

Finite Element Analysis of 3U CubeSat Structure

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Abstract— Our country, Ethiopia, is a victim of drought and other natural disasters due to weather and climate change. As a result, to give an early warning and to take immediate action on such problems and also to increase the agricultural productivity, satellite development is the best solution. Therefore, Ethiopian Space Science & Technology Institute (ESSTI) launched a project to design and develop a 4kg multi-spectral 3U CubeSat for the application of alerting natural disaster and rescue, mapping, forest and land management, weather prediction, crop distribution, etc. This paper, which is part of ESSTI project, presents the finite element analysis of 3U CubeSat structure with the applied quasi-static load of 250N. In the paper stress and deformation analysis is presented procedurally and the results showed that the structure is safe for the lifetime of the satellite.

Index Terms— CubeSat, Finite Element Analysis, Nanosat, Satellites, Stress Analysis, Structural Subsystem

1. INTRODUCTION AND BACKGROUND

Currently, modern science and technology equip human being with a very advanced and smart device which highly simplifies people's lives in the day to day activities. One of these technologies is a satellite. A satellite is an object in space that orbits or circles around a bigger object. There are two kinds of satellites: natural (such as the moon orbiting the Earth) or artificial (such as the International Space Station orbiting the Earth). Artificial satellites, however, did not become a reality until the mid-20th century. The first artificial satellite was Sputnik, a Russian beach-ball-size space probe that lifted off on Oct. 4, 1957. That act shocked much of the western world, as it was believed that the Soviets did not have the capability to send satellites into space. Following that feat, on Nov. 3, 1957 the Soviets launched an even more massive satellite, Sputnik 2, which carried a dog, Laika. The United States' first satellite was Explorer 1 on Jan. 31, 1958. The satellite was only 2 percent the mass of Sputnik 2, however, at 30 pounds (13 kg). The Sputniks and Explorer 1 became the opening shots in a space race between the United States and the Soviet Union that lasted until at least the late 1960s. The focus on satellites as political tools began to give

way to people as both countries sent humans into space in 1961. Later in the decade, however, the aims of both countries began to split. While the United States went on to land people on the moon and create the space shuttle, the Soviet Union constructed the world's first space station, Salyut 1, which launched in 1971. Other countries began to send their own satellites into space as the benefits rippled through society (1).

Starting from the launching of the first Soviet Union satellite, Sputnik, on October 4, 1957, satellite technology is getting breakthrough and advanced from time to time. With the miniaturization of computers and other hardware, it's now possible to send up much smaller satellites that can do science, telecommunications or other functions in orbit. It's common now for companies and universities to create "CubeSats", or cube-shaped satellites that frequently populate low-Earth orbit. These can be lofted on a rocket along with a bigger payload, or sent from a mobile launcher on the International Space Station (ISS). NASA is now considering sending CubeSats to Mars or to the moon Europa (near Jupiter) for future missions, although the CubeSats aren't confirmed for inclusion (2).

Ethiopia is planning to develop an earth observation 3U Cubesat weighing about 4kg and this paper is part of the design document in the design and development process of Ethiopian CubeSat. The goal of this paper is to present the finite element analysis result of the structure describing stress and deformation on the various points of the structure.

2. REVIEW OF RELATED LITERATURES

The CubeSat concept has been developed at the Space Systems Development Laboratory (SSDL), Stanford University by Prof. Bob Twiggs and his colleagues and students in conjunction with California Polytechnic State University (CalPoly) (3). The purpose of the paper is to provide a standard for the design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches. CubeSats are minuscule satellites designed for low earth orbit (LEO) with a purpose to use universities worldwide for space research and exploration (4).

Presently, the CubeSat Project is an international collaboration of over 100 universities, high schools, and private firms developing picosatellites containing scientific, private, and government payloads. The size and cost of spacecraft vary depending on the application; some you can hold in your hand while others like Hubble are as big as a school bus. Small spacecraft (SmallSats) focus on spacecraft with a mass less than 180 kilograms and about the size of a large kitchen fridge. Even with small spacecraft, there is a large variety of size and mass that can be differentiated as Minisatellite, 100-180 kilograms; Microsatellite, 10-100 kilograms; Nanosatellite, 1-10 kilograms; Picosatellite, 0.01-1 kilograms and Femtosatellite, 0.001-0.01 kilograms. CubeSats are a class of nanosatellites that use a standard size and form factor. The standard CubeSat size uses a "one unit" or "1U" measuring 10x10x10 cms and is extendable to larger sizes; 1.5, 2, 3, 6, and even 12U (5). Figure 1 shows different configurations of Cubesat.

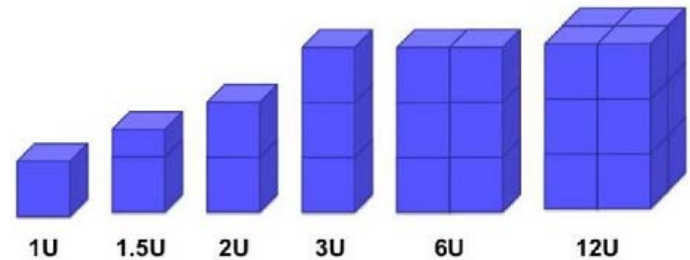


Figure 1: CubeSat Structures (6)

CubeSats are miniature satellites that are commonly used in low Earth orbit for applications such as scientific research, space experiment, remote sensing or communications. They often use commercial off-the-shelf (COTS) components for their electronics and structure. CubeSats are most commonly put in orbit by deployers of the International Space Station, or launched as secondary payloads on a launch vehicle. As engineers become more familiar with the technology, CubeSats are also being considered for flights outside of Earth orbit particularly to locations such as Mars or Jupiter. The design was first proposed in the late 1990s by two professors: Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University. They were trying to help students gain engineering experience in satellites, which are traditionally expensive to build and launch (7).

Using standardized design parameters, CubeSats can be launched from a common mechanism, called a P-POD (Poly Picosatellite Orbital Deployed). The P-POD is mounted in the fairing of a launch vehicle, usually sharing a launch with a much larger spacecraft. CubeSats can support a variety of mission types, including biological research, communications, deep space observations, or technology testing and characterizations. These spacecraft have high educational potential (8).

There are several companies producing flight-ready nanosatellite components. Pumpkin Inc., based in San Francisco, has been prominent in the small satellite community for producing light processors and bus structures for CubeSats (12). Pumpkin's products successfully streamline the

design process, but their high cost limits their use of larger projects at institutions already well-established in the industry.

Once the CubeSat program was formally established at Cal Poly, several papers were published further developing on the capabilities of the platform, including "CubeSats as Responsive Satellites" (10).

3. STRUCTURAL SUBSYSTEM DESIGN AND ANALYSIS

The structure of a nano-satellite has the aim to provide housing for all the payloads and the subsystems, ensuring their integrity during the launch phase. It should also guarantee free accessibility and inspection possibility during the mounting phase and good thermal, mechanical and electrical behavior while maintaining a low weight.

The most influential and distinct parameters of a CubeSat are weight and size. These two basic parameters can determine how big the cubesat to be and what shall be incorporated within it. Due to the reason that all cubesat developer shall abide with the Cal. Poly Cubesat Design Specification (13) document, these parameters must be designed carefully. Therefore, different analysis is performed on the cubesat structure to ensure that it is a well-designed and fulfill all the required qualifications to pass through various tests on the ground and to resist different load exertion during launching and to perform well in orbit. Hence, structural analysis is done to assure how much it can withstand such load exertion at different environment.

In order to perform this structural analysis various tasks are taken into consideration through different steps. These tasks include the selection of launching vehicle, selection of material, final dimensional decision and consideration of cubesat standardization and requirement from CDS of Cal. Poly.tech etc.

3.1 LAUNCH VEHICLE (LV) SELECTION

The selection of launch vehicle is one of the important steps to determine the launch scenario launch loads to do the analysis. Quasi-static load and natural frequency of the rocket will determine the cubesat launch requirement. The launch vehicle to be used is Indian polar satellite launch vehicle. This which is selected due to its affordable cost and ease of accessibility as India is highly involved in the satellite launch technology at the present time.

3.2 MATERIAL SELECTION

A CubeSat structural subsystem must be made of light-weight and also strong material in order to compromise both mass and strength requirement while providing the desired function in orbit. Therefore, material selection is one of the most important steps in structural design to achieve the desired mission. Not only weight and strength but also stiffness, thermal conductivity, thermal expansion, manufacturability and cost factor are considered during material selection for satellite design. As per the CubeSat Design Specification, Aluminum 7075 and 6061 are candidate materials that can be used in the design of cubesat main structure. Based on the aforementioned criteria for selecting structural material for CubeSat data for selecting the optimum material is tabulated as shown in Table 1.

When comparing the two materials (Table 1) which are recommended by Cal. Poly. Tech, Aluminum 7075-T6 meets the required criteria of high strength, lightweight, easy machinability, and cost than Aluminum 6061-T6. Therefore, AL-7075-T6 is selected as the structural material for the CubeSat frame since it has higher yield strength.

Table 1: Comparison of Aluminum 6061-T6 and Aluminum 7075-T6 (14)

Mechanical & Thermal Properties	Aluminum type	
	Al 6061-T6	Al 7075-T6
Brinell hardness	93	150
Elastic modulus (GPa)	69	70
Elongation at break (%)	10	8
Fatigue strength (MPa)	96	160
Poisson's ratio	0.33	0.32
Shear strength	210	330
Ultimate tensile strength	310	560
Yield tensile strength	270	480
Strength to Weight Ratio (KN-m/kg)	115	196
Melting point	580	480
Specific heat capacity	900	870
Thermal conductivity	170	130
Thermal expansion	24	23
Thermal Diffusivity(m ² /s)	68	70

3.3 CUBESAT BUS STRUCTURE DESIGN

The CubeSat structure must be designed to withstand all static and dynamic loads encountered during manufacturing, transportation, launch, and operational life of the satellite. It must be able to withstand the highest loads encountered during its lifespan, and it is also required that the CubeSat structure be durable

during its service life. This is known as designing for the worst case. By ensuring that the satellite will not fail under the worst case loading conditions it can be shown that, the satellite will not fail under any static or dynamic loads during its lifecycle. Therefore, a detailed analysis is made for the satellite structure for all strength analysis cases of loading specified for it.

Satellite developers can purchase prefabricated CubeSat structures and various components from companies that specialize in standardized CubeSat structure manufacturing. Two of the companies that provide CubeSat structures are Pumpkin Incorporated (San Francisco, CA) and Innovative Solutions in Space (ISIS), (Delft, Netherlands). Both companies sell sets of CubeSat structural components for different size satellites, which must be assembled by the developer. Because of its so many advantages we selected the Pumpkin CubeSat structure model for our analysis.

Pumpkin Incorporated offers the CubeSat Kit to developers which contains the entire structure and all components necessary to allow the satellite "to be developed in as short time as possible and at low cost". The CubeSat Kit design is in its fourth generation, and has been delivered to more than 150 customers since 2003. It is claimed to be "the defacto standard in the CubeSat universe". The primary structure consists of six panels of 5052-H32 sheet aluminum fastened together with ten M3x5mm non-magnetic stainless steel flathead screws. The cover plates on the outside surface are made from approximately 1.5 mm thick sheets of 5052-H32. No deviation waiver needs to be submitted for using Al 5052-H32 since the CubeSat Kit design is already preapproved. All other components are made from aluminum 6061-T6. The panels are designed to be compatible with a wide variety of subsystem components and payloads. The approximate mass of the primary 1U CubeSat structure is 241 g, which would yield a structural mass fraction of 0.18 if the total CubeSat mass is at a maximum. The CubeSat frame is to be made of 6 aluminum faces of 2mm thickness. A model of the frame is shown in figure 2 below (9).



Figure 2: Pumpkin's Model 3U CubeSat Structure

4 FINITE ELEMENT ANALYSIS OF CUBESAT STRUCTURE

In order to assure the reliability of the CubeSat structure, the analysis must be performed on CubeSat models. Examples of such "virtual tests" can include a manufacturability test, stress analysis test, and dynamic response analysis test, among others. Performing such studies on the models helps to optimize parts for improved performance in the intended environment and provides a low-cost solution to testing, in which the computer-based model is tested rather than machining the actual CubeSat and testing it multiple times, essentially eliminating multiple field tests. Furthermore, parts can be optimized for mass by performing stress analysis tests on the models to determine the minimum mass needed to have adequate structural strength.

4.1 STATIC ANALYSIS

Static analysis is used to estimate the stresses, strains, displacements, and forces in the structural components of the system. Hence these analyses are essential to measure the strength of the satellite structure. Generally, steady loading and response conditions are assumed during the analysis. In this analysis, it is expected to ensure that the CubeSat will not experience unacceptable stresses or displacements during the launch which could create up to 50 g's load to be acted on the geometric center of the structure while the lower legs of the base are fixed. The maximum deformation and stresses are found at the top sheet and can be seen in Figure 2.

4.2 STRESS ANALYSIS

The greatest stress occurs during launch hence the force likely to be experienced by the CubeSat during launch is modeled and analyzed using Solidworks software. The maximum deformation ($1.63 \times 10^{-4} \text{m}$) is far less as compared to the dimensions of the structure; similarly, the maximum equivalent stress is $3.415 \times 10^6 \text{Pa}$ which is also lower than the yield strength of aluminum. It means structure can sustain the loading conditions, does not fail, and maintains its integrity during actual launch after the application of maximum static load.

The results provided us with von Mises stress varying from 09.2N/m^2 to approximately $57,734.128 \text{N/m}^2 = 0.577 \times 10^6 \text{Pa}$ which is also lower than the yield strength of aluminum.. Even if the stress had reached the largest value on the scale, the yield strength of the Al 7075 T6 is $505 \times 10^6 \text{Pa}$. The areas affected the most by the von Mises stress occurs in the center of the top Face of the CubeSat. The test showed that the material used on the structure should also be able to withstand the vibrational loads throughout the launch period for any of the launch vehicles likely to be used.

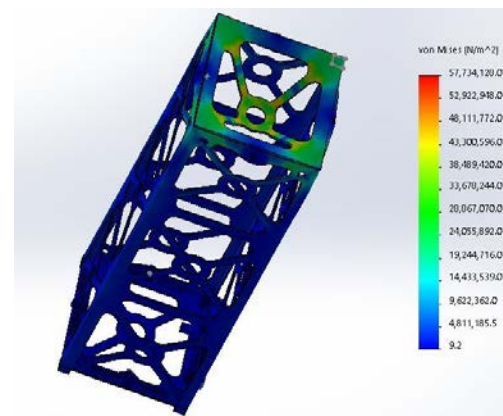


Figure 3: Finite Element Analysis on the CubeSat's Frame for Stress Analysis

4.3 STRAIN AND DEFORMATION ANALYSIS

The next area of concern was the deformation that occurs during launch from random vibrations and static loads. If the loads are too great, the structure

could deform and cause massive damage to the internal components. SolidWorks was able to produce values for the worst-case scenario. The results showed a scaled bowing of the structural top face inwards. But when the values of the physical deformation are looked at, they only varies slightly. These values are extremely small and can be considered negligible with respect to the integrity of the structure during launch, as this set of results represents a worst-case scenario. The critical points of deformation seem to occur once again in the central region of the structure but seem to pose no threat as the material is strong enough to withstand the loads.

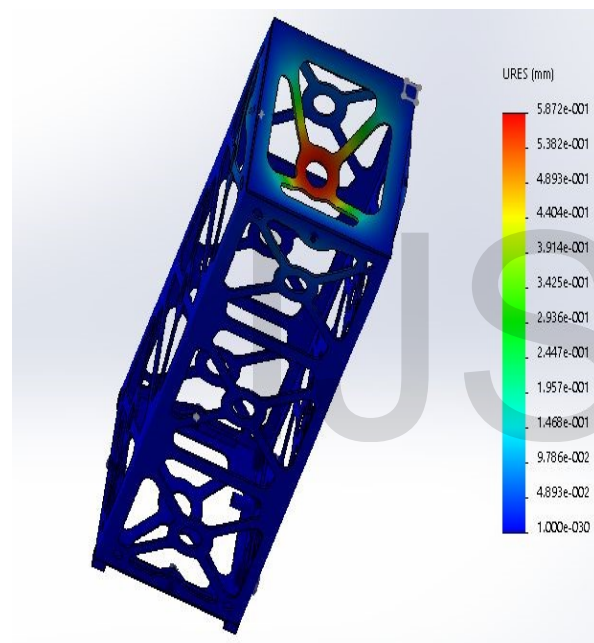


Figure 4: Finite Element Analysis on the CubeSat's Frame for Displacement Analysis

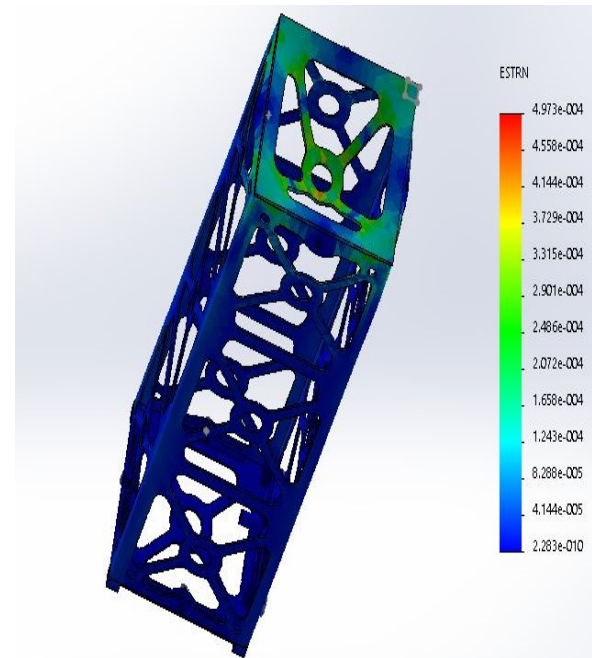


Figure 5: Finite Element Analysis on the CubeSat's Frame for Static Strain Analysis

5 CONCLUSION

In a nutshell, the CubeSat Frame structure is able to withstand the launch static and dynamic vibrations without failing. This preliminary finite element analysis has revealed a significant margin of safety and adequate survivability in terms of worst-case static loading and imposed failure modes.

6 RECOMMENDATION

The acoustic vibrations appear to induce the most critical dynamic response. In this case, the maximum deflections at the center of the plate were observed to occur at the entities fundamental frequency. It is recommended that components mounted at the center of these plates be appropriately bonded and inspected after environmental testing.

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