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Evaluation of GFRP Composite Material in CubeSats Structures

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Abstract

CubeSats are small spacecraft that adhere to strict specifications, making them less expensive to manufacture and launch than conventional satellites. To increase the benefits and applications of CubeSats, it is essential to utilize advanced lightweight materials. This would increase the mass budget allocated to the payload and the other subsystems. In addition to being low in weight, the CubeSat structure must be rigid and strong enough to sustain the other subsystems. This study evaluates the Glass Fiber Reinforced Polymer (GFRP) composite material as an alternative to the conventional aluminium utilized in the structure of a 1U CubeSat. This material has a high strength-to-weight ratio and excellent thermal properties. A 1U CubeSat structure was developed, analyzed, constructed, and tested entirely from GFRP composite material. To ensure that the suggested structure meets the CubeSat design specifications, several finite element simulations were conducted, including both quasi-static and modal analyses. A comparison was made with a commercial off-the-shelf 1U CubeSat structure that has a flight heritage. The results established the proposed structure’s ability to be manufactured and certified for space applications.

Keywords: GFRP material, Quasi-static, modal analysis, finite element, Evaluation

Acronyms/Abbreviations

1U	One Unit
AISI	American Iron and Steel Institute
Al	Aluminium
CDS	CubeSat Design Specification
CFRP	Carbon Fiber Reinforced Polymer
COTS	Commercial off-the-shelf
GFRP	Glass Fiber Reinforced Polymer
JEM	Japanese Experiment Module
P-POD	Poly Picosatellite Orbital Deployer

1. Introduction

A 1U CubeSat, which consists of one CubeSat standard unit, is a 10 cm cube with a mass under 2.0 Kg [1]. CubeSats are available in a variety of sizes that are unit-based. Moreover, they have been used to demonstrate new space technology, whether they be for communication, remote sensing, testing new material, or other uses. Since it is costly and takes a long time to produce, the practice of building huge conventional satellites to test new space technology is currently viewed as an ineffective strategy.

The mechanical, onboard computer, electrical power, attitude determination and control, and communication systems are just a few of the subsystems found in a CubeSat [2]. A CubeSat's mechanical subsystem is one of the most important subsystems. In addition, the structure attaches the satellite to the launch vehicle, supports all satellite subsystems, and enables ordnance-activated separation [3]. Along with offering protection from atomic oxygen and cosmic radiation. Any CubeSat's structure must be able to withstand the hostile launch environment as part of its purpose, which calls for a high degree of stiffness and strength. The structure must adhere to requirements regarding its size, mass, volume, and material characteristics. A CubeSat must also pass certain tests to be qualified for the space environment. This includes the vibration test that mimics the launch vehicle's environment. Due to the large heat cycles, the CubeSat will experience while in orbit, thermal testing in a thermal vacuum chamber is particularly crucial.

Mass, stiffness, and strength must be carefully balanced when designing space structural systems. While stiffness is necessary to assure the instrumentation's ability to survive, it is also feasible to enhance payload by lowering the bulk of the structure, which improves agility and lowers launch costs [4]. It is crucial to select the right material [5] and structural configurations to decrease mass since a satellite's structural and mechanical components often account for a significant portion of its mass.

Thousands of CubeSats have been launched to space since 1999. Most of these CubeSat structures are made of Aluminium 6061 or Aluminium 7075. Moreover, Glass Fiber Reinforced Polymer (GFRP) continued to be a particularly promising material for space applications. Its use provides advantages in terms of mass and strength compared with traditional Al 6061 or Al 7075, and the necessary stiffness may be attained by making the right choices for better kinds and laminate orientation [6]. Additionally, it has a low thermal conductivity, which might be advantageous for the thermal insulation of low-temperature components [7]. On the other hand, GFRP is suitable for temperatures below 300ºC, limiting its use for space exploration missions [8].

Related work focused on the evaluation of Carbon Fiber Reinforced Polymer (CFRP) in CubeSats structures. Ampatzoglou et al. [9] evaluated the performance of CFRP in the structure of a 1U CubeSat. A significant mass reduction of 40% was achieved by utilizing CFRP compared with conventional Aluminium alloy. In addition, the maximum stress on the 1U CubeSat structure and the maximum displacement was reduced as a result of utilizing the CFRP. Another research by Capovilla et al. [10] proposed a new design of smart power management tile where CFRP is used as the structure material. Furthermore, a huge reduction of 46.5% in the mass of the structure of the smart power management tile was achieved because of using the CFRP material instead of the conventional Aluminium alloy.

This study focuses on the application of GFRP in the CubeSat structures, which is considered less expensive than the CFRP [11]. To the best of the authors' knowledge, no open literature addresses this topic. With this solution, all CubeSat and launch requirements will be met while the mass is decreased. The steps taken in this study take into account the design requirements.

2. Material constitutive model

The material used in this study is the S-2 glass fiber reinforced with Hexcel 913 epoxy resin. The reason for selecting this material is that it has more strength compared with the E-glass fiber [12]. In addition, S-2 glass fiber has a flight heritage [13]. Table 1 shows the full set of properties of the material considered. For the CubeSat structure analysis, an Aluminium structure composed of the 6061-T6 Aluminium alloy was taken into consideration. Table 2 lists the characteristics of the Al 6061 alloy utilized in the analysis. The bolts, rods, and spacers that were used to connect the various components of the two CubeSat structures are made of AISI 304 stainless steel, where its properties are shown in Table 3.

Table 1. List of S-2 glass fiber reinforced Hexcel 913 epoxy resin properties [14]

Property	Value
Ultimate tensile strength	1231 MPa
Yield tensile strength	560 MPa
Compressive strength	450 MPa
Flexural strength	790 MPa
Modulus of Elasticity	56.2 GPa
Density	2.5 g/cm^3
Specific heat capacity	0.7 J/gºC

Table 2. List of Aluminium 6061 properties [15], [16], [17]

Property	Value
Ultimate tensile strength	310 MPa
Yield tensile strength	276 MPa
Compressive strength	142 MPa
Flexural strength	299 MPa
Modulus of Elasticity	69 GPa
Density	2.7 g/cm^3
Specific heat capacity	0.9 J/gºC

Table 3. List of AISI 304 stainless steel properties [18], [19]

Property	Value
Ultimate tensile strength	505 MPa
Yield tensile strength	215 MPa
Compressive strength	205 MPa

Modulus of Elasticity	193 GPa
Density	8 g/cm^3
Specific heat capacity	0.5 J/g°C

3. Methodology

This study used a 1U structure meeting the CubeSat Design Specifications (CDS) [1] to conduct finite element analysis. The main purpose of the analysis is to ensure the survivability of the GFRP material as a 1U CubeSat structure and to compare the results with using the Al 6061 material. Moreover, internal dummy masses were used to simulate the internal components of CubeSats. Two structural simulations were done namely the quasi-static and modal analyses. Figure 1 depicts the methodology followed to produce the results of this study.

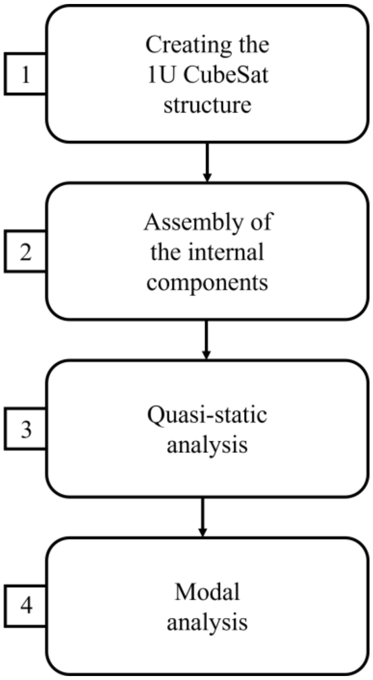


Fig. 1. Methodology of the study

4. Finite element analysis

CubeSats experience accelerations during the launch that are many times greater than the gravitational acceleration [20]. This is in addition to extremely dynamic loads like random vibrations with low and high frequencies. When CubeSats malfunction due to launch vibrations, both the deployer case and the CubeSats may sustain damage. Therefore, it is crucial to estimate the response of CubeSats to the loading environment of the launch vehicle in order to avoid these potential problems. This is typically accomplished in simulations using quasi-static and modal analyses. Figure 2 shows the design of the 1U structure that will be used to conduct the analyses and to compare the GFRP with Al 6061. The main purpose of having the internal dummy masses is to simulate the force employed by the internal components on the CubeSat structure. Figure 3 shows an exploded view of the 1U CubeSat structure where orange, black, and grey colors represent the AISI 304 stainless steel connections, GFRP or Al 6061 CubeSat structure, and the Al 6061 internal components, respectively.

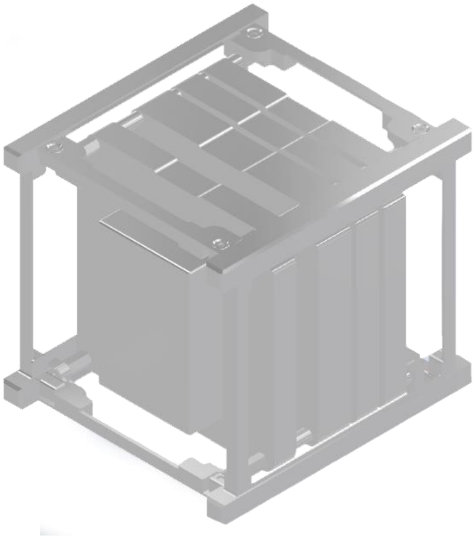


Fig. 2. Design of the 1U CubeSat structure

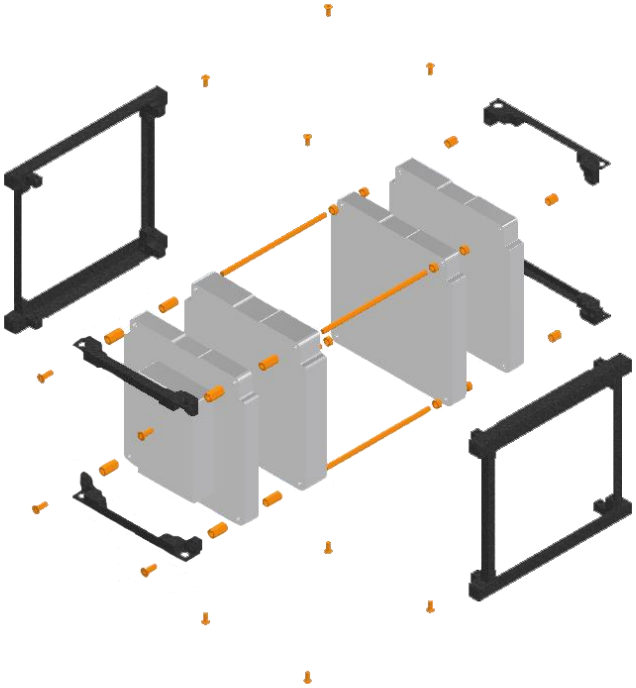


Fig. 3. Exploded view of the 1U CubeSat structure including internal dummy components

The boundary conditions that were defined in the finite element analysis are based on the interaction between the CubeSat and the CubeSat deployer, known as the P-POD, see Figure 4. Fixing the CubeSat's -Z face in all directions and providing a 46.6 N compression load to each of the +Z face's corners are both necessary for the quasi-static analysis [21]. The backplate and mainspring's force on the CubeSat is reflected in this compression load. According to the JEM Payload Accommodation Handbook [21], the CubeSat's +z and -z faces should be treated as fixed supported for the modal analysis. By employing such boundary conditions, the CubeSat's surfaces will be less limited, and the outcomes will more accurately reflect the worst-case situation.

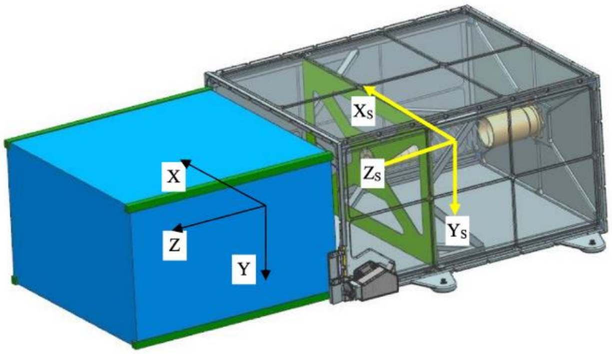


Fig. 4. Methodology of the study [21]

Liftoff can be simulated by applying static loads to a numerical analysis to model the spacecraft's acceleration against gravity. These static loads are commonly applied in units of g-force and vary depending on the launch vehicle being utilized. Additionally, because it is uncertain how the CubeSat would be oriented in the launch vehicle, three potential loading scenarios—each in a different direction—were taken into account. Each time, the loading was applied in one of the axes' (x, y, or z) directions. The Orbital Cygnus vehicle's quasi-static loading of 18.1g was used in the analysis because it is considered the worst case scenario [21].

In order to ensure the safety of the CubeSat, the yield and ultimate margins of safety were calculated, and they are both greater than zero. According to [22], the yield factor of safety was assumed to be 1.1 and the ultimate factor of safety to be 1.4. The yield margin of safety and the ultimate margin of safety calculations are shown in Equations 1 and 2, respectively.

$$\text{Yield margin of safety} = \frac{\text{Material's yield stress}}{\text{Max stress analysis} \times \text{Yield factor of safety}} - 1 \geq 0 \tag{1}$$

$$\text{Ultimate margin of safety} = \frac{\text{Material'sultimate stress}}{\text{Max stress analysis} \times \text{Ultimate factor of safety}} - 1 \geq 0 \tag{2}$$

The CubeSat experiences random vibrations from the engine of the launch vehicle. Hence, it may suffer serious damage as a result of these vibrations. Therefore, it is necessary to undertake a dynamic/modal analysis to show how the structure would react to such dynamic loads. The CubeSat's first mode frequency shall be higher than 100 Hz, as specified in the CDS [1].

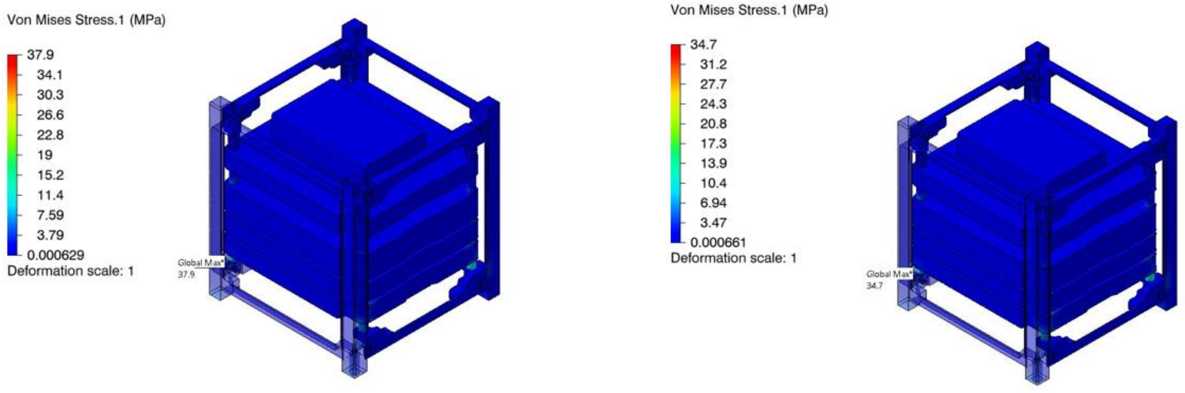
5. Results and discussion

To guarantee that the yield and ultimate margin of safety are more than zero, the quasi-static analysis was done on a 1U CubeSat structure composed of GFRP. In order to confirm that the frequency in the first mode is larger than 100 Hz, a modal analysis was also performed. The outcomes were also contrasted with a 1U CubeSat structure composed of Al 6061. Table 4 compares the mass of a 1U CubeSat structure built of Al 6061 with a 1U CubeSat structure made of GFRP. The GFRP structure has a little reduced mass, as indicated in Table 4, which makes it preferable for space applications.

Table 4. Mass comparison between GFRP structure and Al 6061 structure

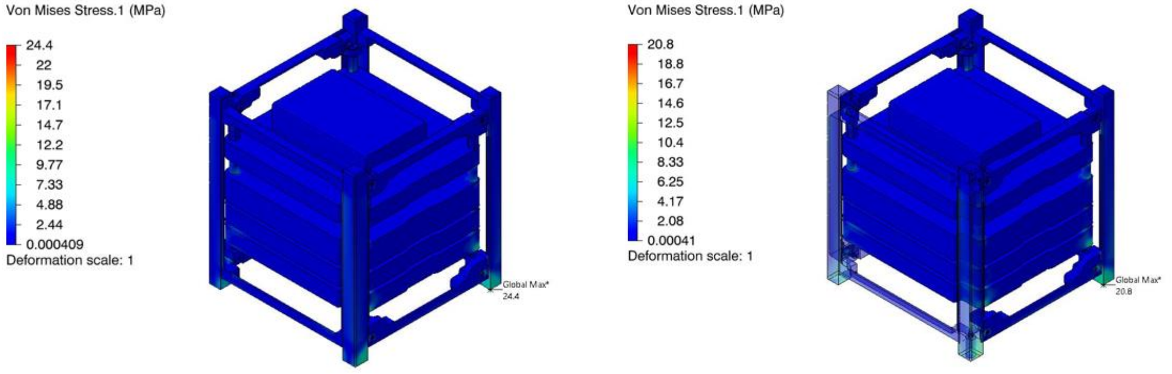
Item	Mass (g)
AISI 304 stainless steel connections	35
Al 6061 internal components	1094.4
GFRP 1U CubeSat	1203.3
Al 6061 1U CubeSat	1209.8

The quasi-static analysis was carried out for both structures, namely the GFRP structure and the Al 6061 structure. Figures 5–7 display the quasi-static findings for the three different loading conditions. The yield and final margin calculations for the three situations under consideration are shown in Table 5. Table 5 demonstrates that the yield and ultimate margins are always more than zero, satisfying the condition [1]. In addition, the GFRP structure is preferred because it has a higher yield and final margins than the Al 6061 structure.



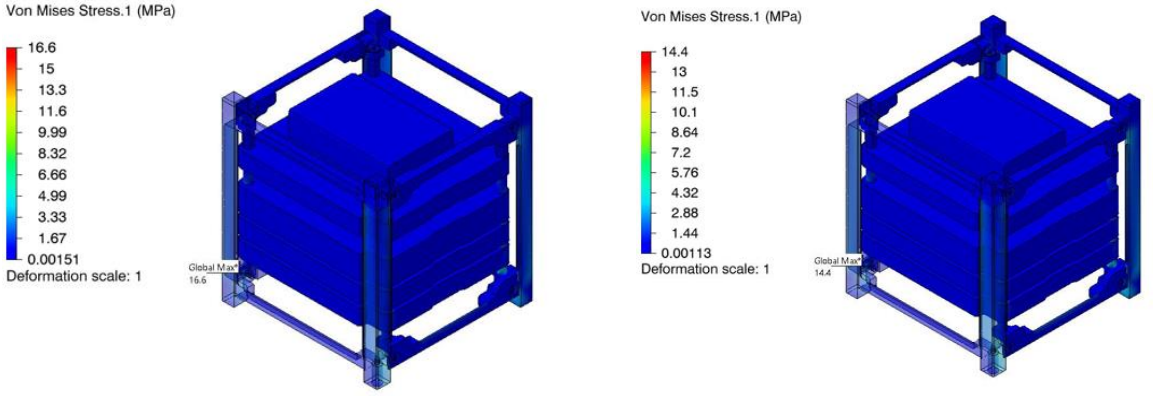
(a) (b)

Fig. 5. (a) Maximum stress on the GFRP structure for the x-axis scenario. (b) Maximum stress on the Al 6061 structure for the x-axis scenario.



(a) (b)

Fig. 6. (a) Maximum stress on the GFRP structure for the y-axis scenario. (b) Maximum stress on the Al 6061 structure for the y-axis scenario.



(a) (b)

Fig. 7. (a) Maximum stress on the GFRP structure for the z-axis scenario. (b) Maximum stress on the Al 6061 structure for the z-axis scenario.

Table 5. The yield and ultimate margins of safety for the three scenarios

Scenario	GFRP yield margin of safety	Al 6061 yield margin of safety	GFRP ultimate margin of safety	Al 6061 ultimate margin of safety
X-axis scenario	12.4	6.2	22.2	5.4
Y-axis scenario	19.9	11.1	35.0	9.6
Z-axis scenario	30.0	16.4	52.0	14.4

In order to meet the criteria in the CDS document [1], the modal analysis was done to ensure that the first mode's frequency is considerably greater than 100 Hz. The findings of the modal analysis of the GFRP structure in comparison to the Al 6061 structure results are displayed in Table 6. Table 6 shows that the GFRP structure's first mode frequency is more than 100 Hz, which exceeds the criteria.

Table 6. The modal analysis results of the GFRP and Al 6061 structures

Structure	1st frequency mode (Hz)	2nd frequency mode (Hz)	3rd frequency mode (Hz)	4th frequency mode (Hz)
GFRP	503.7	569.5	776.2	1221.2
Al 6061	519.0	586.9	799.3	1245.4

6. Conclusions

The composite material can be used to manufacture CubeSats structure. The literature has contributed to evaluating some types of composite materials, such as the CFRP. The primary objective of this study is to demonstrate the advantages of using the GFRP in the CubeSat structure. Therefore, a new CubeSat structure made of GFRP was proposed in this study. The material used as a GFRP CubeSat structure is S-2 glass fiber reinforced with Hexcel 913 epoxy resin which has a flight heritage. The proposed GFRP structure has a slightly less mass of 6g compared with conventional Al 6061. Additionally, the GFRP structure outperformed the Al 6061 structure in the quasi-static analysis. The yield and ultimate margins of safety all exceeded zero, meeting the requirements of the CubeSat design. The initial mode frequency, 503.7 Hz, exceeds 100 Hz and complies with the CubeSat design specifications [1]. The GFRP CubeSat structure and Al 6061 CubeSat structure were compared in the first four frequency modes. The findings indicate that the Al 6061 structure frequencies in all three modes are marginally greater to those of the GFRP structure.

References

[1] C. D. Specification, "rev. 14.1," The CubeSat Program, Cal Poly SLO, 2022.
[2] R. Fléron, "Satellite Forensics: Analysing Sparse Beacon Data to Reveal the Fate of DTUsat-2", International Journal of Aerospace Engineering, vol. 2019, pp. 1-12, 2019. Available: 10.1155/2019/8428167.
[3] Wiley J. Larson, James R. Wertz, *Space Mission Analysis and Design*, 3rd ed, 1999.
[4] Sarafin Thimas P, Larson Wiley J. Spacecraft structures and mechanisms from concept to launch, Microcosm, Inc, 1995.
[5] ECSS-E-ST-32-08C, "rev. 1," Space engineering - Materials, European Cooperation for Space Standardization, 2014.
[6] H. Bansemir and O. Haider, "Fibre composite structures for space appli-cations—recent and future developments", Cryogenics 38 (1998) 51–59, Elsevier Science Ltd, 1998.
[7] Timo Brander, Kristof Gantois, Harri Katajisto, Markus Wallin, “CFRP Electronics Housing for a Satellite”, European Conference on Spacecraft Structures, Materials & Mechanical Testing, Noordwijk, ・ e Netherlands, 10-12 May 2005.
[8] S. Alsayed, Y. Al-Salloum, T. Almusallam, S. El-Gamal, and M. Aqel, "Performance of glass fiber reinforced polymer bars under elevated temperatures," Composites Part B: Engineering, vol. 43, no. 5, pp. 2265–2271, 2012.
[9] A. A, B. A, K. A, and K. V, "Qualification of composite structure for Cubesat Picosatellites as a demonstration for small satellite elements," International Journal of Aeronautical Science & Aerospace Research, pp. 1–10, 2014.

[10] G. Capovilla, E. Cestino, L. Reyneri, and G. Romeo, "Design of a multifunctional composite structure for modular CubeSat applications," MATEC Web of Conferences, vol. 304, no. 07001, 2019.

[11] A. D. Nugraha, M. I. Nuryanta, L. Sean, K. Budiman, M. Kusni, and M. A. Muflikhun, "Recent progress on natural fibers mixed with CFRP and GFRP: Properties, characteristics, and failure behaviour," Polymers, vol. 14, no. 23, p. 5138, 2022.

[12] Z. Hasan, Tooling for Composite Aerospace Structures: Manufacturing and Applications. Kidlington, Oxford: Butterworth-Heinemann, an imprint of Elsevier, 2020.

[13] "Fiber-Reinforced Polymer Composite Material Selection," NASA. [Online]. Available: https://llis.nasa.gov/lesson/689.

[14] M. Kinsella, D. Murray, D. Crane, J. Mancinelli, and M. Kranjc, "Mechanical properties of polymeric composites-technical." [Online]. Available: http://s2-glass.com/wp-content/uploads/2016/04/Mechanical_Properties_of_Polymeric_Composites-Technical.pdf.

[15] "6000 Series Aluminum Alloy; Aluminum Alloy; Metal; Nonferrous Metal," ASM material data sheet. [Online]. Available: https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6.

[16] G. PITCHAYYAPILLAI, P. SEENIKANNAN, P. BALASUNDAR, and P. NARAYANASAMY, "Effect of nano-silver on microstructure, mechanical and tribological properties of cast 6061 aluminum alloy," Transactions of Nonferrous Metals Society of China, vol. 27, no. 10, pp. 2137–2145, 2017.

[17] M. Satheesh and M. Pugazhvadivu, "Flexural Strength Behavior of Al 6061matrix Reinforced with SiC and Coconut shell ash," SSRG International Journal of Mechanical Engineering (SSRG-IJME), 2018.

[18] "AISI Type 304 Stainless Steel," ASM material data sheet. [Online]. Available: https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mq304a.

[19] N. Alloys, "304 STAINLESS STEEL - THE MOST COMMONLY USED STEEL," 304 Stainless Steel, AISI 304, EN 1.4301, S30400 UNS Number, AFNOR Z7Cn18-09, BS 304S15 - Austenite steel. [Online]. Available: https://www.neonalloys.com/304-stainless-steel.

[20] C. Nieto-Peroy and M. R. Emami, "CubeSat mission: From design to operation," Applied Sciences, vol. 9, no. 15, p. 3110, 2019.

[21] Japan Aerospace Exploration Agency (JAXA), JEM Payload Accommodation Handbook. 2013.

[22] I. Raju, J. Stadler, J. Kramer-White, and R. Piascik, "White paper on factors of safety," 2012.