Finite Element Analysis of a Cubesat

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Abstract

This paper aims to analyse the behaviour of a selected aluminium CubeSat frame subjected under static and vibrational loads using finite element analysis. Failures of CubeSats due to instability caused by vibration during launch can result in damage of the CubeSats and Launch Vehicle. Hence there is the need to analyse the maximum von-mises stress and strain of the CubeSat before production and launch to avoid these failures and losses. The CubeSat is modelled and analysed using Solidworks 2014. Finally, the results obtained are an indication of whether or not the frame structure is able to safely withstand the worst-case scenario static loading and imposed failure modes.

Keywords: static load, vibrational load, and finite element analysis.

1. Introduction

The CubeSat concept has been developed at Space Systems Development Laboratory (SSDL), Stanford University by Prof. Bob Twiggs and his colleagues and students in conjunction with California Polytechnic State University (Cal-Poly) (Hansen, 2001). 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 (Israr, 2014). 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 (NASA, 2015). 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 (NASA, 2015). Figure 1 shows the cubesat.

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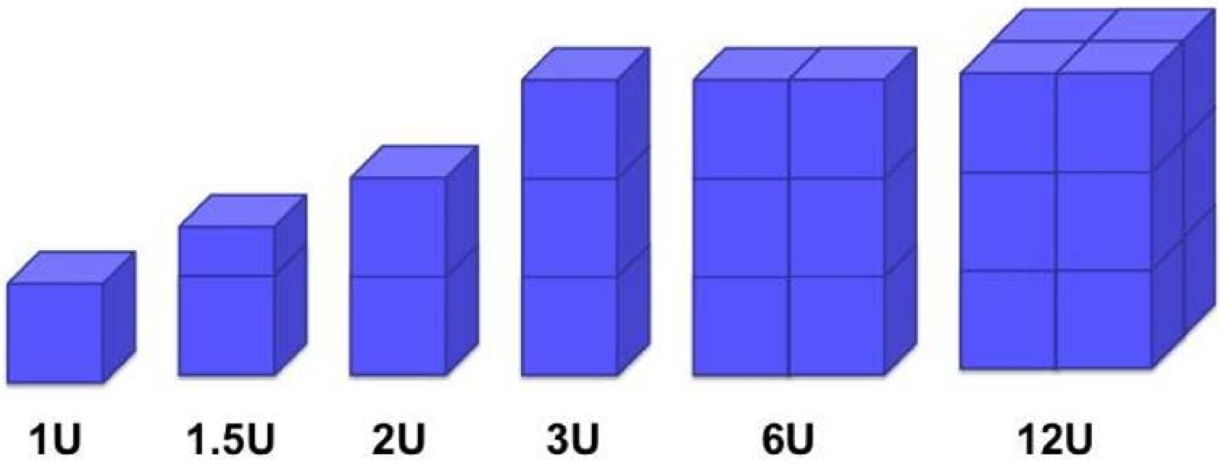

Figure 1. Cubesat units

The cube-shaped satellites are approximately four inches long, have a volume of about one quart and weigh about 3 pounds. To participate in the CSLI program, CubeSat investigations should be consistent with NASA's Strategic Plan and the Education Strategic Coordination Framework. The research should address aspects of science, exploration, technology development, education or operations (NASA, 2016).

Figure 2. A set of NanoRacks CubeSats

Compared to traditional multi-million-dollar satellite missions, CubeSat projects have the potential to educate the participants and implement successful and useful missions in science and industry at much lower costs (Cube sat kit, 2013).

1.1 Finite Element Analysis of a cube

The aim of offshore structural engineering is to produce structures which are safe, functional, economical, and able to resist the forces included by man and environment or required period of time. Finite Element Analysis (FEA) is an engineering method of calculating stresses and strains in all materials (Prasad Konda and Tarannum SA, 2012). Lal et al. have dealt with nonlinear free vibration of laminated composite plates on elastic foundation with random system properties. The basic formulation of the problem is based on higher-order shear displacement theory including rotatory inertia effects and von Karman-type Non-linear strain displacement relations. A $C0$ f inite e lement i s u sed f or descretization of the laminate. A direct iterative method in conjunction with first-order Taylor series based perturbation technique procedure is developed to solve random nonlinear generalized eigenvalue problem. The

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developed probabilistic procedure is successfully used for the nonlinear free vibration problem with a reasonable accuracy.

Malekzadeh has developed differential quadrature large amplitude free vibration analysis of laminated skew plates based on FSDT based on the first order shear deformation theory (FSDT) using differential quadrature method (DQM). The geometrical nonlinearity is modeled using Green's strain and von Karman assumptions in conjunction with the FSDT of plates. After transforming and discretizing the governing equations, which includes the effects of rotary inertia, direct iteration technique as well as harmonic balance method is used to solve the resulting discretized system of equations. The effects of skew angle, thickness-to-length ratio, aspect ratio and also the impact due to different types of boundary conditions on the convergence and accuracy of the method are studied. A mesh-free least-squares-based finite difference (LSFD) method is applied for solving large amplitude free vibration problem of arbitrarily shaped thin plates by Wu et al.. In this approximate numerical method, the spatial derivatives of a function at a point are expressed as weighted sums of the function values of a group of supporting points. This method can be used to solve strong form of partial differential equations (PDEs), and it is especially useful in solving problems with complex domain geometries due to its mesh-free and local approximation characteristics. In this study, the displacement components of thin plates are constructed from the product of a spatial function and a periodic temporal function. Consequently, the nonlinear PDE is reduced to an ordinary differential equation (ODE) in terms of the temporal function (Saurabh and Yudhvir Yadav, 2016).

Gajbir et al. have studied Nonlinear vibration analysis of composite laminated and sandwich plates with random material properties Nonlinear vibration analysis is performed using a C0 assumed strain interpolated finite element plate model based on Reddy's third order theory. An earlier model is modified to include the effect of transverse shear variation along the plate thickness and Von-Karmann online ar strain terms. Monte Carlo Simulation with Latin Hypercube Sampling technique is used to obtain the variance of linear and nonlinear natural frequencies of the plate due to randomness in its material properties. This chaotic nature of the dispersion of nonlinear eigen values is also revealed in eigen value sensitivity analysis (Saurabh and Yudhvir Yadav, 2016).

Jayakumar et al. have studied on nonlinear free vibrations of simply supported piezo-laminated rectangular plates with immovable edges utilizing Kirchhoff's hypothesis and von Karman strain–displacement relations. The effect of random material properties of the base structure and actuation electric potential difference on the nonlinear free vibration of the plate is examined. The study is confined to linear-induced strain in the piezoelectric layer applicable to low electric fields (Saurabh and Yudhvir Yadav, 2016).

The von Karman's large deflection equations for generally laminated elastic plates are derived in terms of stress function and transverse deflection function. A review of the recent development of the finite element analysis for laminated composite plates from 1990 is presented by Zhang et al. The literature review is devoted to the recently developed finite elements based on the various laminated plate theories for the free vibration and dynamics, buckling and post-buckling analysis, geometric nonlinearity and large deformation analysis, and failure and damage analysis of composite laminated plates. The material nonlinearity effects and thermal effects on the buckling and post-buckling analysis, the first-ply failure analysis and the failure and damage analysis were emphasized specially (Saurabh and Yudhvir Yadav, 2016).

2. Structural Subsystem

The objective of the structural subsystem for the CubeSat project is to provide a simple, steady structure that will survive launch loads, while providing an easily accessible data and power bus for debugging and assembly of components. Because of the size constraints of the CubeSat and small expense budget, this must be done with the philosophy of maximizing usable interior space, while minimizing the complexity and cost of the design. The design of the CubeSat conforms to the structural and launcher requirements set by the Stanford/Calpoly CubeSat program. The shape of CubeSat is essentially a cube, with outer dimensions of 10 x 10 x 10 cm, with 3.0 mm clearance above each face of the cube for mounting exterior components such as antenna, data link and power charger inlet port. The maximum allowable mass of CubeSat is 1 kg, and it is desired that the structure be no more than approximately 30% of the total CubeSat mass, and should be able to withstand a minimum of 50 g's load (Wells, 2003).

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3. Material Selection

LEO satellites are commonly used for communication and earth imaging enclosed by a payload of signal processing module only. In designing of LEO satellite, the model is premeditated by an appropriate selection of material based on low weight, high strength to weight ratio, and space qualified. In addition, basic geometry of the satellite body is also defined by considering the factors such as heat distribution and heat dissipation, weight of fasteners, accessibility and maintainability, accommodation of subsystems, centre of gravity, and manufacturing cost.

The suggested material for the main satellite structure is Aluminium 7075 or 6061, Stainless Steel, Titanium, Composites, and Honey Comb. If other materials are used, they must have the equal or more value for thermal expansion and yield strength as the aluminium. Table 1 lists several materials along with their strength, density, and cost for a 12 x 12 inch sheet.

Table 1: Material Analysis

Material	Yield Strength	Density	Machinability	Cost/ft^2
Stainless Steel	790MPa	7760kg/m^3	Easy	$6.25
Titanium	900MPa	4429kg/m^3	Hard	$57.40
AL-6061-T6	320MPa	2850 kg/m^3	Easy	$2.42
AL-7075-T6	340MPa	2796 kg/m^3	Easy	$2.87
Composites	640MPa	~1000 kg/m^3	Hard	$43.80
Inconel	848MPa	8321 kg/m^3	Hard	$96.25

The above table clearly indicates that AL-6061-T6 and AL-7075-T6 meet the required criteria of high strength, light-weight, easy machinability, and cost; therefore, Aluminium 7075 was chosen as the structural material for the CubeSat frame since it has higher yield strength.

4. CubeSat Frame Design

In short, it is necessary to have a structure that is light, strong, versatile, and easy to disassemble (Campbell, 2002). The CubeSat frame is to be made of 6 aluminium faces of 2mm thickness. The CubeSat frame will have a pumpkin structure in order to reduce its weight and to make it easier to mount the solar cells and other components. A model of the frame is created using Solidworks software and it is as shown in figure 3 below.

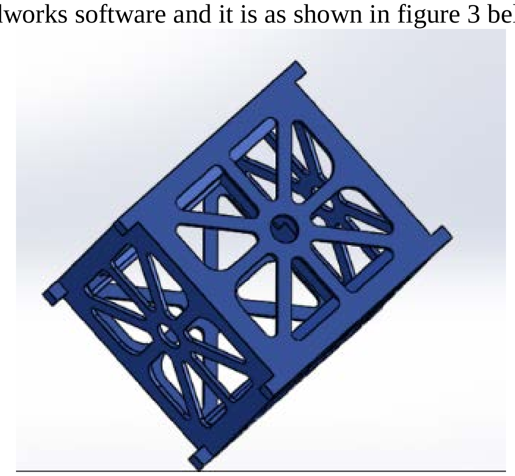

Figure 3: CubeSat Frame

5. Finite Element Analysis of CubeSat Frame

In order to properly design and construct a CubeSat, 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

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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.

5.1 Stress Analysis

The greatest stress occurs during launch hence the force likely to be experienced by the CubeSat during launch is to be modelled and analysed using Solidworks simulation.

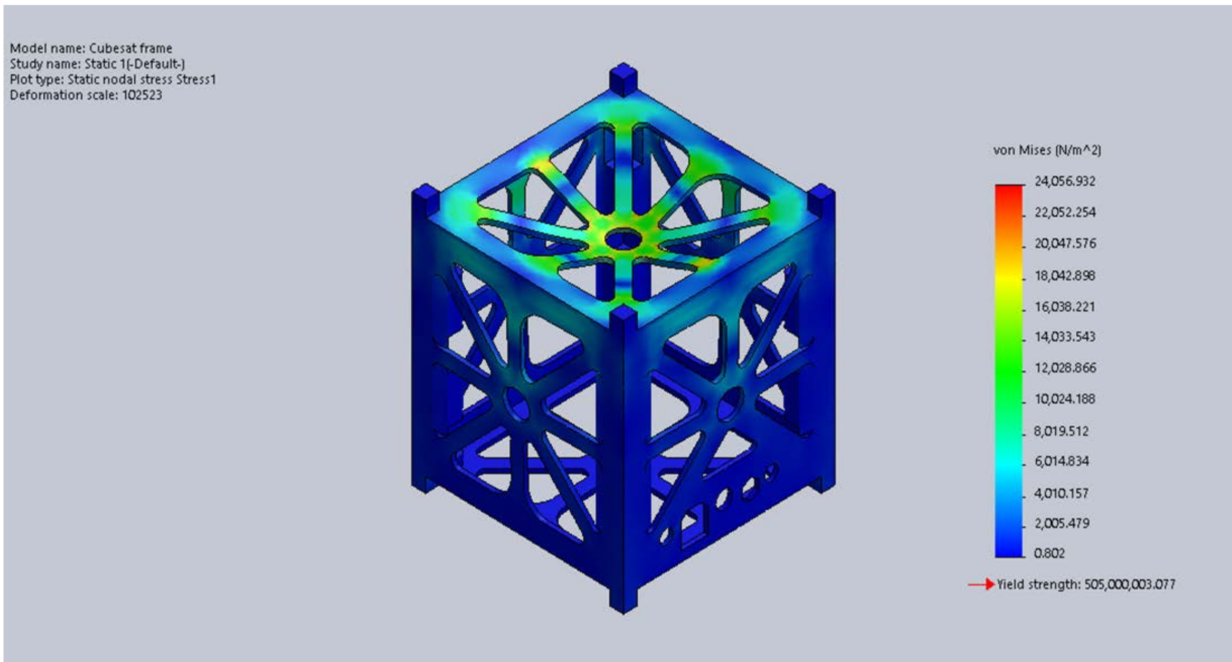

Figure 4: Finite Element Analysis on the CubeSat's Frame for stress Analysis

The results provided us with von Mises stress varying from 0.802 Nm^2 to approximately 16038.221Nm^2. Even if the stress had reached the largest value on the scale, approximately 24056.932Nm^2, the yield strength of the Al 7075 T6 is 5.05e+008 N/m^2. The areas affected the most by the von Mises stress occur on the centre of the top Face of the CubeSat. The test showed that the material used on the Pumpkin structure, assumed for the CubeSat, should be able to withstand the vibrational loads throughout the launch period for any of the launch vehicles likely to be used.

5.2 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.

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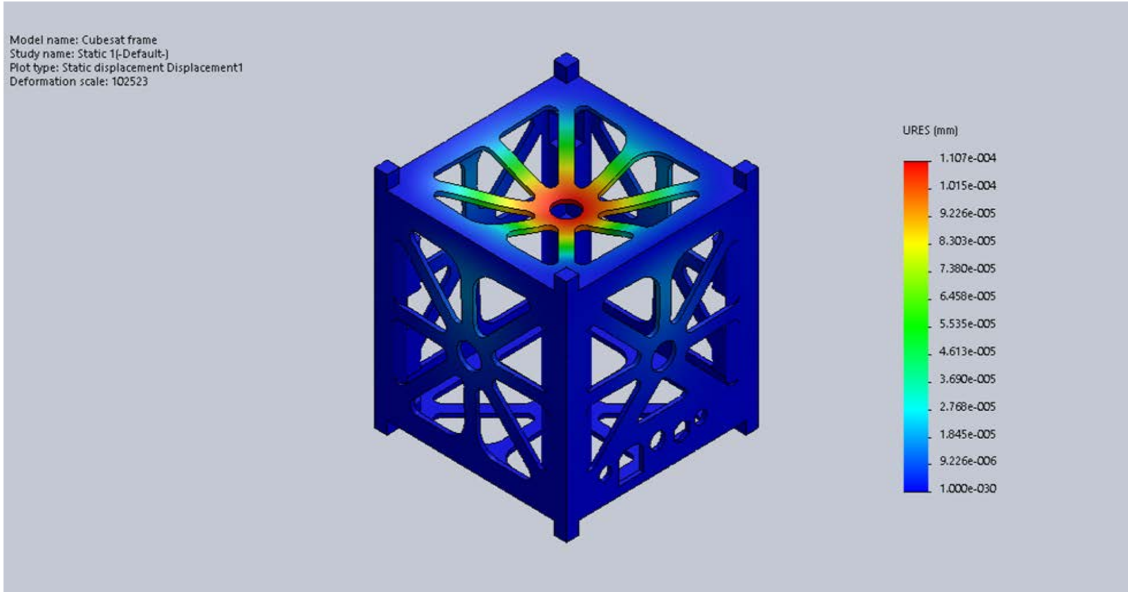

Figure 5: Finite Element Analysis on the CubeSat's Frame for Displacement Analysis

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 vary 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.

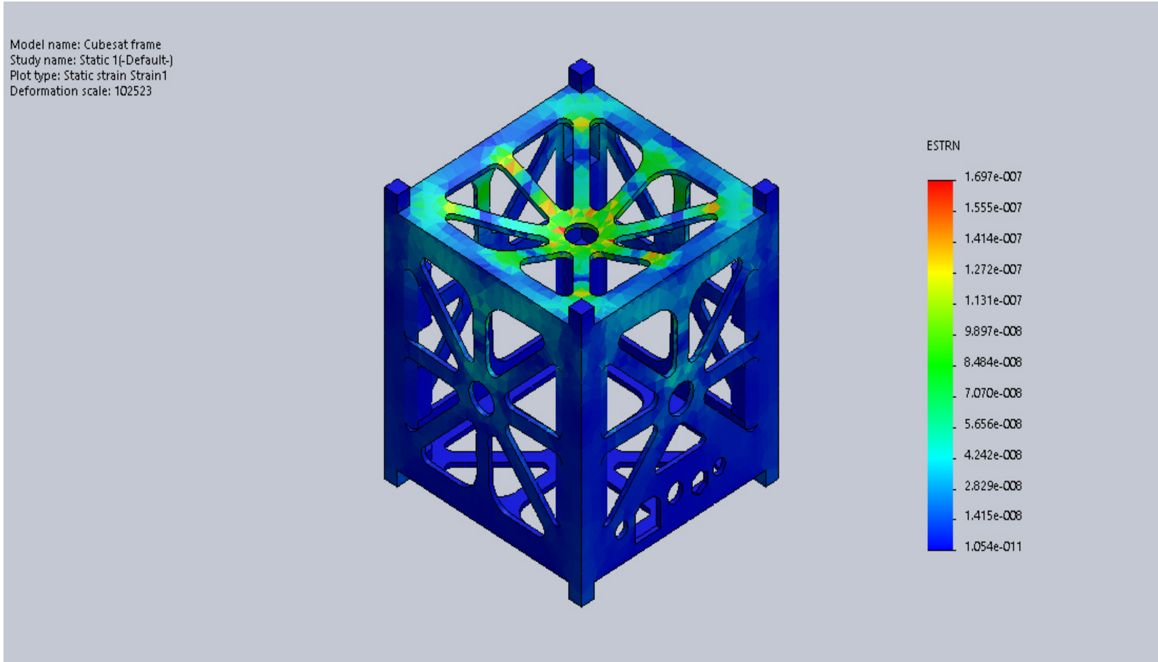

Figure 6: Finite Element Analysis on the CubeSat's Frame for Static Strain Analysis

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6. 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.

7. 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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Biography

Kudzanai Sekerere is a student who recently completed a Bachelor of Engineering (Honours) Degree in Mechatronics at the Chinhoyi University of Technology in Zimbabwe. He has interned for a year with the Zimbabwe Power Company where he has attained experience in thermal power generation. His main interests are in the fields of industrial automation, instrumentation and control and robotics.

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