Developing efficient structural systems for small satellites

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ABSTRACT

The growing demand for small satellites, including CubeSats and nanosatellites, is reshaping the space industry by offering affordable, versatile, and rapidly deployable solutions for Earth observation, communications, and scientific missions. Despite these advantages, their compact form presents significant engineering challenges—particularly in developing structural systems that are both lightweight and capable of withstanding the stresses of launch and the extreme conditions of space. Tackling these issues is essential to improve mission reliability and long-term sustainability.

This study aims to develop structural designs that minimize weight while preserving mechanical strength and load-bearing performance. It utilizes advanced optimization techniques, such as topology optimization and genetic algorithms, to generate innovative and efficient structural solutions. The research also investigates iso-grid and honeycomb structures, known for their excellent strength-to-weight ratios and compatibility with modern fabrication methods.

Additive Manufacturing (AM) commonly known as 3D printing—is central to this approach. It enables the creation of complex geometries and customized components that traditional manufacturing methods cannot easily produce. AM not only supports material-efficient designs but also allows for rapid prototyping and cost-effective production, making it especially suitable for small satellite development. Combining AM with iso-grid and honeycomb structures further enhances design flexibility for various mission profiles.

In summary, this work presents a comprehensive framework for designing efficient and sustainable structural systems for small satellites. The outcomes are expected to boost mission efficiency, increase accessibility, and drive innovation in satellite engineering in response to the growing needs of the space sector.

Keywords: *CubeSats; iso-grid; honeycomb; additive manufacturing; 3D printing*

1 Introduction

The small satellite industry, particularly CubeSats and nanosatellites, has transformed space accessibility over the past decade. These compact platforms enable diverse missions—from Earth observation and communications to scientific experiments—at a fraction of traditional satellite costs. By lowering financial and technical barriers, small satellites have democratized space access, enabling universities, commercial startups, and emerging space nations to participate in orbital operations and drive innovation in the sector.

However, miniaturization introduces significant engineering challenges. Limited physical volume creates competing demands: structures must be lightweight to reduce launch costs, yet mechanically robust enough to survive harsh launch environments and operational conditions. In aerospace systems, mass directly correlates with mission economics—each additional kilogram substantially increases propellant requirements and launch expenditure. Structural designers must therefore optimize mass while maintaining sufficient strength, stiffness, and reliability throughout the mission lifecycle.

This research addresses the mass-strength paradox through the development of structurally optimized small satellite platforms. The primary objective is designing lightweight structures capable of withstanding launch-induced vibrations, mechanical shocks, and on-orbit thermal cycling, while remaining cost-effective to manufacture and adaptable across mission profiles. The approach integrates computational optimization methods with Additive Manufacturing (AM) technologies to achieve performance targets unattainable through conventional fabrication techniques.

Additive Manufacturing has fundamentally disrupted aerospace component production. Traditional subtractive methods—machining, casting, forging—impose geometric constraints and generate substantial material waste. These processes typically yield conservative designs with excess mass to ensure safety margins. Conversely, AM's layer-by-layer deposition enables fabrication of complex geometries previously considered unmanufacturable, including internal lattice networks, conformal cooling channels, and functionally graded materials. This design freedom allows structures to be tailored precisely to their loading conditions.

The research employs topology optimization as its primary design strategy. This computational method iteratively removes material from a design domain while maintaining structural performance under specified loads. The algorithm identifies optimal load paths and material distribution, producing organic, biomimetic forms that maximize stiffness-to-weight ratios. For small satellites, topology optimization can reduce structural mass by 30-50% compared to conventional designs without compromising mechanical integrity.

Complementing topology optimization, the study implements genetic algorithms for multi-objective design exploration. These evolutionary computation techniques generate populations of candidate designs and improve them through selection, crossover, and mutation operations mimicking biological evolution. Genetic algorithms excel at navigating complex design spaces with competing objectives—simultaneously minimizing mass while maximizing natural frequency and factor of safety. Their probabilistic nature enables discovery of non-intuitive solutions that gradient-based methods might overlook.

The structural design incorporates three high-performance geometric patterns: lattice structures, isogrids, and honeycomb cores. Lattice structures feature periodic networks of thin struts providing exceptional stiffness per unit mass. Isogrid reinforcement patterns—characterized by triangular stiffening ribs—deliver quasi-isotropic mechanical properties ideal for cylindrical and planar components. Honeycomb architectures offer outstanding compressive strength and energy absorption through their cellular geometry. All three configurations leverage AM's capability to produce intricate internal features impossible with conventional manufacturing.

Material selection considers mission-specific thermal, mechanical, and electromagnetic requirements. Titanium alloys (Ti-6Al-4V) provide high strength and corrosion resistance for demanding applications. Aluminium alloys (AlSi10Mg) offer favourable strength-to-weight ratios and thermal conductivity for general-purpose structures. High-performance polymers enable rapid prototyping and specialized applications requiring electromagnetic transparency. Manufacturing utilizes Selective Laser Melting (SLM) for metallic components and Fused Deposition Modelling (FDM) for polymer structures.

Design validation combines computational simulation with physical testing. Finite Element Analysis (FEA) predicts structural response under launch vibrations (quasi-static loads up to 10g), random vibration profiles, acoustic loads, and thermal extremes (-150°C to +120°C). Simulations identify stress concentrations and verify adequate safety factors before fabrication. Subsequently, AM-produced prototypes undergo qualification testing—random vibration tests per NASA-GEVS standards, thermal vacuum cycling, and mechanical load testing—to demonstrate flight readiness.

Anticipated outcomes include 40-60% mass reduction compared to traditionally manufactured equivalents, improved stress distribution eliminating localized failure modes, and enhanced platform modularity. These advances translate directly to mission value: increased payload capacity, extended operational lifetime through reduced structural fatigue, and decreased launch costs enabling more frequent missions. Additionally, AM's rapid iteration capability compresses development timelines from months to weeks, accelerating technology maturation and market responsiveness.

The research contributes to sustainable space operations through resource-efficient design and manufacturing. Lightweight structures require less raw material extraction and processing energy. Reduced launch mass decreases propellant consumption and associated emissions. AM's near-net-shape production minimizes material waste compared to subtractive machining that discards 70-90% of stock material. Furthermore, distributed AM manufacturing enables regional production, reducing transportation-related environmental impacts and supply chain vulnerabilities.

This study advances small satellite structural engineering by utilizing computational optimization with additive manufacturing techniques. The methodology produces application-specific designs that uses AM's geometric freedom while maintaining aerospace qualification standards. Beyond immediate CubeSat applications, the techniques developed here inform future spacecraft design paradigms. As satellite constellations proliferate and missions diversify, such optimization-driven approaches become essential for economically viable and environmentally responsible space systems.

2 Research Methods

2.1 Design, Verification, and Fabrication

The Design and Analysis included developing conceptual and detailed models of the satellite chassis using honeycomb and isogrid configurations in CAD software. These designs were chosen for their strength-to-weight ratios in aerospace applications. Further, they were refined to incorporate internal compartments for subsystem placement and standardized mounting interfaces for future operations.

Finite Element Analysis (FEA) was employed to assess the mechanical performance of these designs under simulated space launch conditions, including vibration, acceleration, and thermal expansion. This simulation-driven process allowed for the iterative refinement of material layout and structural reinforcements to mitigate stress concentrations.

During the Verification and Comparison phase, the performance of the isogrid and honeycomb models was documented and compared based on critical performance indicators: weight, maximum stress experienced, factor of safety (FoS), and natural frequency. While honeycomb structures generally demonstrated superior performance in evenly distributing loads, isogrid structures excelled under localized point loads. This comparative analysis determined the optimal structure based on the intended mission profile, while also verifying the design's practicality for manufacturability.

The project further employed fabrication using AM, specifically the Fused Deposition Modelling (FDM) technique. FDM was selected for its cost-effectiveness and capacity to produce complex structural components using space-compatible thermoplastic filaments. Functional features such as wire routing paths and component mounts were directly integrated during the printing process, reducing the need for secondary manufacturing and post-assembly work.

2.2 Analysis and Simulation Objectives

The structural development of small satellites is guided by the necessity to ensure a precise and innovative framework under stringent constraints. The key objectives guiding the development and analysis are summarized in **Table 1**.

Table 1: Analysis and Simulation Objectives

Objective	**Rationale and Significance**	**Design Approach**
Mass Efficiency	Minimizing structural mass maximizes payload capacity and reduces launch costs.	Use of advanced lightweight materials (e.g., carbon fibre composites) and Topology Optimization via FEA.
Modularity & Scalability	Enables easy reconfiguration for diverse missions and future capability expansion.	Development of standardized, compartmentalized modules with common, interchangeable interfaces.
Manufacturing	Allows for rapid prototyping, customization, and efficient mass reduction of complex geometries.	Utilization of Additive Manufacturing (AM) with space-grade materials (e.g., Aluminium 7075) and integrated feature printing.
Integration	Ensures the structure accommodates and supports all subsystems (power, propulsion, payload).	Design of flexible mounting platforms, vibration isolation techniques, and integrated cooling/wiring pathways.
Thermal Management	Facilitates passive heat control, critical for satellites lacking active thermal systems.	Integration of heat sinks, radiative surfaces, and use of thermally conductive materials or phase-change materials.
Reliability	Guarantees endurance under extreme launch loads and the orbital environment.	Thorough FEA, conservative safety margins (FoS > 1.5), and use of shock-absorbing joints.
Sustainability	Minimizes space debris in alignment with environmental concerns.	Design for complete deorbit within the mission lifetime and incorporation of deorbiting mechanisms.

2.3 Finite element analysis

The structural performance was analysed using Ansys 2025R1 Student Version. The simulation study focused on static structural analysis to evaluate the design's strength against the axial, lateral, and torsional forces encountered during launch.

The simulation setup defined boundary conditions, mimicking the attachment of the satellite structure to the launch vehicle by applying fixed constraints at the mounting interfaces. External forces were introduced to simulate the intense dynamic loads, acceleration, and vibrational frequencies characteristic of a Low-Earth Orbit launch mission.

The analysis utilized the material properties of Aluminium 6061-T6, a standard aerospace-grade alloy. The mechanical input parameters are summarised in **Table 2.**

Table 2: Mechanical input parameters

Property	**Value**	**Unit**
Yield Strength	276	MPa
Modulus of Elasticity	68.9	GPa
Poisson’s Ratio	0.33	dimensionless

(a) (b)

Figure 2.1: Small Satellite Structure with (a) honeycomb body panel and (b) with iso-grid body panel

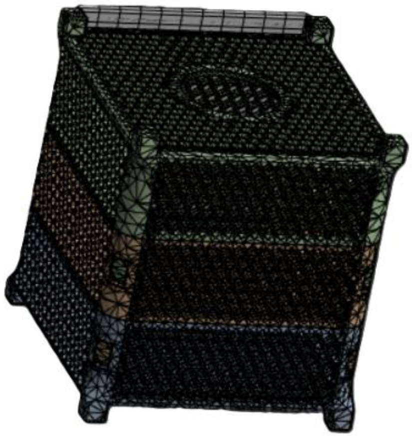

Figure 2.2: Small satellite structure used for FEA analysis and 3D printing

2.3 Additive Manufacturing

The Structure was printed in the Additive Manufacturing lab(G07) in GD Naidu block, VIT , Vellore, using the QIDI X-MAX3 Machine as illustrated in **Figure. 2.3** . The material used was PLA (polylactic acid) for the prototype. It was a polymer-based prototype and it demonstrated an actual 3d printed material along a support structure required in the printing process.

Figure 2.3 : QIDI X-MAX3 3d printing machine

3 Results and Discussion

3.1 Product design and Analysis

The structural performance of the satellite frame was analysed using Ansys 2025R1 Student Version, with a focus on static structural analysis.

The boundary conditions applied in the simulation included fixed constraints at the mounting points and external forces to simulate launch loads. The forces were applied in accordance with industry standards for satellite launches, considering both gravitational and vibrational forces during lift-off. The simulations aimed to ensure that the satellite structure could withstand the loads without exceeding the material's yield strength.

The material properties of Aluminium 6061-T6 were input into the simulation, including its yield strength (276 MPa), modulus of elasticity (68.9 GPa), and Poisson's ratio (0.33). The analysis confirmed that the structure had a sufficient safety margin, with stress levels well below the yield point of the material.

The static structural analysis performed in SolidWorks provided valuable insights into the behaviour of the small satellite structure under the defined load conditions. The key results from the simulation are as follows:

Von Mises Stress: The stress analysis revealed that the Von Mises stress across the structure ranged from 1.021×10^2 N/m² to 9.804×10^7 N/m². The highest stress occurred in areas with concentrated loads but remained significantly below the yield strength of aluminium 6061-T6 (276 MPa). This indicates that the structure will not undergo plastic deformation or failure under the applied forces.

Resultant Displacement: The maximum displacement recorded was 0.1521 mm, a minimal value demonstrating that the structure retains its shape and integrity during launch and operation, even under substantial external forces.

Equivalent Strain: The equivalent strain varied between 1.778×10^{-9} and 6.406×10^{-4}, showing controlled and minimal deformation. This confirms that the strain remains well within acceptable limits, ensuring material reliability.

Factor of Safety (FOS): The factor of safety ranged from 2.805 (minimum) to 2.695×10^6 (maximum). With the minimum FOS exceeding 2, the design is considered highly robust and capable of withstanding more than double the applied loads without risk of failure, ensuring operational reliability.

One of the primary objectives of this study was to reduce the satellite structure's weight while preserving its structural strength. By incorporating lattice structures and utilizing topology optimization, the total weight was decreased from 300 g to 240 g, achieving a 20% reduction. This weight savings is crucial in aerospace applications, were minimizing mass leads to lower launch costs and improved payload efficiency. The integration of lattice structures in non-critical load regions effectively reduced material usage without compromising overall structural performance. This contributes to both cost-effectiveness and compliance with strict lightweighting requirements in the space industry.

The final design successfully met all load-bearing and performance criteria. Simulation results confirmed that both von Mises stress and deformation remained well within safe limits, verifying the structure's ability to endure the stresses experienced during launch, including axial loads, vibrations, and other mechanical forces. Additionally, the high factor of safety further highlights the reliability of the design, indicating intentional overengineering for added security.

The design was tailored for manufacturing through laser bed 3D metal printing, specifically using the Selective Laser Melting (SLM) process. The simulation and optimization process ensured that the structure could be fabricated in three separate parts, preserving the intricate lattice geometries while simplifying production. This partitioned approach minimizes manufacturing complexity, reduces the need for support structures, shortens build time, and cuts material waste, making the process both time- and cost-efficient.

The materials considered for this project included aluminium 6061-T6 and AlSi10Mg. aluminium 6061-T6 was selected due to its excellent strength-to-weight ratio and compatibility with additive manufacturing. On the other hand, AlSi10Mg, commonly favoured in industrial-level additive manufacturing, offers superior mechanical properties, including better flow characteristics during printing and higher tensile strength. While aluminium 6061-T6 was primarily used in this study due to its availability and mechanical performance, AlSi10Mg may offer additional advantages in terms of thermal stability and print quality in future applications.

Further, **Table 3** highlights the key properties of the small satellite structure considered for the study.

Table 3: Meshed Small Satellite Structure

Document name and reference	Treated As	Volumetric properties
Small Satellite Structure	Solid Body	Mass: 0.0931576 Volume: 3.45028e-05 m^3 Density: 2,700 kg/m^3 Weight: 0.0912944N

Table 4 highlights the boundary conditions considered for the study.

Table 4: Boundary conditions used in the study

Parameters	Options Selected
Analysis type	Static
Mesh type	Solid mesh
Thermal effect	On
Thermal option	Include temperature tools
Zero strain temperature	298 Kelvin
Solver Type	Automatic
In plane Effect	Off
Soft Spring	Off
Inertial Relief	Off
Incompatible Bonding Options	Automatic
Large Displacements	Off
Compute Free Body Forces	On
Friction	Off
Use Adaptive Method	Off

Table 5 highlights the materials properties considered for the study.

Table 5: Material Properties

Model Reference	Properties	Value
	Yield Strength	2.75e+08 N/m^2
	Tensile Strength	3.1e+08 N/m^2
	Elastic Modulus	6.9e+10 N/m^2
	Poisson's Ratio	0.33
	Mass Density	2700 kg/m^3
	Shear Modulus	2.6e+10 N/m^2
	Thermal Expansion Coefficient	2.4e-05 /Kelvin

The structural integrity of the developed satellite system was rigorously evaluated using key criteria derived from Finite Element Analysis (FEA), specifically the Von Mises stress, resultant displacement, equivalent strain, and the corresponding Factor of Safety (FOS). The results presented below elucidate the system's mechanical performance under simulated load conditions.

Von Mises stress is the primary criterion used to assess the likelihood of material yielding under complex, multi-axial loading. The minimum nodal stress recorded was 1.021×10^{2} N/m^2. This low value is consistent with regions near free or unconstrained boundaries that are subjected to negligible loading. The peak stress concentration was observed at Node 91026, registering 9.804×10^{7} N/m^2. This location merits close examination to confirm that the observed stress remains comfortably below the material’s yield strength. The overall nodal stress distribution is visually represented in **Figure 3.1**.

Resultant Displacement (URES) quantifies the total structural movement induced by the applied load, as depicted in **Figure 3.2**. A minimum displacement of 0.000 mm was recorded at Node 59599. This finding is consistent with the fixed or constrained anchoring boundary conditions applied at this node in the simulation. The maximum displacement was found to be 0.1521 mm at Node 100455. The extremely small magnitude of this peak displacement (significantly below 1 mm) confirms the structure’s satisfactory stiffness and integrity under the simulated load. The complete displacement field is presented in **Figure 3.2**.

Equivalent Strain (ESTRN) provides a composite measure of structural deformation and change in shape. As shown in **Figure 3.3**, the strain field analysis yielded the following results. The minimum strain recorded was 1.778×10^{-9} in Element 83487, reflecting non-deformed or rigid structural regions. The maximum strain was found to be -6.406×10^{-4} in Element 49009. This element typically corresponds to domains subject to pronounced bending or sections carrying the highest load. The distribution and regions of notable strain are visualized in **Figure 3.3**.

Safety margins are a pivotal metric in aerospace engineering, and the Factor of Safety (FOS) quantifies the strength margin beyond the applied operational loads. The FOS results are mapped in **Figure 3.4**. The minimum observed FOS of 2.805 occurred at Node 91026, which coincides with the location of maximum Von Mises stress. This margin is deemed acceptable for aerospace applications, where standards generally require FOS values above 2.0 for critical components. The maximum FOS was 2.695×10^{6} at Node 253438. This extremely high value is expected in underloaded regions that are removed from major stress paths. Additionally, the Fatigue Assessment, presented in **Figure 3.5**, supports the static evaluation by providing insights into the structure's long-term durability under anticipated cyclic loading scenarios.

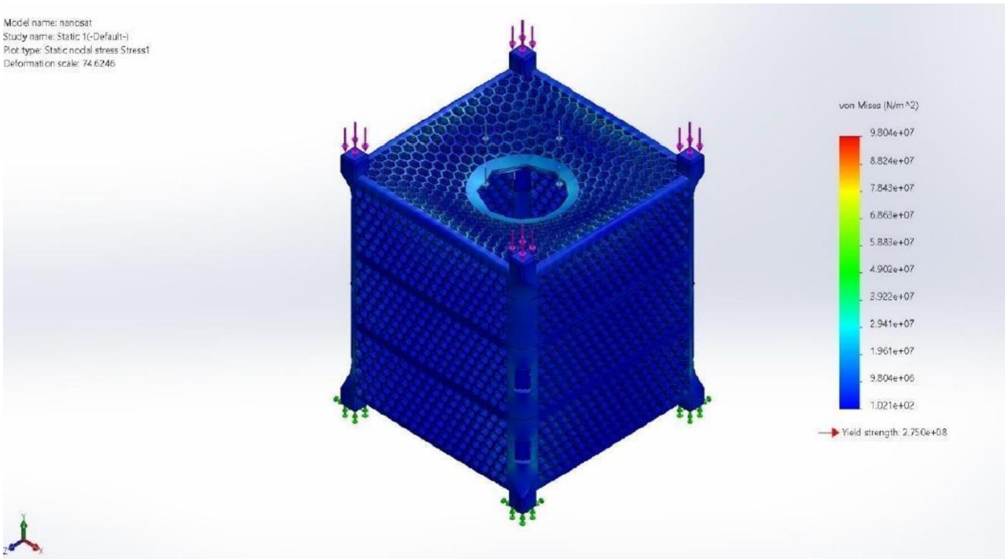

Figure 3.1: Static Nodal Stress

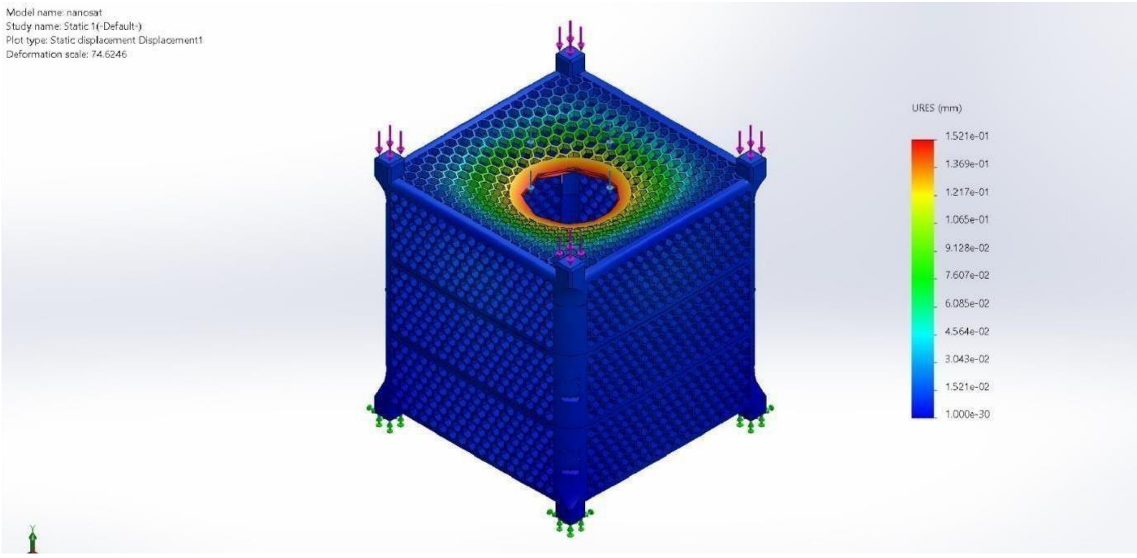

Figure 3.2: Static Displacement

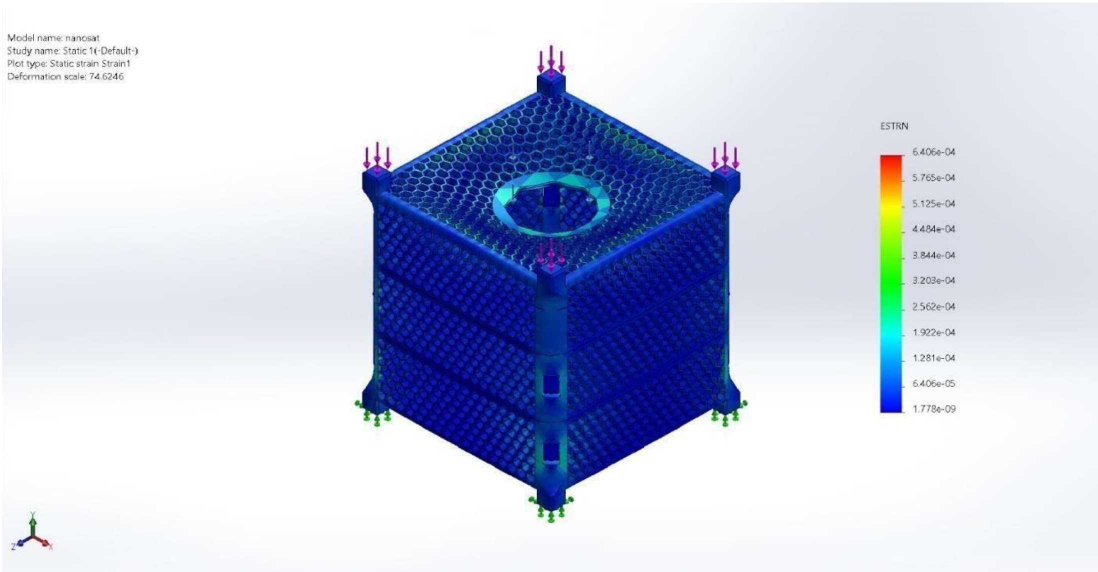

Figure 3.3: Static Strain

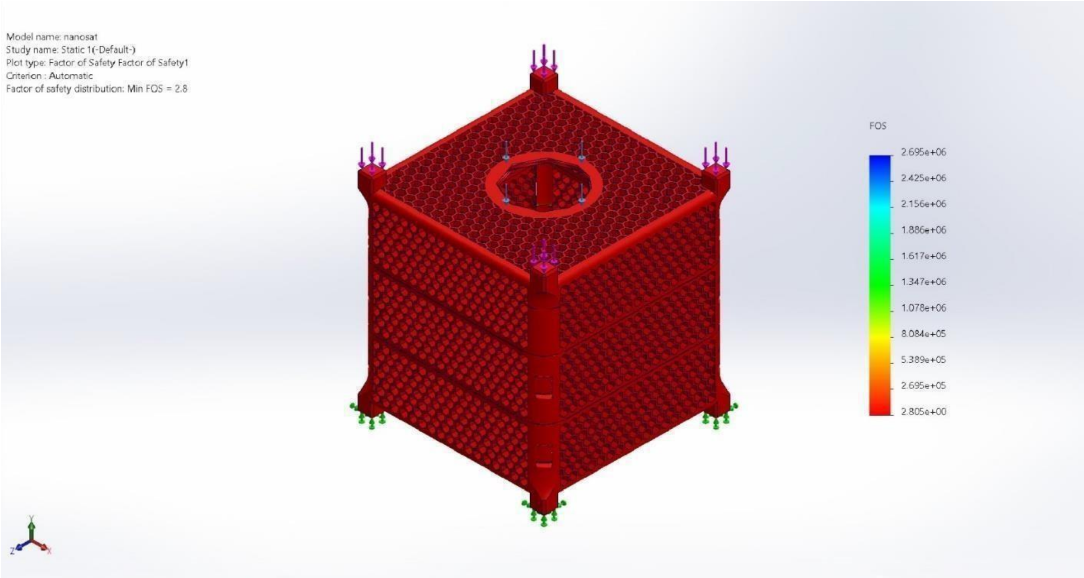

Figure 3.4: Factor of Safety

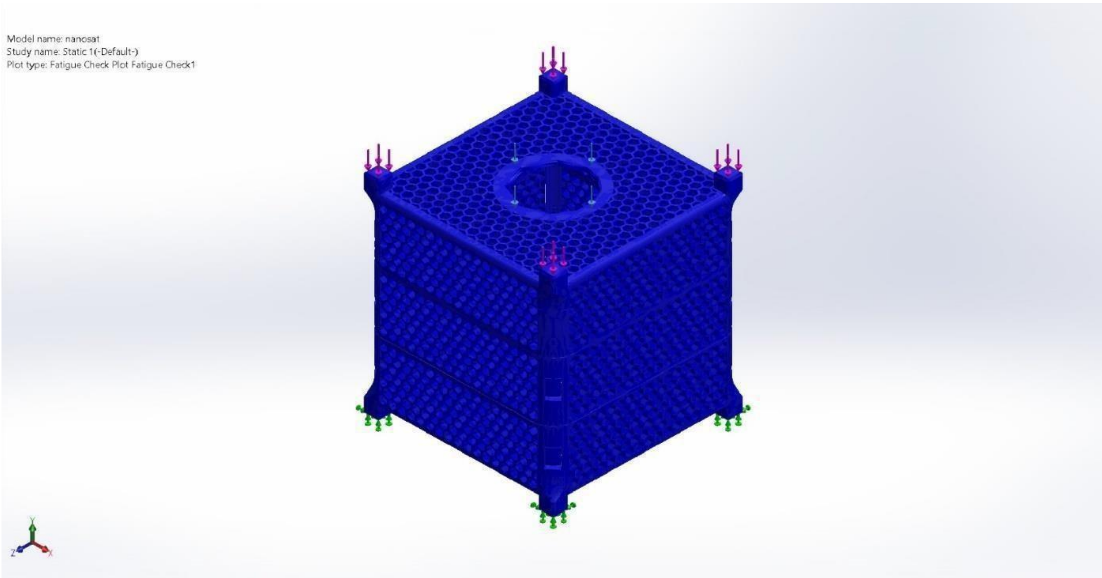

Figure 3.5: Fatigue Check

Table 6 summarizes the minimum and maximum results per metric for clarity.

Table 6: Minimum and maximum results of simulation study

Metric	**Type**	**Minimum (Location)**	**Maximum (Location)**
Static Nodal Stress	Von Mises Stress	1.021×10^2 N/m^2 (Node: 253438)	9.804×10^7 N/m^2 (Node: 91026)
Displacement	Resultant (URES)	0.0 mm (Node: 59599)	0.1521 mm

			(Node: 100455)
Strain	Equivalent (ESTRN)	1.778×10^{-9} (Element: 83487)	-6.406×10^{-4} (Element: 49009)
Factor of Safety	Automatic	2.805 (Node: 91026)	2.695×10^{6} (Node: 253438)

3.2 Additive Manufacturing Process

The final design was tailored for manufacturing through fused deposition modelling. The simulation and optimization process ensured that the structure could be fabricated in three separate parts, preserving the intricate lattice geometries while simplifying production. This partitioned approach minimizes manufacturing complexity, reduces the need for support structures, shortens build time, and cuts material waste, making the process both time- and cost-efficient.

The prototype model of the satellite structure was produced using Fused Deposition Modelling (FDM) with Polylactic Acid (PLA) as the primary material. This approach allowed for rapid and cost-effective prototyping before committing to metal-based manufacturing. The prototype was fabricated in the additive manufacturing lab located in the G.D. Naidu block, utilizing the QIDI X-MAX3 3D printing machine. This step was essential for verifying form, fit, and assembly aspects of the design prior to final production.

For real-time production, the selected material is aluminium alloy, which offers superior strength and durability under operational conditions. The use of aluminium in combination with advanced additive manufacturing techniques like SLM ensures that the final product will meet the stringent requirements of space applications. Additionally, the project considered the use of AlSi10Mg, an aluminium alloy commonly employed in industrial additive manufacturing, due to its excellent mechanical properties, better printability, and enhanced thermal stability. AlSi10Mg may be particularly useful in future iterations of the design, especially where high precision and thermal performance are critical.

Figure 3.6: 3D printed base part

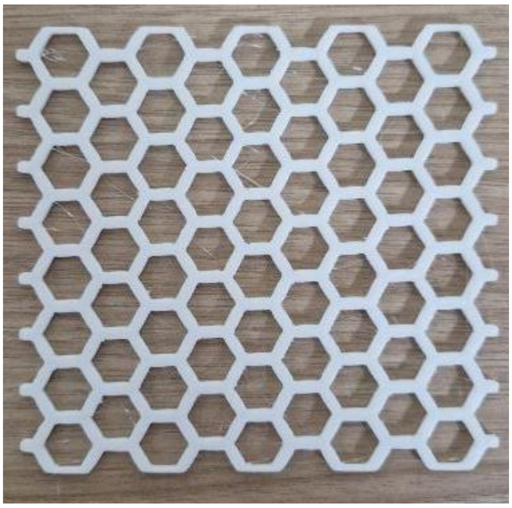

Figure 3.7: 3D printed honeycomb panel

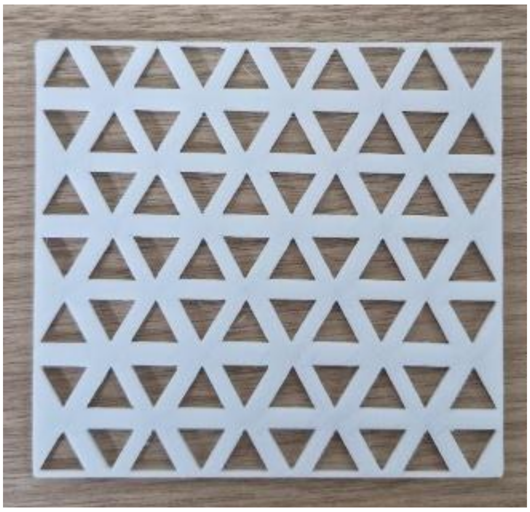

Figure 3.8: 3D printed iso-grid panel

Figure 3.9: 3D printed sidebar

Figure 3.10: 3D printed top part

Figure 3.11: 3D printed small satellite structure

All these structures were printed with a total time taken around 38-40 hrs. The satellite structure took 18 hrs to complete while the other structures took around 4 hrs to complete each part. Detailed description about time taken to print each component is mentioned in **Table 7**.

Table 7: Time taken to print each component

Name of the part	**Time Taken**
Side bar	10 mins
Base	4 hrs
Top	5 hrs
Honeycomb panel	5 hrs
Isogrid panel	5 hrs

The Table 7 outlines the estimated or recorded time spent on manufacturing or assembling key components of satellite structure. Each row corresponds to a specific part, along with the time taken to either fabricate or integrate it into the complete system.

Side bar (10 minutes): The side bar is a relatively simple structural component, likely fabricated quickly due to its small size or straightforward geometry. This short time suggests minimal complexity, possibly a standard part made using rapid techniques like laser cutting or 3D printing.

Base (4 hours): The base forms a foundational component of the satellite, providing structural support for the rest of the system. The 4-hour duration reflects the need for precision and perhaps more robust materials or multiple sub-assemblies.

Top (5hours): Like the base, the top part of the satellite requires careful fabrication, especially if it supports antennas, solar panels, or deployment mechanisms. The slight increase in time may indicate added complexity in geometry or integration with other subsystems.

Honeycomb panel (5 hours) : The honeycomb panel is likely a structural or protective component used for strength and lightweighting. Its fabrication involves careful layering or bonding processes, which justifies the time spent. The consistent 5-hour timeframe with other panels shows a standard fabrication effort for such advanced structures.

Iso-grid panel(5 hours): Like the honeycomb panel, the isogrid panel is a lightweight structural component designed for stiffness and strength. Fabricating iso-grid structures may involve complex machining or 3D printing with internal patterns, accounting for the identical time spent as the honeycomb panel.

Satellite(18 hours): This represents the total time required to assemble all components, integrate subsystems, perform fit checks, and possibly preliminary testing. It is significantly longer than the time for individual parts, highlighting the complexity of full satellite integration and the attention to detail needed to ensure structural and functional reliability.

4. Conclusions

The design and development of the small satellite structure highlighted the effectiveness of integrating advanced engineering techniques, such as topology optimization and lattice structure integration, to achieve significant weight reduction while maintaining the necessary structural integrity. These modern design approaches allowed for the efficient distribution of material, ensuring that strength was retained only where needed, ultimately contributing to an optimized and lightweight design suitable for space applications. Static analysis, conducted using Ansys R12025 Student Version, played a crucial role in evaluating the structural performance of the satellite under various load conditions typically encountered during launch and orbital operation. The boundary conditions applied in the simulation included fixed constraints at the mounting points and external forces to simulate launch loads. The forces were applied in accordance with industry standards for satellite launches, considering both gravitational and vibrational forces during lift-off. The simulations aimed to ensure that the satellite structure could withstand the loads without exceeding the material's yield strength.

The material properties of Aluminium 6061-T6 were input into the simulation, including its yield strength (276 MPa), modulus of elasticity (68.9 GPa), and Poisson's ratio (0.33). The analysis confirmed that the structure had a sufficient safety margin, with stress levels well below the yield point of the material. The static structural analysis performed in SolidWorks provided valuable insights into the behaviour of the small satellite structure under the defined load conditions.

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The successful deployment and operation of small satellites heavily depend on the efficiency of their structural systems. By focusing on optimizing mass-to-strength ratios, enhancing modularity, adopting additive manufacturing, and addressing challenges related to subsystem integration, thermal management, and sustainability, engineers can significantly improve the performance, reliability, and affordability of small satellite missions. The continuous evolution of structural materials and design methodologies will further open new frontiers in small satellite engineering, ensuring this compact spacecraft play a pivotal role in the future of space exploration and utilization.

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