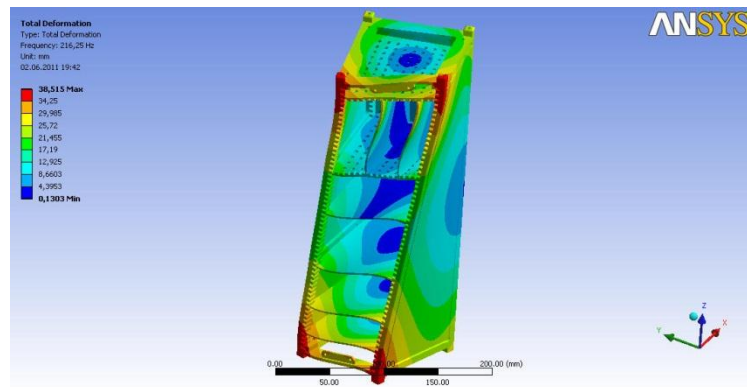


Figure 5.12 : First Mode of Concept-B

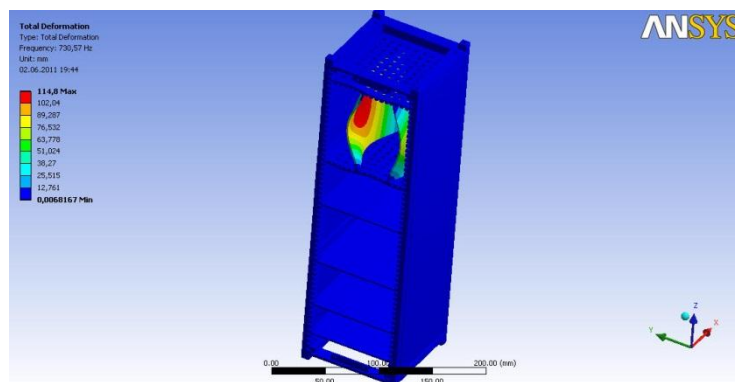


Figure 5.13 : Second Mode of Concept-B

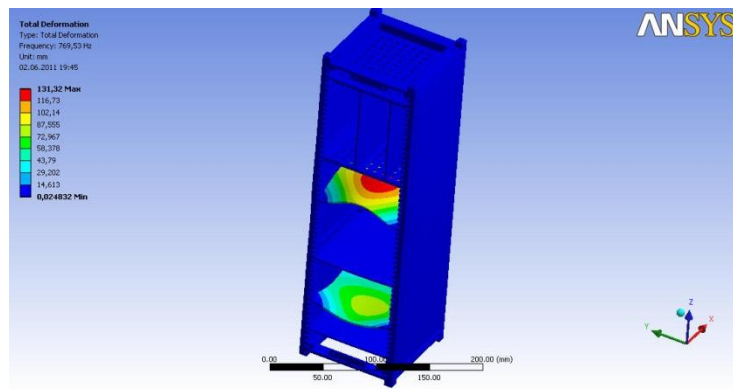


Figure 5.14 : Third Mode of Concept-B

6. CONCLUSION

There are five main steps in designing of a satellite. First step is modeling, second step is analyzing, third, fourth, and fifth are manufacturing, integration, and testing respectively. In this thesis, modeling and analyzing of satellite structure have been studied.

As a research section of this thesis, ITU pSAT II satellite is discussed. Firstly, previous cubesat missions are debated. Secondly, missions of ITU pSAT II are determined within the scope of project. According to these missions, subsystems and equipment are determined. Requirements of the subsystems are the main determiner in order to design satellite structure. Not only requirements of subsystems but also launch environment determined the basics of design philosophy. Requirements in CDS and project, launch and ground environment, deployment systems, and space materials are investigated elaborately.

Several project groups study structural design of a 3U cubesat previously. However, those all are developed specific missions. We tried to develop a new conceptual, modular, innovative cubesat structure and respond to all necessity.

Designing is a challenging process. In this process, we have to perform an iterative work. By considering all constraints and environments, which satellite will be exposed, we have developed two different structure designs for ITU pSAT II. Both of Concept-A and Concept-B are designed according to necessities. We make comparison between each other and others that designed universities. Finally, these two designs have modeled and completed. In this way, modeling step has been finished.

In addition, Concept-A and Concept-B have been analyzed as structural. Static analysis have been performed for Concept-A. Moreover, static and modal analyses have been performed for Concept-B. Results are discussed. Concept-A is not accessible for satellite structure for this moment because of high stress value. If some

modeling changes performed, Concept-A model can be acceptable. However, Concept-B is accessible model for nano-satellites. According to static and modal analyses, the structure can be manufactured. This thesis covers modeling and analyzing phase.

For further work, all phases that should be in satellite structural design process can be completed. After that, for ITU pSAT II nano-satellite manufacturing, integration, and testing phases will be completed in order to finalize structural design.

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APPENDICES

APPENDIX A.1 : 3U Cubesat Design Specification

APPENDIX A.2: Assembly of Concept-B

APPENDIX A.1 : 3U Cubesat Design Specification

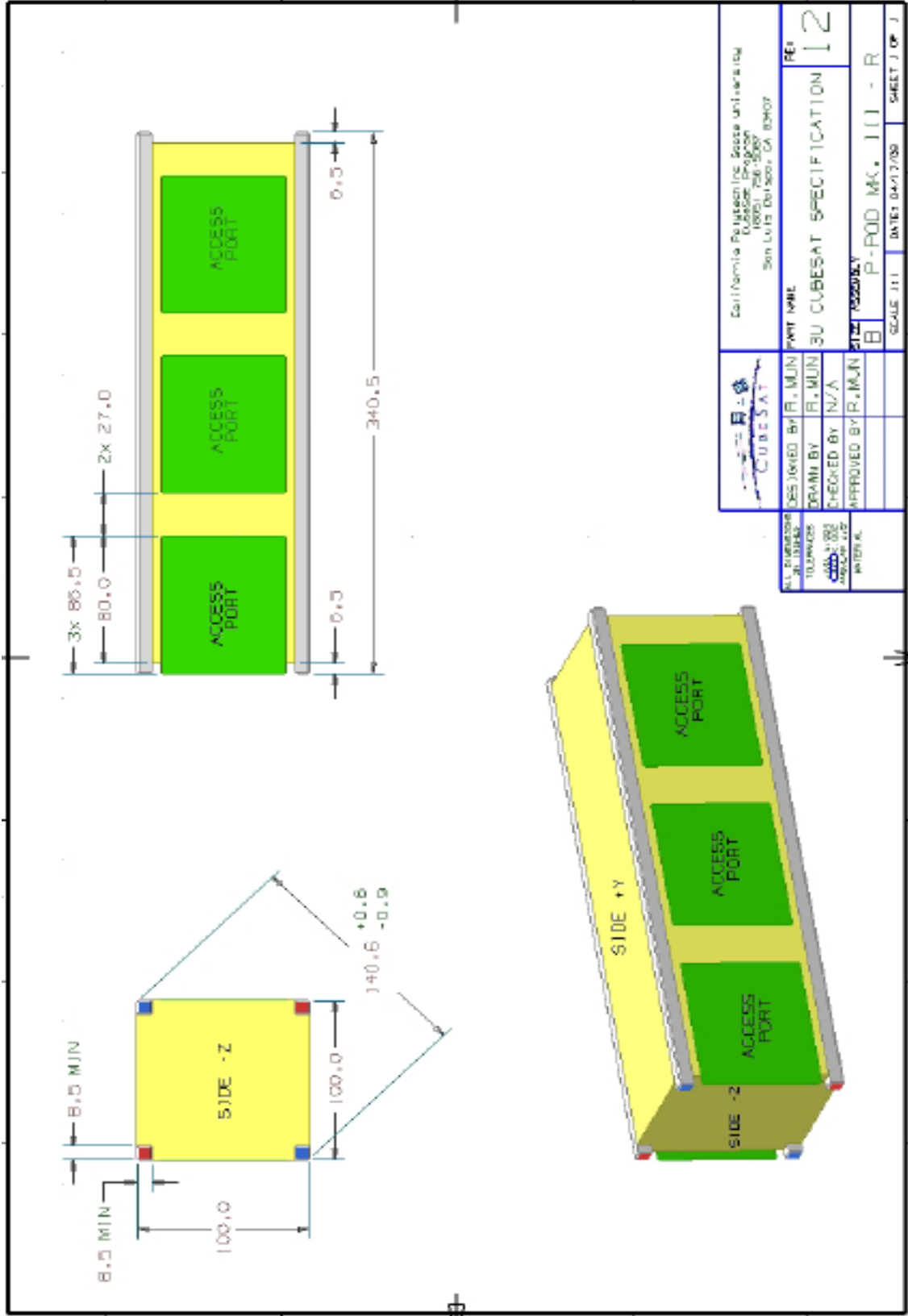
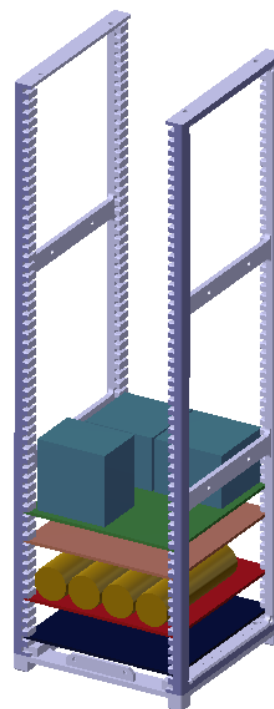
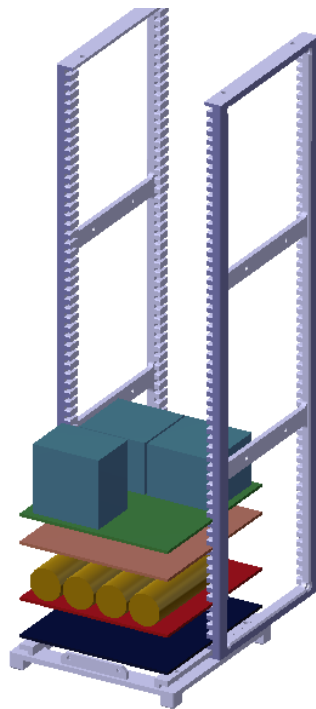
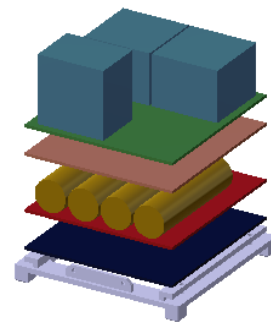
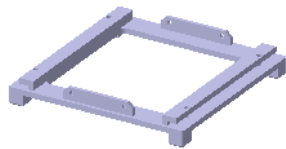


Figure A.1 : CDS Drawing

APPENDIX A.2: Assembly of Concept-B



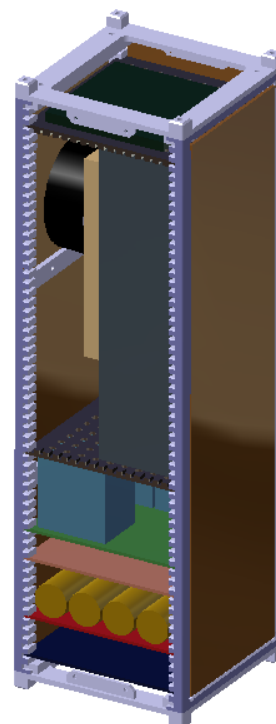
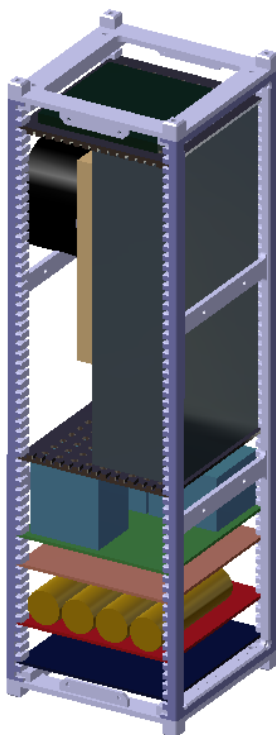
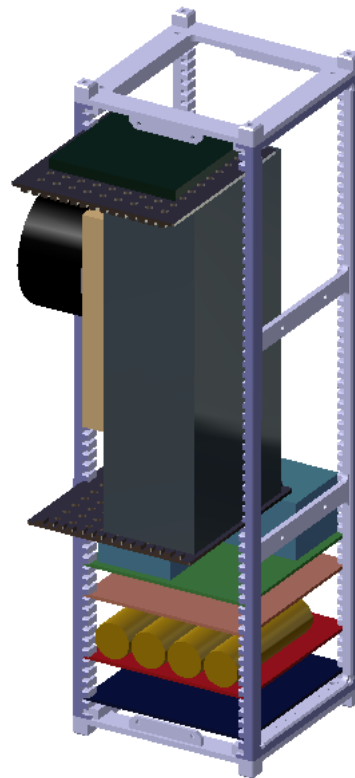
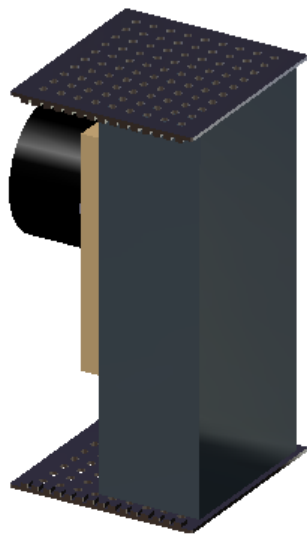


Figure A.2 : Assembly of Concept-B

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