A NOVEL MODULAR CUBESAT DESIGN IMPLEMENTING ADDITIVELY MANUFACTURE COMPONENTS

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Abstract

In this paper, a scalable 1U CubeSat design capable of being additively manufactured as a monolithic structure on a fused deposition printer is investigated. This design aims to allow expandability between the 1U-12U CubeSat family while maintaining a cost-effective approach that maximizes the available payload mass. The design is verified through the use of finite element analysis with its loading conditions derived from the Soyuz-2-Fregat rocket.

Introduction and Background

In the dynamic landscape of space applications, nanosatellites have emerged as pivotal platforms for scientific research, technological innovation, and educational endeavors. The increasing popularity of nanosatellite designs, coupled with the rising accessibility of low Earth orbit (LEO), has resulted in a revolutionary increase in commercial and educational space-based missions. In recent years, there has been an exponential increase in the frequency of nanosatellite launches with 334 recorded in 2022, 396 in 2023, and 576 projected for 2024 [1]. With the high demand and rising frequency of these launches, the need for an adaptable and reliable design has become apparent.

Many researchers in the past have created modular CubeSat designs that fulfil this need to varying degrees but have been limited by the constraints introduced from subtractive manufacturing techniques. It is for this reason, that additive manufacturing (AM) methods will be investigated within this paper to introduce a new avenue to CubeSat design.

CubeSat Design Specification

A CubeSat is a subclass of nanosatellites introduced in 1999 by California Polytechnic State University (Cal Poly) based upon 10cm x 10cm x 10cm cubes, also known as a "U" A 1U CubeSat is comprised of a singular U with a mass of up to 2 kg, a 2U CubeSat is comprised of two Us with a mass of up to 4kg, etc. [2]. The CubeSat Design Specification (CDS) explicitly outlines the requirements for CubeSat structures throughout the 1U to 12U form factor and will be used to drive design requirements.

Manufacturing Decision

CubeSats have traditionally utilized a method of manufacturing known as subtractive manufacturing (SM), a process where material is taken away via cutting, boring, drilling, and grinding of the material. This method has long stood as the precedent for satellite design due to the vast infrastructure and in depth understanding of the SM process. However, this method of manufacturing introduces numerous limitations onto the designer [3].

The intricate and lightweight components required to achieve high payload-structure mass ratios in CubeSat missions often require complex geometries in small form factors which may require the use of multiple SM machines, leading to elevated costs and increased lead times. In comparison AM techniques, which fabricate designs layer upon

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layer, efficiently utilize the selected material with minimal waste and faster lead times [3]. This layer-by-layer fabrication introduces the opportunity for new parametric designs such as internal latticing and complex interior geometries previously unmanufacturable by SM methods. The new design routes offered by AM enables designers to consolidate a multipart assembly into a single component, reducing the number of fasteners and, subsequently, the points of failure.

Design and Requirements

Printer Selection

The AM technique utilized for the modular CubeSat design is a Fused Deposition Modeling (FDM) printer with the specifications shown in Table 1:

Table 1. FDM Printer Specifications

Build Volume	256 mm^3
Nozzle	0.4mm Hardened Steel
Max Hot End Temp	300°C
Filament Diameter	1.75mm
Max Build Plate Temp	120°C

An FDM printer was selected as the AM method of choice due to its wide availability and low-cost nature, increasing its accessibility to CubeSat programs within Academia who may not have access to more expensive means of AM such as Selective Laser Sintering.

Material Selection

The selection of material for a structure is one of the most critical choices in the design process. Material selection dictates the efficiency, performance, and longevity of a component. In order to obtain a component capable of fulfilling its required functions, the environment in which it operates is critical. In the environment of Space, new challenges are presented to designers in the form of temperature fluctuations, cold-welding, and other environmental factors. The average temperature ranges a CubeSat experience in a LEO is -65°C on the eclipse side and +125°C on the sun side, necessitating a material that can withstand cyclic temperature fluctuations while maintaining its mechanical properties [4]. Additionally, cold-welding is of concern when two metallic surfaces encounter each other. Cold welding occurs when the gap between two metal surfaces becomes small enough that the atoms of the two surfaces share valence electrons, bonding to one another. This phenomenon is of concern in the CubeSat-Dispenser interface, where two smooth surfaces will slide against one another during deployment. To avoid this, a polymer or other non-metallic material can be used for the CubeSat rails. A commercially available nylon-carbon fiber, PolyMide PA6-CF, composite functions ideally in both scenarios above (Table 2). With minimal deflection up to 180°C and the inability to cold-weld this FDM filament is a prime candidate for the modular CubeSat structure.

Table 2. PolyMide PA6-CF Printer Specifications [5]

Nozzle Temp	280-300°C
Bed Temp	25-50°C
Chamber Temp	25-50°C
Printing Speed	60 mm/s
Cooling Fan	OFF

Table 3. PolyMide PA6-CF Material Specifications [5]

Young’s Modulus (X-Y)	7453 ± 656 MPa
Young’s Modulus (Z)	4354 ± 206 MPa

Tensile Strength (X-Y)	105 ± 5.0 MPa
Tensile Strength (Z)	67.7 ± 4.7 MPa
Elongation at Break (X-Y)	3.0 ± 0.3 %
Elongation at Break (Z)	2.5 ± 0.7 %
Bending Modulus (X-Y)	8339 ± 369 MPa
Bending Modulus (Z)	N/A
Bending Strength (X-Y)	169.0 ± 4.7 MPa
Bending Strength (Z)	N/A
Charpy Impact Strength (X-Y)	13.34 ± 0.5 kJ/m^2
Charpy Impact Strength (Z)	N/A

Structure Requirements

The CDS defines the standard for the interaction between CubeSats and their dispenser. The applicable requirements for the modular CubeSat's structure as derived from the CDS documentation are [2]:

- Rails may have a max surface of roughness of 1.5 µm.
- ±Z faces of the rails shall have a minimum surface area of 6.5 mm^2
- 75% of rails must be in contact with the dispenser.
- Center of gravity of the CubeSat must fall within ±2 cm of its geometric center.
- No component shall protrude farther than 6.5 mm normal to the surface from the plane of the rails.
- Rails shall have a minimum width of 8.5 mm from the leading edge of the rail to the first protrusion on each face.
- Exterior surfaces of the CubeSat (excluding rails) should not contact the dispenser.

Loading Conditions

The modular CubeSat bus will need to endure a variety of loading conditions during its journey from the launchpad into space. To ensure the ruggedness of this design, values for these loading conditions must be identified and quantified in a conservative manner.

The five primary forms of mechanical loading of concern to the CubeSat are— (i) static loading, (ii) steady-state accelerations, (iii) dynamic loads, (iv) shocks, (v) and thermal loading [6]:

(i) Static loading occurs when stresses are generated by the assembly of components such as pre-load in bolts.

(ii) Steady-state accelerations are comprised by the longitudinal and lateral accelerations imparted upon the satellite by the launch vehicle.

(iii) Dynamic loads encompass sinusoidal vibrations, random vibrations, and acoustic loads.

(iv) Shocks occur due to the activation of pyrotechnic devices triggered at the separation of launch vehicle stages and payloads.

(v) Thermal loading occurs as a result of the rocket's friction with air and the temperature increase due to combustion within the engine.

Launch Vehicle Characteristics

The launch vehicle selected for a CubeSat mission plays a crucial role in determining the properties of the five loading conditions referenced above. Characterizing the loading conditions (Table 4) for this study will be the Soyuz-2-Fregat rocket [7].

Modular Design

The aim of the modular CubeSat design is to offer scalability throughout the entire CubeSat family (1U-12U) with as few boundaries to access as possible. For these reasons a monolithic 1U module as shown in Figure 1 has been developed that can be printed entirely self-contained.

Table 4. Loading Conditions and their Occurrence During Flight Stages and Separation Steps [6]

Loading condition	**Quasi-Static loading**	**Sine vibration (SV)**	**Random vibration (RV)**	**Acoustic load***	**Shock**
Source / Launch steps	Acceleration of the rocket	Engine operation	Engine vibration and noise, air friction	Engine, air friction, etc.	Pyro devises used to separate launch vehicles or satellite
Lift-off	**Maximum longitudinal and lateral accelerations**	**SV levels for operation of launch vehicle stages**	**RV for 1st stage flight**	**Sound pressure level spectrum**	
1st stage flight					
1st stage separation			**RV for 2nd and 3rd stage flight**		**1st stage SRS****
2nd stage flight					
Fairing separation					**Fairing SRS****
2nd stage separation					**2nd stage SRS****
3rd stage flight					
3rd stage separation		**SV levels for Fregat flight**	**RV for Fregat flight**		**3rd stage SRS****
Fregat flight					
Fregat separation					**Upper stage SRS****
1st payload release					**First payload SRS****
2nd payload release					

***applied directly onto the spacecraft when inside the fairing**

**** SRS: Separation shock response spectrum**

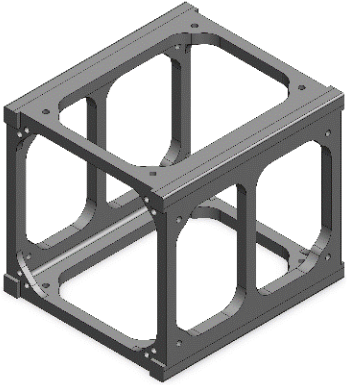

Figure 1. Monolithic 1U CubeSat Module

The capability to print the entirety of a 1U CubeSat structure eliminates stress concentrations that would occur at traditionally bolted joints in exchange for a smoother transition. This allows the designer to simplify analysis of the satellite bus and direct more focus designing other systems of the CubeSat. Furthermore, the ability to receive a nearly flight-ready structure right off the build plate drastically improves project lead time. The only post-processing required of the structure after removal from the print bed is the removal of supports and smoothing of the rail surfaces to 1.5 µm. The 1U modules can be assembled to create larger form factors in two ways – (i) print multiple modules together monolithically on a large enough print bed, or (ii) bolt 1U modules together at the holes depicted in Figure 2.

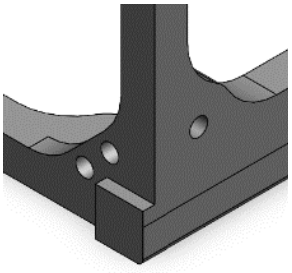

Figure 2. Panel and Module Mounting Holes

Combining multiple 1U modules in a monolithic manner, the resulting CubeSat family is obtained as shown in Figure 3.

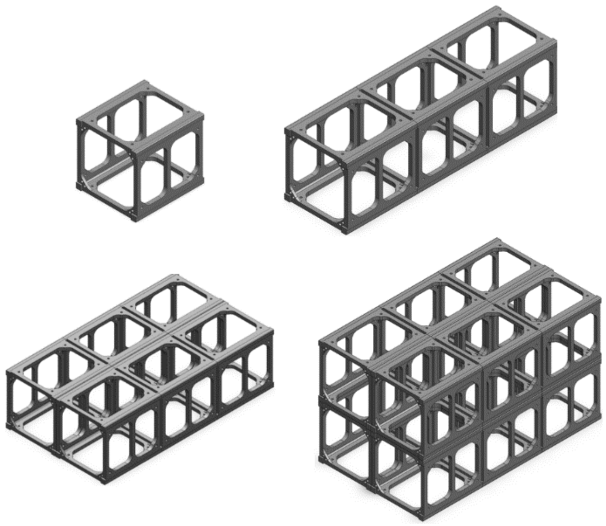

Figure 3. CubeSat Family (1U, 3U, 6U, 12U)

Table 5. Structure-payload Mass Ratio of CubeSat Family

	1U	3U	6U	12U
Structure Mass	0.114 kg	0.340 kg	0.680 kg	1.359 kg
Payload Mass	1.886 kg	5.660 kg	11.320 kg	22.641 kg
Structure-Payload Mass Ratio	6.045%	6.007%	6.007%	6.003%

Finite Element Analysis

To verify functionality and analyze strain on the family of structures, Finite Element Analysis (FEA) will be performed.

Assumptions

To simplify the analysis of the modular CubeSat design, the following set of assumptions have been made:

1) Only structural members will be considered in FEA testing.
2) Analysis of bolts connecting 1U modules will be neglected.
3) Shocks caused by pyrotechnic devices enabling the release of launch vehicles and stages of the rocket will be neglected.
4) Influences of random vibrations on the structure will be neglected.
5) Thermal influences on material properties will be neglected.
6) Material properties will be taken with regards to the “Dry” state.
7) Standoffs in contact with the ±Z face of the CubeSat will be considered fixed to the dispenser.

Quasi-Static Loading

Quasi-Static loading of the CubeSat family will analyze the accelerations enacted upon the CubeSat structure by converting them to a force in terms of gravity. The values utilized as boundary conditions for the FEA will utilize the highest anticipated accelerations to ensure a conservative analysis (Figure 4).

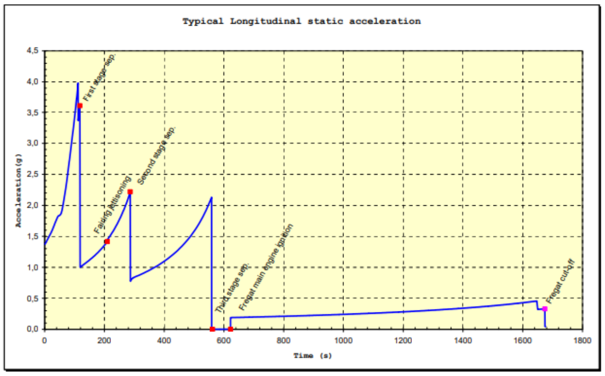

Figure 4. Typical Longitudinal Acceleration of the Soyuz Rocket [7]

Comparing the maximum longitudinal and lateral accelerations measured between various available sources (Table 6).

Table 6. Maximum Acceleration Values [6, 7]

	Longitudinal Acceleration [G]	Lateral Acceleration [G]
Mission Environment	**10**	**5**
Soyuz User Manual	4.3	0.4

Taking the maximum acceleration values to be 10 G in the longitudinal direction and 5 G in the lateral direction, the testing parameters shown in Table 7 are obtained.

Table 7. Quasi-static Loading

Coordinate	Acceleration [G]
X direction	5
Y direction	10
Z direction	5

FEA Setup

To conduct a FEA within the software utilized within this study, SolidWorks, three criteria are required. (i) Designating fixture types to define the degrees of freedom (DoF) of your component. (ii) External loads to replicate anticipated forces. (iii) Defining the components mesh to achieve the desired accuracy of results.

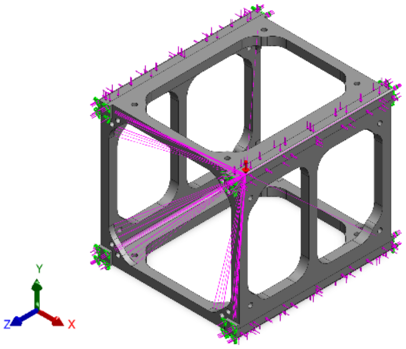

Figure 5. FEA Setup of 1U module

Depicted in Figure 5 is the FEA setup for the 1U module. Green arrows indicate fixed geometry and have been placed at each standoff where the CubeSat will interface with the dispenser. Purple lines indicate a remote mass of 2 kg, the maximum weight of a 1U CubeSat, at the geometric center of the structure. Purple arrows represent the loads identified in Table 6 applied to the rails of the CubeSat. Lastly, the red arrow signifies the direction of gravity. To setup FEA of any scale of the CubeSat family depicted in Figure 4, the methodology for the 1U module can be replicated to yield the appropriate results.

Results

The FEA of the family of structures yields the results shown in Figure 6 and Table 7.

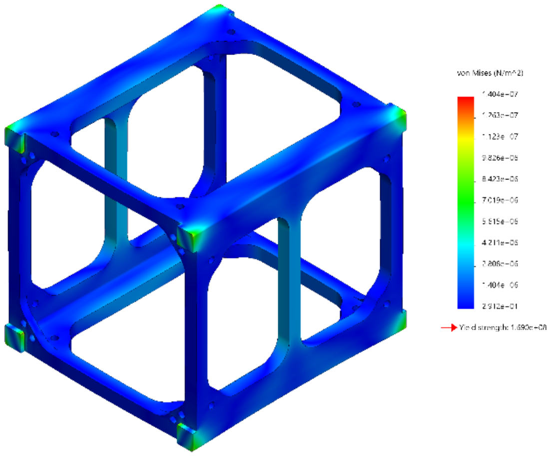

Figure 6. Stress Plot on 1U Module

Table 7. Stress Results of CubeSat Family

	1U	3U	6U	12U
Von Mises (N/m^2)	4.21E +06	1.90E +07	4.90E +07	1.08E +08
Yield Strength (N/m^2)	1.69E+08			

All four form factors of the CubeSat family successfully passed the stress analysis, with Von Mises stresses less than the yield strength by a power of at least a power of ten except for the 12U form factor. A closer analysis of the 12U form factor will be required if a factor of safety greater than 1.56 is required. To quantify the maximum acceptable displacement, the standard practice for maximum beam deflection will be followed.

$$deflection_{max} = \frac{Beam\ Length}{300} \qquad (1)$$

The beam analogy is used to quantify maximum displacement as the areas of highest deflection are the beam-like struts between the CubeSat rails. Using the length from standoff to standoff of a 1U module, the maximum allowable deflection (Eq. 1) is obtained.

$$deflection_{max} = \frac{115.3\ mm}{300} = 0.378\ mm$$

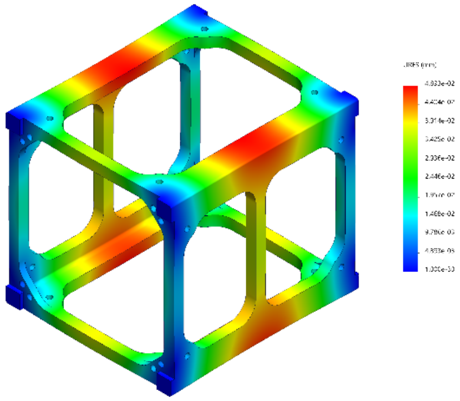

Figure 7. Displacement Plot on 1U Module

Table 8. Displacement Results of CubeSat Family

	1U	3U	6U	12U
Displacement	0.049 mm	0.192 mm	0.326 mm	0.739 mm
Maximum Displacement	0.378 mm			

Looking at the results depicted in Table 8, three out of four form factors fell within the maximum acceptable displacement values. The 12U form factor experienced nearly two times the acceptable displacement and will require modification to its rigidity before it can be used.

Sine Vibration

The vibrational loading resulting from the engine operation are negligent if the spacecraft of study has a natural frequency greater than 40 Hz [8]. The natural frequency of the CubeSat family of structures are greater than 40 Hz and therefore the effects of sine vibration will be neglected.

Acoustic Load

The influence of acoustic loads within the Fregat's fairing are negligible if there are no large, thin, panels such as solar panels [6]. For this reason, acoustic loading will be neglected as the structure of study does not meet the criteria to necessitate testing.

Conclusion

In this paper, an AM CubeSat design was proposed which consisted of 1U modules capable of constructing form factors throughout the CubeSat family. The modular CubeSat design served to expand accessibility to space system missions for the commercial sector and academia by providing a cost-effective and low-lead-time satellite bus while maximizing the available payload mass. Using FEA to verify the design's function under anticipated mechanical loads, it was determined that the 1U, 3U, and 6U form factors are ready for use while the 12U form factor requires modifications to increase stiffness.

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