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Launch-Load Structural Assessment of a 1U Al 6061-T6 CubeSat Frame: A Review of Finite Element Modal, Static and Random Vibration Practice with Supporting Simulation Results

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Abstract: ***CubeSats have become a widely adopted platform for low-cost space missions, yet their compact 10 cm × 10 cm × 10 cm envelope leaves little margin for structural error under the severe mechanical and thermal loads of launch and orbital operation. Nanosatellites are structurally most at-risk during launch, when they face quasi-static acceleration and broadband random vibration while mounted in a deployer. This paper surveys how finite element analysis is used to qualify 1U CubeSat structures for these conditions, limited to three analysis types: modal (eigenfrequency) extraction, static structural loading and random vibration based on power spectral density (PSD). The survey covers common modelling choices, including material selection, meshing, constraint idealization, load definition and acceptance criteria such as minimum fundamental frequency, stress margin against yield and 3σ response limits. To show how these practices work in use, a 1U frame of aluminium 6061-T6 was modelled in SolidWorks and analyzed in ANSYS Workbench with the base fixed. The modal solution gave twelve modes between 539.67 Hz and 1076.3 Hz, well above the stiffness thresholds usually quoted by launch providers. Under a 650 N static load, the peak deflection was 0.3769 mm and the maximum von Mises stress was 65.66 MPa, about a quarter of the 276 MPa yield strength. The random vibration run, pre-stressed by the modal solution, produced a smooth response PSD with its highest value at the 20 Hz lower bound of the input spectrum and no resonant amplification. Taken together, the review and the results show that the frame is stiff and structurally sound for launch. The paper also highlights common gaps in the literature, such as inconsistent boundary conditions and incomplete reporting of PSD inputs.***

Keywords: ***1U CubeSat; finite element analysis; modal analysis; static structural analysis; random vibration; PSD; Al 6061-T6; launch environment.***

I. INTRODUCTION

Over the past two decades, CubeSats have changed who can build and fly a spacecraft. The format was proposed in the late 1990s as a standardized nano satellite built from 10 cm cubic units, and it has since moved from teaching laboratories into commercial, scientific and defense missions. A 1U unit is a 10 × 10 × 10 cm cube of about 1.33 kg, small enough to share a rocket with other payloads and so lower the launch cost. Its size and mass also leave little room for structural margin. The frame has to carry the electronics, hold the dispenser interface and survive launch, and it has to do this with very little material.

Launch is usually the most severe mechanical event in a CubeSat's life. During ascent the structure is shaken by engine-induced and aerodynamic vibration, and quasi-static acceleration builds up through the stages. A frame that resonates within the launch vehicle's excitation band, or whose stress approaches the yield strength of its material, risks damage to the satellite or to the dispenser and other payloads. For this reason, launch providers and design standards set requirements on stiffness, load capacity and random vibration tolerance. Physical qualification testing is expensive, so these requirements are normally checked first in a finite element (FE) model, and the model results are used to decide what changes are needed before hardware is built and tested.

Three FE analyses carry most of this early structural assessment. Modal analysis finds the natural frequencies and mode shapes, which show how close the structure comes to the excitation band. Static structural analysis gives displacement and stress under a defined load and is judged against the yield strength through a margin of safety. Random vibration analysis uses a PSD input to estimate the statistical response, normally reported at the 3σ level, and builds on the modal solution. Together the three answer the main questions for a launch-ready frame: where it resonates, whether it is strong enough, and how it responds to broadband excitation.

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Many published studies use these analyses, but they differ in how they model the structure. Studies vary in material (for example, different aluminium alloys), constraint idealisation, load definition, mesh refinement and acceptance criteria, and they often do not report the PSD input or the boundary conditions in enough detail to be reproduced. This makes it hard to compare results from different studies or to judge how far a reported margin can be trusted.

This paper has two aims. The first is to review how modal, static structural and random vibration analyses have been applied to 1U CubeSat structures, and to identify the modelling choices and reporting gaps that most affect the outcome. The second is to give a worked example of these practices, using an Al 6061-T6 1U frame modelled in SolidWorks and analyzed in ANSYS Workbench. The review covers only these three analyses; thermal, buckling, harmonic, transient and fatigue studies are outside its scope.

II. SCOPE AND OBJECTIVES OF PRESENT WORK

A. *Objectives*

The work has the following objectives:

1) To review how modal, static structural and random vibration analyses have been applied to the structural assessment of 1U CubeSat frames, with attention to material choice, meshing, constraint idealization, load definition and acceptance criteria.

2) To identify the modelling decisions and reporting gaps in the reviewed studies that most affect the reliability and comparability of the results.

3) To build a finite element model of a 1U CubeSat frame in Al 6061-T6 and use it to extract natural frequencies and mode shapes, so the frame's stiffness can be compared with the minimum fundamental frequencies that launch providers commonly require.

4) To find the displacement, strain and von Mises stress of the frame under a static load, and to judge the stress against the yield strength of the material through a margin of safety.

5) To obtain the random vibration response of the frame to a PSD base excitation, using the modal solution as its basis, and to examine the response PSD and the 3σ stress and deformation for signs of resonant amplification.

6) To relate the simulation results to the reviewed literature, so that the example shows what the surveyed practices produce when applied to one case.

B. *Scope of Present Work*

1) Analyses included. The paper covers three linear FE analyses: modal (eigenfrequency) analysis, static structural analysis and random vibration (PSD) analysis. Other analyses were run in the underlying project but are deliberately left out so that the review stays focused. These are buckling, harmonic response, response spectrum, transient structural, transient thermal and fatigue analyses.

2) Structure and material. The study considers a single 1U CubeSat frame (10 × 10 × 10 cm, within the 1.33 kg mass limit of the 1U format), made of aluminium 6061-T6 with yield strength of about 276 MPa and elastic modulus of about 68.9 GPa. Other alloys and composite options are mentioned only where they appear in the reviewed literature.

3) Modelling and solution. The geometry was prepared in SolidWorks and analyzed in ANSYS Workbench. The base of the frame was fixed. Modal extraction covered the first twelve modes up to 2000 Hz. The static case applied a 650 N force, and the random vibration case used a PSD acceleration spectrum between 20 Hz and 2000 Hz.

4) Literature coverage. The review is limited to work on CubeSat and small-satellite structures that use FE-based modal, static or random vibration analysis, together with the design specifications and launch-environment documents these studies rely on. Satellite subsystems, orbital performance and mission design are outside its scope.

C. *Limitations*

The results come from a linear FE model of the bare frame. They do not include internal components such as PCBs and batteries, the fasteners, or the contact behavior at the deployer interface, and they have not been checked against physical vibration or static tests. The results should therefore be read as a design-stage assessment and not as a qualification result.

III. METHODOLOGY

The methodology adopted for this study follows a sequential design-to-analysis workflow, beginning with two-dimensional drafting of the CubeSat envelope and concluding with validation of the finite element results. Each stage is outlined below.

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A. Drafting of the 2D Model

Table 3.1 :- Design Parameter

Parameter	Value / Specification
CubeSat Form Factor	1U (10 cm x 10 cm x 10cm)
Material Used	AA-6061-T6 (Aluminum Alloy 6061 – T6)
Structure Type	Monocoque / Frame – based
Wall Thickness	1.5 – 3 mm (Variable for optimization)
Fasteners & Joints	Bolted / Riveted / Welded (based on design feasibility)
Mass Limit	≤ 1.33 Kg (As Per CubeSat Standard)
Deployment System Compatibility	P-POD (Poly – Picosatellite Orbital Deployer)

Design work began with two-dimensional layout drawings — front, top, and bottom views — establishing the overall envelope and key dimensional references for the 1U structure. These drawings were developed against parameters drawn from established CubeSat literature, including the Enduro Sat Structure 1U datasheet, which documents a proven mechanical frame configuration for 1U missions, and the CubeSat Design Specification (CDS) Rev. 14.1 issued by the Cal Poly CubeSat Program, the primary industry standard governing the design, testing, and launch qualification of CubeSats from 1U through 12U. The CubeSat development process itself follows three broad stages: defining mission requirements (orbit, payload, mass and power budgets), a preliminary design review establishing subsystem interfaces, and a critical design review preceding fabrication. The system architecture identified at this stage includes the structural frame (Al 6061/7075 with hard-anodized, dispenser-compatible rails), the electrical power subsystem (solar panels and batteries), a communications package with deployable antennas, an onboard computer, an attitude determination and control subsystem, and the mission payload.

B. Building the 3D CubeSat Model in SolidWorks

The CubeSat geometry was then developed as a full parametric 3D model in SolidWorks, following the standardized 1U convention of a 10 × 10 × 10 cm outer envelope for compatibility with standard launch dispensers. SolidWorks was selected as the CAD platform for its established role in detailed 3D product design and its support for dimensioned, tolerance-controlled component modeling suited to aerospace hardware. Component mass allocation and the full bill of materials/software list were tabulated at this stage to keep the assembly within CubeSat mass limits.

Aluminum 6061-T6 was selected as the structural material based on several characteristics relevant to a spaceframe: a high strength-to-weight ratio favorable for lightweighting; strong toughness and workability; good response to anodized surface finishing; ready availability and machinability; and a thermal expansion coefficient compatible with the Al 7075-T73 material typically used in the P-POD deployer, reducing thermal-fit issues at the rail interface.

The model was also checked against the governing CubeSat configuration rules, including: all components remaining fixed to the structure through launch, ejection, and operation; exclusion of hazardous materials; a total 1U mass below 1.33 kg; a center of gravity within 4.5 cm of the geometric center; use of Al 6061 or 7075 for the primary structure; hard-anodized dispenser contact surfaces; an outer envelope of 100 ± 0.1 mm per axis; no protruding component exceeding 6.5 mm beyond the cube surface; no contact between the CubeSat's exterior and the dispenser's interior surface; and a minimum rail width of 8.5 mm.

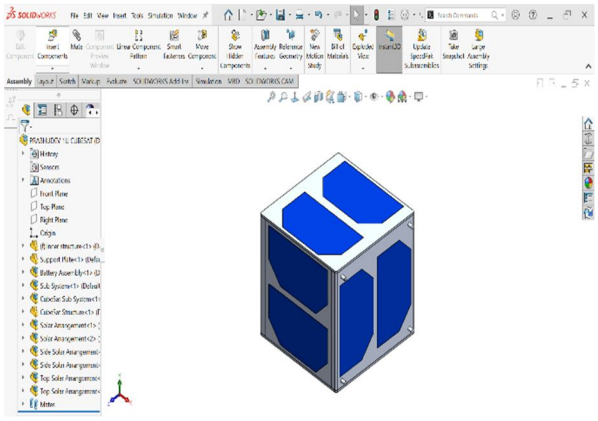


Figure 3.1 :- CubeSat Isometric View

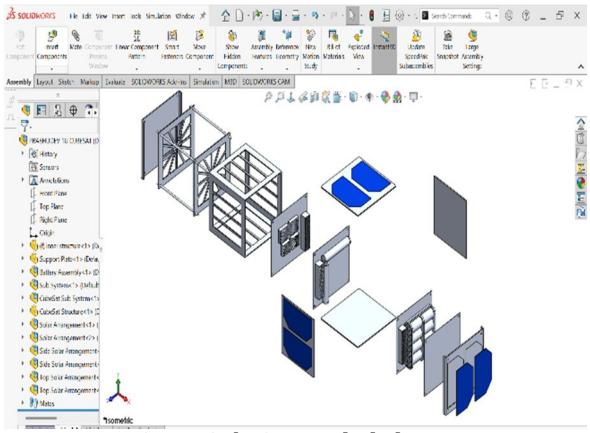


Figure 3.2 :- CubeSat Exploded View

C. *Importing the Model into ANSYS*

The completed SolidWorks assembly was imported into ANSYS Workbench, a general-purpose finite element analysis environment that discretizes a continuous structure into small elements, applies governing physical equations to each, and assembles the results into a system-level solution. ANSYS was chosen for its unified project schematic linking geometry, meshing, physics setup, solving, and post-processing in one workflow; its Multiphysics coupling capability, which allows a thermal solution to feed directly into a structural solver for coupled thermal-stress evaluation; its native, parametric CAD linkage to SolidWorks (so geometry edits automatically propagate through the mesh and re-solve); and its automated meshing tools.

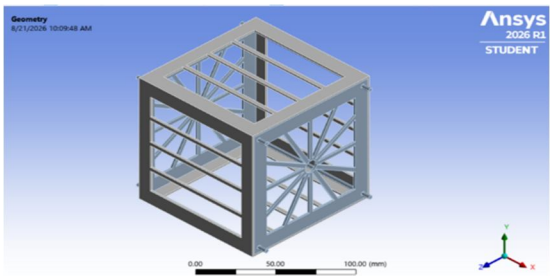


Figure 3.3 :- CubeSat Structure imported to Ansys Workbench

D. *Meshing the Model*

The imported geometry was discretized into a finite element mesh, a step that directly governs the accuracy, convergence behavior, and computational cost of the subsequent solution. Because mesh generation typically consumes a significant share of total analysis time, care was taken in element sizing and refinement to balance solution accuracy against solve time.

The finite element mesh for the CubeSat model was generated in ANSYS Workbench using tetrahedral elements with first order (linear) formulation. A Fine mesh sizing option was applied under the Mechanical physics preference, with element order set to Program Controlled and a default element size of 5.0 mm. The model's bounding box diagonal measured 184.66 mm, with an average surface area of 355.65 mm² and a minimum edge length constraint of 1.5 mm. Mesh quality was actively monitored during generations, with quality checking enabled under the "Aggressive Mechanical" error limit setting and medium-level smoothing applied; mesh optimization and additional mesh metrics were not employed. Automatic inflation layers were not used for this mesh (Use Automatic Inflation set to None), though the inflation option was configured with a Smooth Transition scheme, a transition ratio of 0.272, a maximum of 5 layers, and a growth rate of 1.2, using wedge-type inflation elements applied in a pre-inflation algorithm sequence, should inflation be activated. On the advanced settings side, the number of CPUs for meshing was left as program controlled, straight-sided elements were disabled (allowing curved/higher-fidelity element edges), and rigid body behavior was set to Dimensionally Reduced. The triangle surface Mesher was left as program controlled, with topology checking enabled and a default pinch tolerance of 0.225 mm; pinch-on-refresh and auto-mapping of fillets were both disabled. For automatic meshing methods, sheet bodies were meshed using a Quad Dominant approach, while sweepable bodies used the Sweep method.

E. *Mesh Statistics*

The final mesh consisted of 112,957 nodes and 64,342 elements. Since first-order (linear) tetrahedral solid elements were used, each node possesses 3 translational degrees of freedom, giving a total of: Total DOF = 112,957 nodes × 3 DOF/node = 338,871 degrees of freedom

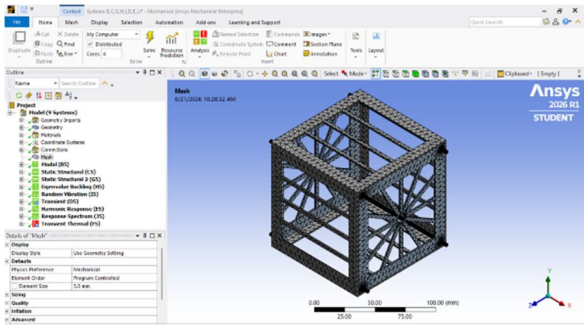


Figure 3.4 :- Meshed CubeSat

F. Applying Boundary Conditions

Boundary conditions — the constraints required to solve the governing differential equations over the model domain — were defined individually for each analysis type: fixed supports at the corner rails for modal analysis, applied load and fixed-support combinations for static structural analysis, a compressive load case for eigenvalue buckling, PSD-based excitation for random vibration analysis, and corresponding load/constraint sets for transient structural, harmonic response, response spectrum, and transient thermal analyses.

G. Finite Element Analysis

With boundary conditions defined, nine distinct analyses were carried out to characterize the CubeSat's structural and thermal performance: modal (normal mode) analysis, static structural analysis, eigenvalue buckling analysis, random vibration (PSD) analysis, harmonic response analysis, response spectrum analysis, transient structural analysis, transient thermal analysis, and fatigue life analysis. Together these cover the principal load environments a CubeSat experiences from pre-launch through orbital operation.

H. Validation

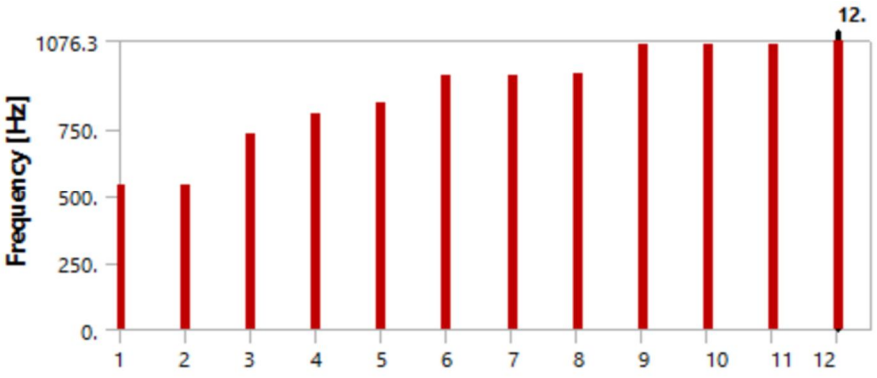
The overall analysis approach was validated against standard CubeSat design practice. Geometric validation confirmed the 100 × 100 × 100 mm envelope, minimum 8.5 mm rail width, and 1.5–2.5 mm wall thickness typical of lightweighted frames. Modal validation required the fundamental natural frequency to remain safely above the ~100 Hz threshold generally specified by launch providers to avoid resonance with the launch vehicle. Static structural validation applied representative 10–15g inertial launch loads and checked resulting von Mises stress against the 276 MPa yield strength of Al 6061-T6, targeting a minimum factor of safety of 1.25–1.5. Random vibration validation followed the standard practice of scaling the 1-sigma von Mises stress result to 3-sigma (representing 99.73% of expected load occurrences) and confirming it remained below the material's ultimate tensile strength. Finally, mesh and mass validation confirmed convergence at refined regions (thin corners, bolt holes), verified that the CAD model's computed mass matched the physical target (≤1.33–2.0 kg), and cross-checked reaction forces at the fixed supports against the expected F = ma value for the applied load case.

IV. RESULTS AND DISCUSSION

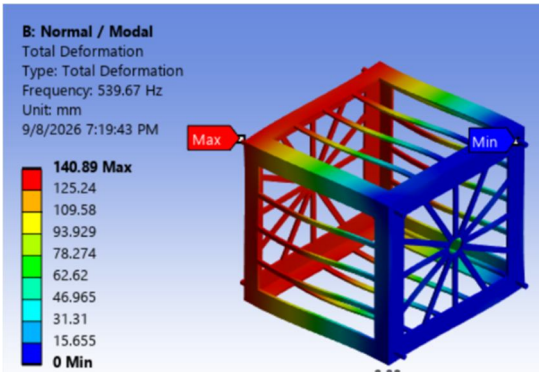
All simulations reported in this chapter were carried out in ANSYS 2026 R1 (Student Version) on the SolidWorks-derived 1U CubeSat model. Three distinct Modal, Structural and Random Vibrational analyses were performed to characterize the frame's behavior across the mission timeline, from pre-launch through orbital operation.

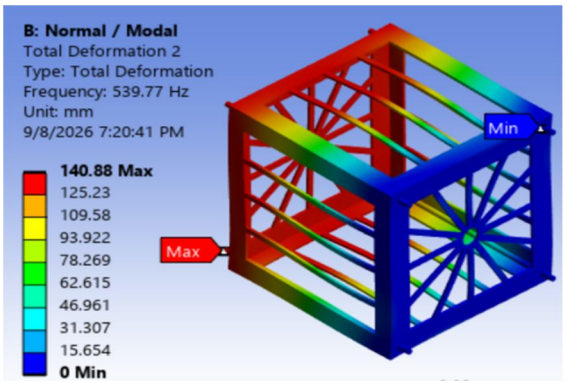
A. Modal Analysis / Normal Analysis

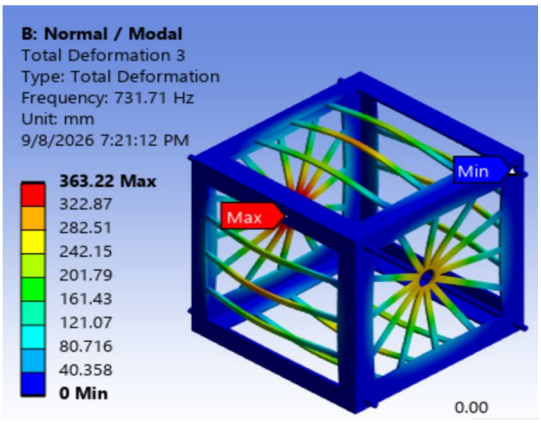
A modal analysis was carried out to extract the CubeSat's inherent natural frequencies and mode shapes — parameters that govern how the structure responds to dynamic loading and determine its susceptibility to resonance. With the bottom face fixed as the boundary condition and a solution range set to 2000 Hz for the first twelve mode shapes, the analysis returned a fundamental (Mode 1) natural frequency of 539.67 Hz, with the full set of twelve modes spanning up to 1076.3 Hz. This result comfortably clears the typical launch-vehicle stiffness requirement of 90–100 Hz for structures constrained within deployer rails, confirming the frame is stiff enough to avoid resonant amplification during the high-vibration launch phase. Since dynamic loading drops substantially once the satellite reaches orbit, this high fundamental frequency is primarily a launch-survivability metric rather than an on-orbit concern.

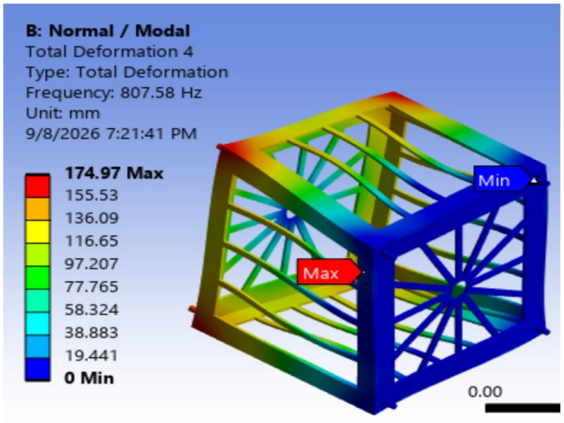


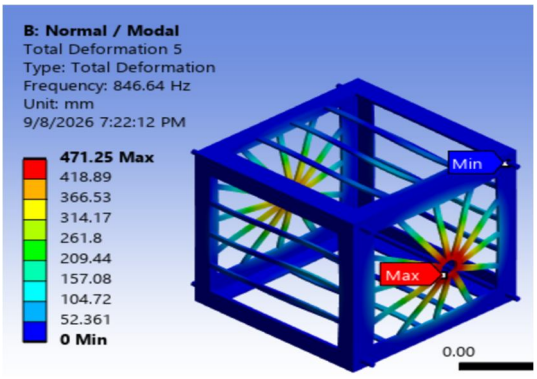
	Mode	Frequency [Hz]
1	1.	539.67
2	2.	539.77
3	3.	731.71
4	4.	807.58
5	5.	846.64
6	6.	947.19
7	7.	947.74
8	8.	951.61
9	9.	1061.7
10	10.	1066.1
11	11.	1066.1
12	12.	1076.3

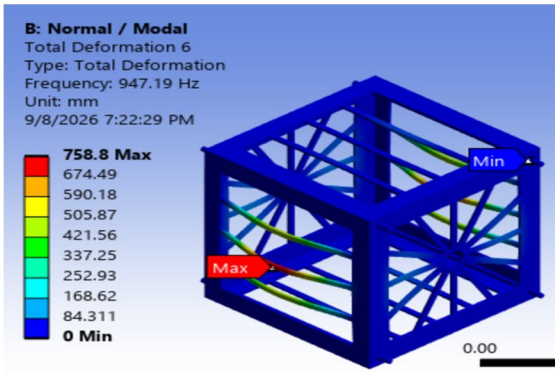


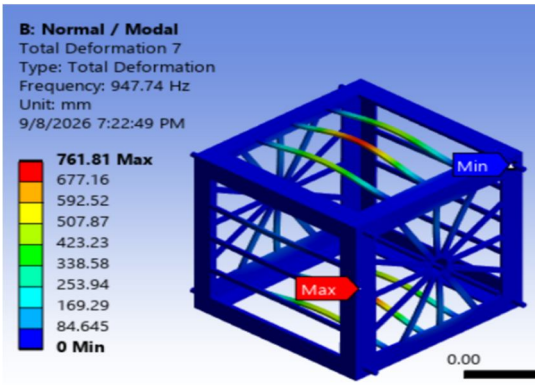


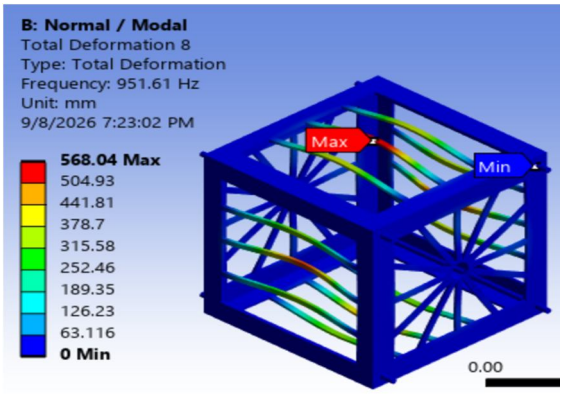












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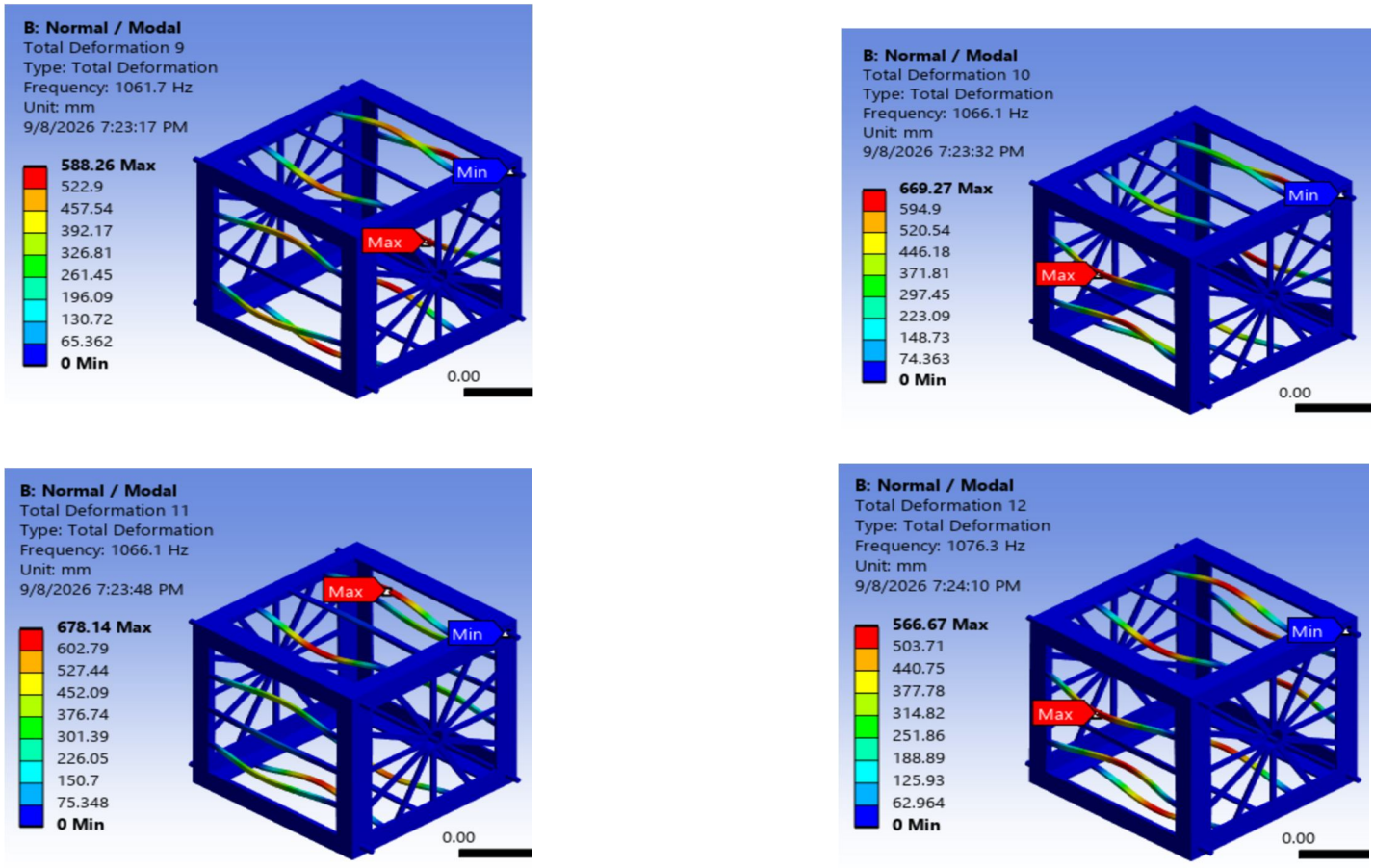


Figure 4.1:- Modal Analysis of CubeSat for 12 Different Mode Shapes (Left to Right)

B. Static Structural Analysis

To evaluate the frame's response under sustained mechanical loading, a static structural analysis was performed with the bottom face fixed, and a 650 N load applied across all remaining faces. The analysis returned to a maximum total deformation of 0.3769 mm, a peak equivalent (von Mises) stress of 65.66 MPa, and a maximum equivalent elastic strain of 0.0009836 (0.098%). Since the resulting stress remains well below the 276 MPa yield strength of Aluminum 6061-T6, the structure deforms only within its elastic regime and returns fully to its original shape once the load is removed — corresponding to a factor of safety of approximately 4.2.

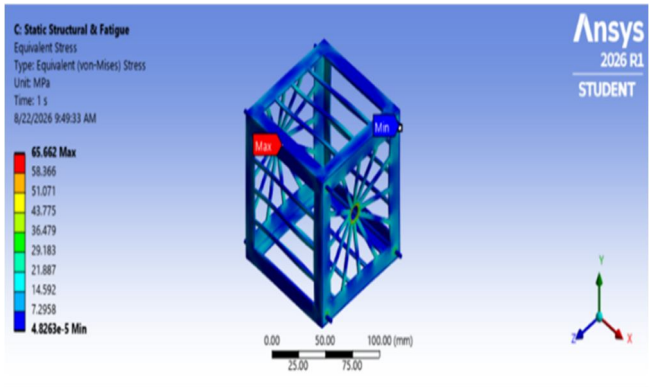


Figure 4.2:- von – mises Stress of CubeSat

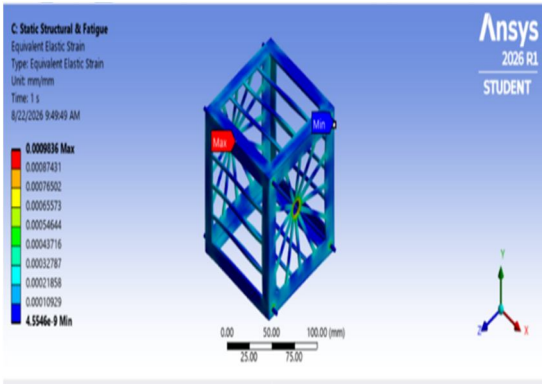


Figure 4.3:- Equivalent Strain of CubeSat

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C. *Random Vibration (PSD) Analysis*

Random vibration analysis was performed to capture the structure's statistical response to the broadband acoustic and mechanical noise generated during launch — a loading condition that is one of the most common causes of CubeSat structural failure. The modal analysis results were carried forward as the pre-stress condition, and a PSD acceleration profile was applied as the excitation input. The resulting 3-sigma equivalent stress (covering 99.73% of expected load occurrences) was 0.005068 MPa, negligible against the 276 MPa yield strength, while the corresponding 3-sigma deformation was just 4.37×10^{-6} mm — indicating an exceptionally rigid frame. The response PSD curve peaked near the lowest excitation frequency (20 Hz) at approximately 1.0053×10^{-8} mm²/Hz and rolled off smoothly at higher frequencies without sharp resonant spikes, consistent with the structure's high fundamental frequency attenuating rather than amplifying random excitation. This response curve additionally serves as a practical vibration input for subsystem-level qualification of internally mounted components such as PCBs and battery packs. For the graph i.e. refer to figure 4.5 is plotted by taking Frequency [HZ] along X axis against its RESPONSE PSD [(mm^2)/HZ] along Y axis.

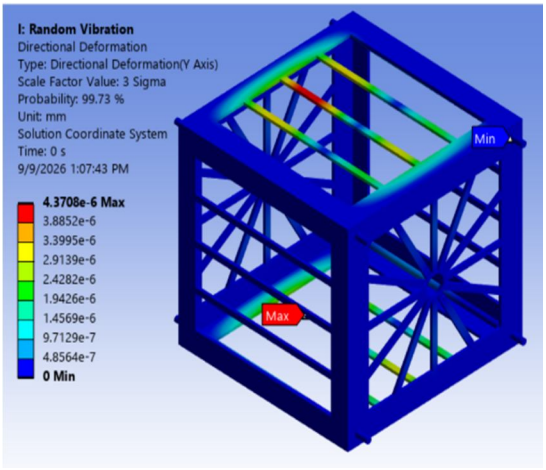


Figure 4.4:- Directional Deformation

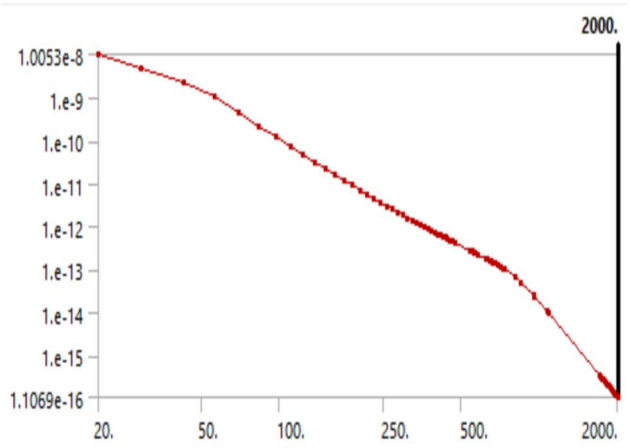


Figure 4.5:- PSD Response of CubeSat

V. VALIDATION OF RESULTS

The results generated in each of the analyses described in the preceding chapter were cross-checked against benchmark values drawn from the literature reviewed in Chapter, to confirm that the CubeSat design meets accepted industry thresholds. The overarching validation objective throughout was to demonstrate that the CubeSat structure achieves a minimized overall mass while remaining capable of withstanding the full range of stresses encountered during its operational life in space.

A. *Modal Analysis*

The modal analysis was intended to establish the structure's natural frequencies and mode shapes so that resonance with the launch vehicle's dominant excitation frequencies could be ruled out. With fixed supports applied across the twelve outer faces and a solution search set to 0–2000 Hz for the first twelve modes, the analysis targets the fundamental frequency (f_1) as its key output — a value that major launch providers (SpaceX, Rocket Lab, NASA's GEVS standard) typically require to exceed roughly 45–90 Hz for a stiff-structure CubeSat, in order to prevent dynamic amplification during ascent. Since launch represents the most mechanically severe phase of the mission, and on-orbit dynamic loading is comparatively mild, a high fundamental frequency chiefly serves to keep the structure from resonating during this critical window. The behavior is governed by the classical eigenvalue equation of motion:

$[M]\{\ddot{U}\} + [K]\{U\} = 0$

where [M] is the mass matrix, [K] the stiffness matrix, $\{\ddot{U}\}$ the nodal acceleration vector, and {U} the nodal displacement vector.

Modal behaviour. The twelve extracted modes lie between 539.67 Hz and 1076.3 Hz. The fundamental frequency is several times higher than the minimum values commonly quoted for CubeSat launch, so the frame is unlikely to resonate with the vehicle's low-frequency excitation.

B. Static Structural Analysis

This analysis reproduces the quasi-static acceleration experienced during peak launch loading (staging and max-Q conditions). With the twelve outer faces fixed and a 650 N axial load ramped over 1 second, the model returned a maximum total deformation of 0.3769 mm, a peak equivalent (von Mises) stress of 65.662 MPa, and a maximum equivalent elastic strain of 0.0009836 mm/mm. Comparing this peak stress against Aluminum 6061-T6's yield strength ($\sigma y \approx 276$ MPa) and ultimate tensile strength ($\sigma u \approx 310$ MPa) confirms the frame remains safely within its elastic range under this load, with a factor of safety comfortably above the 1.5 baseline typically required in aerospace structural design. The analysis is governed by the linear stiffness relation:

$[K]\{x\} = \{F\}$

where [K] is the stiffness matrix, {x} the displacement vector, and {F} the applied static force vector.

Static strength. Under the 650 N load, the maximum deflection was 0.3769 mm, the maximum equivalent elastic strain was 0.0009836 and the peak von Mises stress was 65.66 MPa. Against the 276 MPa yield strength, this gives a positive margin of safety of +2.36 when a factor of 1.25 is applied, and the response remains elastic.

C. Random Vibration Analysis

This analysis reproduces the acoustic and aerodynamic shaking of a CubeSat experience during atmospheric ascent. A PSD acceleration spectrum spanning 20–2000 Hz was applied at the fixed supports, using the modal analysis as the pre-stress basis. The resulting 3-sigma equivalent stress of 0.005068 MPa and a peak response PSD displacement of 1.0053×10^{-8} mm²/Hz are both extremely low relative to material limits, confirming a wide safety margin under this load type.

Table 5.1 :- Random Vibration Analysis output

Result Parameter	ANSYS Output (3σ)	Engineering Significance
Directional Deformation	4.37×10^{-6} mm	Confirms adequate clearance from deployer rails and internal components
Equivalent Stress	0.005068 MPa	Confirms the structure retains ample strength margin against yield or fracture under launch excitation
Response PSD	Peak 1.0053×10^{-8} mm²/Hz	Characterizes frequency-domain energy transfer, providing an input load profile for internal subsystem qualification (e.g., PCBs)

The root-mean-square acceleration response associated with the PSD curve is given by:

$Grms = \sqrt{[(\pi/2) \cdot F_n \cdot Q \cdot (Ads\ input)^2]}$

where Grms is the RMS acceleration, F_n the natural frequency, Q the transmissibility factor, and Ads input the input acceleration spectral density.

Random vibration response. The response PSD, driven by the modal solution, falls smoothly across the 20–2000 Hz band. Its highest value occurs at the lowest excitation frequency and there is no sharp resonant peak, which is consistent with the high fundamental frequency found in the modal analysis.

VI. CONCLUSION FROM THE PROJECT

Project: Design and Analysis of 1U CubeSat for Space Application

Structural Material: Aluminum 6061-T6 ($\sigma y = 276$ MPa, $\sigma u = 310$ MPa, $E = 68.9$ GPa, $\rho = 2700$ kg/m³)

CAD and FEA Environment

PARAMETER	TOOL	TECHNOLOGY
CAD	SolidWorks 2023	Designing, Drafting & Assembling
FEA	Ansys Workbench 2026 R1 Student Version	Finite Element Methods

Executive Summary and Overall Verdict

This paper reviewed how modal, static structural and random vibration analyses are used to assess 1U CubeSat frames for launch, and it applied those practices to an Al 6061-T6 frame modelled in SolidWorks and analyzed in ANSYS Workbench. The review found that the three analyses are well established for early structural checks. It also found that published studies differ widely in constraints, load definitions and PSD reporting, which makes direct comparison difficult.

Within the limits of a linear model of the bare frame, the Al 6061-T6 1U structure is stiff and strong enough for the launch conditions considered. It meets the usual frequency criterion by a wide margin and stays far below yield under the static load, and its random vibration response shows no sign of resonant amplification. These results show that geometry is a sound starting point for detailed design. They do not qualify the structure for flight.

Table 6.1 :- Summary of all Analysis

Check	Result	Reference	Verdict
Fundamental frequency	539.67 Hz	Typical minimum of about 90–100 Hz	Satisfied
Peak von Mises stress (650 N)	65.66 MPa	Yield strength 276 MPa	Satisfied (MoS +2.36)
Peak static deflection	0.3769 mm	No resonance or yielding concern	Satisfactory
Random vibration response	Smooth roll-off, no resonant peak	No amplification	Satisfactory; 3σ values to be confirmed

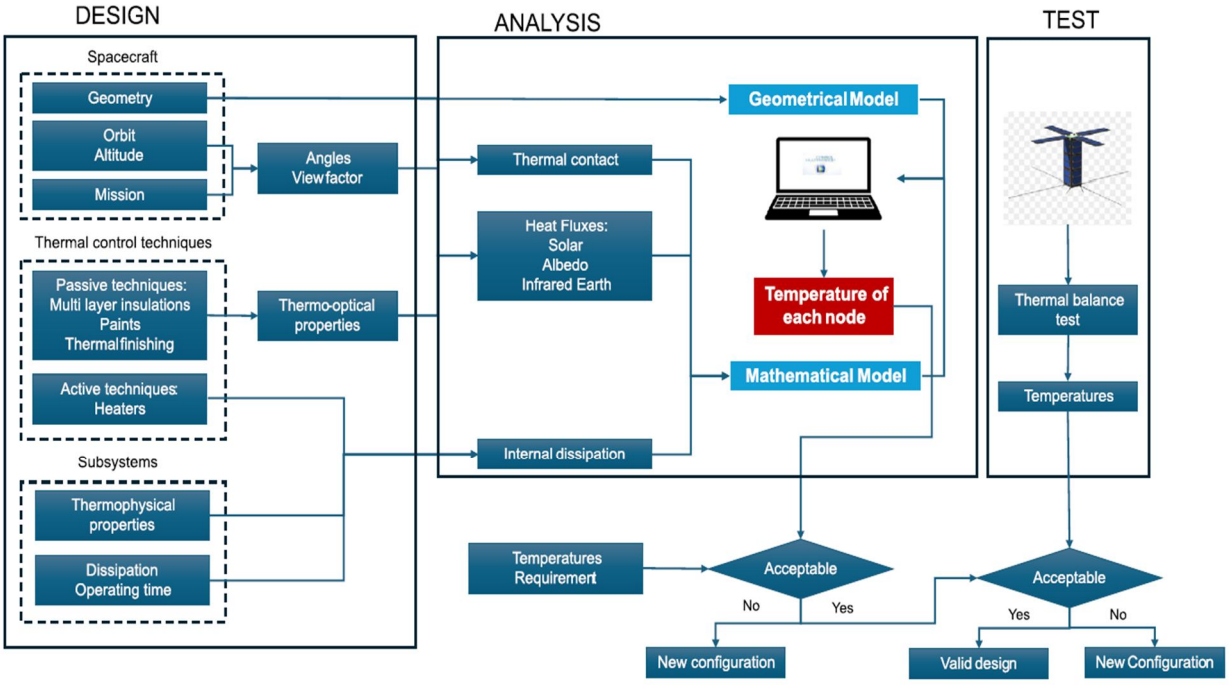


Figure 6.1 :- Framework of Design, Analysis and Test of CubeSat in LEO

VII. SCOPE FOR FUTURE WORK

The present investigation analyzed a simplified 1U CubeSat model constructed in Aluminum 6061-T6 using the ANSYS 2026 R1 (Student Version) finite element package. Building on this baseline, future work could extend the model to a more detailed CubeSat geometry and evaluate alternative structural materials — (i) add internal components and bolted joints, (ii) apply a launch-provider PSD and quasi-static load set, (iii) compare other aluminium alloys and composite options, (iv) pursue lightweighting, such as wall pocketing, and (v) validate the model with shake-table and static tests.

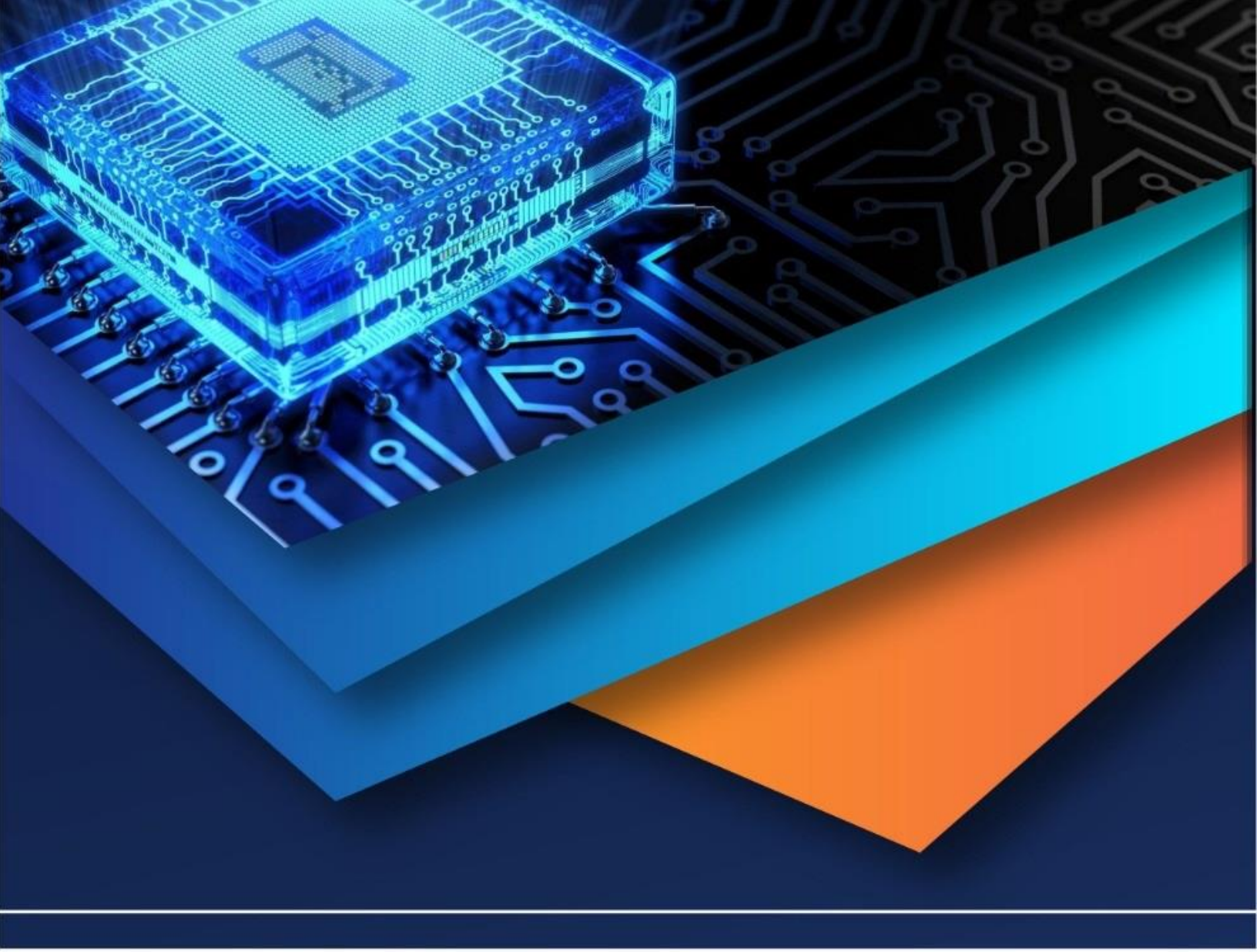
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