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Finite Element Screening of Sustainable Solar Panel Frame Materials for an OceanSat-3 Inspired Sun Tracking Satellite Architecture

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Abstract: *A motor-driven solar-array mechanism can improve an Earth-observation satellite's ability to maintain a favorable angle between the solar panels and incoming sunlight. However, the supporting frame must remain lightweight, stiff, dimensionally stable, and durable under orbital loading conditions. This study presents a conceptual OceanSat-3-inspired satellite bus equipped with a direct-current motor mechanism coupled to deployable solar-panel frames. The work evaluates fiber-reinforced polymer and MFHB hybrid-composite configurations through a preliminary material-screening study using SolidWorks Simulation. A CAD-to-FEA workflow was developed that included material assignment, bonded contact definition, structural constraints, gravitational and mechanical loading, thermal conditions, meshing, and linear-static analysis. The configurations were assessed using von Mises stress, resultant displacement, equivalent strain, and estimated structural safety. Although the simulations indicate clear differences in structural response, inconsistencies in the material properties, loading conditions, thermal definitions, and mesh settings prevent a direct material ranking or flight-qualification conclusion. The study therefore emphasizes the importance of conducting standardized reruns using verified material data and identical boundary conditions. Further validation should include orthotropic characterization, mesh-convergence analysis, thermal-vacuum cycling, outgassing assessment, atomic-oxygen and ultraviolet exposure, radiation evaluation, and fatigue testing. The proposed workflow provides a foundation for developing and evaluating sustainable solar-array support structures for future Earth-observation satellite applications.*

Keywords: OceanSat-3, EOS-06, finite-element analysis, flax-fiber reinforced polymer, sustainable composite, MFHB-60/40

I. INTRODUCTION

Earth observation spacecraft depend on stable electrical power while simultaneously meeting strict mass, stiffness, thermal-stability, and reliability constraints. EOS-06, also known as OceanSat-3, is the third-generation mission in India's Oceansat series and carries instruments for ocean colour, sea-surface temperature, ocean-wind, and ARGOS services [1]. The present work does not reproduce flight hardware; it uses an OceanSat-3-inspired bus as an educational engineering platform for studying an actively rotated solar-array support architecture.

The proposed architecture places a direct-current motor and coupling at the bus to array interface. Rotation of the shaft is intended to orient the photovoltaic surface toward the Sun as orbital geometry changes. In principle, reducing the incidence angle can limit cosine losses and improve energy capture. In practice, the same mechanism introduces bearing reactions, local stress concentrations, backlash, jitter, wiring constraints, motor power demand, and additional failure modes. Solar-array rotary mechanisms therefore require integrated structural, thermal, control, and reliability analysis rather than a purely geometric demonstration [2], [3].

A second objective is to explore whether a natural-fiber or wood-containing composite can replace a conventional frame material. This objective joins two different sustainability questions. Carbon footprint is a terrestrial life cycle measure associated with raw materials, processing, transport, launch mass, replacement, and end of life. Space environmental burden is instead associated with orbital lifetime, debris risk, contamination, erosion products, and mission reliability. A longer lasting lightweight frame can potentially support both goals, but a static stress plot alone cannot quantify either one.

This paper compares the three supplied simulation reports, reconstructs their common and differing assumptions, calculates derived margins, and tests whether the evidence supports claims concerning strength, stiffness, pointing accuracy, energy efficiency, service life, and environmental benefit. The contribution is intentionally framed as a preliminary screening and data-quality study, because reproducibility and physical consistency are essential before a material ranking can be published.

A. Research objectives

- Develop an integrated CAD concept comprising a satellite bus, motor, shaft/coupling, hinge or rotary interface, and two solar-panel frames.
- Compare the material definitions, load cases, meshes, and reported structural responses in the three SolidWorks studies.
- Evaluate strength margin and deformation as preliminary indicators of structural suitability.
- Separate quantities actually measured by the simulations from claims that require orbital tracking, fatigue, environmental exposure, or life-cycle data.
- Define a controlled rerun protocol capable of producing publication-grade comparative evidence.

II. LITERATURE REVIEW

A. Solar-array tracking and pointing mechanisms

Solar-array drive mechanisms maintain electrical performance by rotating an array relative to the spacecraft body. Their design is coupled to attitude dynamics because array motion can transmit disturbance torque and structural vibration to the bus. Zhu et al. modelled and dynamically analysed a high-precision solar rotary mechanism for the China Space Station, illustrating the need to predict failure modes and vulnerable parts under extreme conditions [2]. Merriam et al. demonstrated a two-degree-of-freedom compliant pointing mechanism for spacecraft payload or solar-array applications, showing how mechanism topology and joint design can reduce conventional bearing complexity while preserving controlled motion [3]. These studies support the proposed motorized interface, but they also show that static strength is only one part of mechanism verification.

Pointing performance should be evaluated through angular error, motor resolution, backlash, structural flexibility, array-mode excitation, and control stability. For direct irradiance, the idealized geometric contribution varies approximately with the cosine of the incidence angle. This relationship motivates tracking, but net energy gain must subtract actuator and control-system consumption and must be integrated over representative orbits. No orbital Sun-vector history, motor-control simulation, or photovoltaic power model is included in the supplied reports; accordingly, energy-efficiency improvement remains a design hypothesis.

B. On-orbit solar-array degradation

Solar-array output changes with temperature, radiation damage, contamination, interconnect failure, and ageing. On-board monitoring studies have used photovoltaic models and telemetry to infer degradation and identify periods associated with space-weather events [4]. These results are relevant because a tracking system can improve instantaneous incidence while the array itself continues to age. A credible service-life claim must therefore combine structural durability, mechanism reliability, and electrical end-of-life power, rather than treating a lower static stress as direct evidence of longer panel life.

C. Natural-fiber composites and sustainability

Natural-fiber composites are attractive because plant fibers have low density, renewable feedstock's, and potentially lower production energy than conventional synthetic fibers. Reviews by Faruk et al. and Pickering et al. describe the rapid development of these materials while emphasizing the influence of fiber orientation, fiber volume fraction, moisture, processing, interface quality, and test direction on measured properties [8], [9]. Flax-epoxy laminates are inherently anisotropic and can exhibit nonlinear or bilinear tensile behavior, which limits the realism of a single isotropic elastic modulus and a von Mises failure criterion [10]. Fatigue performance is also sensitive to stress level, lay-up, environment, and damage evolution [11].

Recent comparisons reinforce the need for a trade-off rather than a universal sustainability ranking. Koronis et al. combined flexural testing, finite-element modelling, and life-cycle assessment and reported lower climate impact for plant-based panels in the studied production system [12]. Margoto and Milani found that flax/bioresin composites could provide competitive density and energy-absorption characteristics, while carbon-fibre hybridization increased tensile properties at the cost of reduced bio-based content [13]. Lopez-Arraiza et al. reported a 14% reduction in global-warming potential for a flax/bio-epoxy ship-hull case, but also a large increase in terrestrial ecotoxicity linked to fertiliser use [14]. These results support investigating a bio-based frame, yet none can be transferred directly to a spacecraft without a mission-specific inventory and functional unit.

D. Low-Earth-orbit material exposure

Polymer-matrix composites in low Earth orbit are exposed to atomic oxygen, ultraviolet radiation, ionizing radiation, vacuum, contamination, thermal cycling, and hypervelocity particles. Grossman and Gouzman review how these factors erode or modify polymers and can alter morphology and surface properties [5]. Long-duration exposure records show atomic-oxygen-driven material loss and thermal-cycle micro cracking in organic composites [6]. Protective multilayer barriers can mitigate atomic-oxygen and ultraviolet degradation, but coating integrity, pinholes, adhesion, and outgassing must be verified [7]. A natural-fiber or wood-containing composite must therefore be treated as an unqualified candidate until its resin system, moisture content, protective coating, outgassing, erosion yield, and retained properties have been experimentally established.

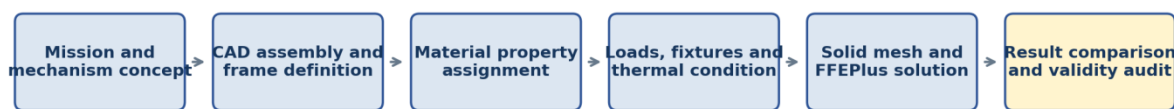
Table 1. Literature synthesis and design implications

Evidence area	Key finding	Implication for this study
Solar rotary mechanisms	Tracking accuracy and structural dynamics are coupled [2], [3].	Add angular-error, jitter, modal, and drive-torque analyses.
PV ageing	Electrical output degrades through environmental and system effects [4].	Use orbit-resolved power and end-of-life performance metrics.
Flax composites	Properties depend strongly on lay-up, processing, moisture, and direction [8]-[11].	Use measured orthotropic properties and a composite failure criterion.
Environmental impact	Benefits are case- and boundary-dependent [12]-[14].	Perform a project-specific LCA; do not infer carbon savings from material name.
LEO exposure	AO, UV, radiation, vacuum, and thermal cycling degrade polymers [5]-[7].	Require coating, outgassing, and exposure qualification before flight use.

E. Research gap

The literature contains mature methods for solar-array mechanisms, natural fiber composite characterization, and LEO exposure testing, but limited open evidence joins these themes in a single solar-panel frame study. The present project addresses this gap at concept level by integrating a motorized array architecture with a comparative finite-element workflow. Its novelty is not a claim that MFHB is already space-qualified; it is the combined design framework and the explicit validation route needed to determine whether a bio-derived hybrid can become a viable frame material.

III. MATERIALS AND METHODS



All comparisons retained the values exported in the three supplied SolidWorks reports.

Figure 1. Research workflow used to reconstruct and audit the three supplied simulations.

A. CAD system architecture

The conceptual assembly comprises a prismatic Earth-observation satellite bus, two opposed solar-panel frames, a DC motor, a shaft coupling, and bus-side support or hinge components. The motor is intended to rotate the panel-frame axis in response to a Sun-tracking command. The CAD model was simplified for finite-element analysis by representing the principal bus and array-frame solids while omitting electrical harnesses, fastener preload, detailed bearing contacts, cell laminates, and deployment latches. This simplification is appropriate for an initial screening study but not for qualification.

The present bonded-contact model does not establish the detailed load-transfer path or local stiffness through the hinge, shaft, bearing, motor interface, and frame attachments.

Because detailed bearing contacts and fastener preload are omitted, the predicted displacement and load distribution should not be interpreted as joint-qualified values. In the next model, the relevant joint/contact behavior should be represented explicitly, or equivalent connector stiffness should be justified using documented or measured values.

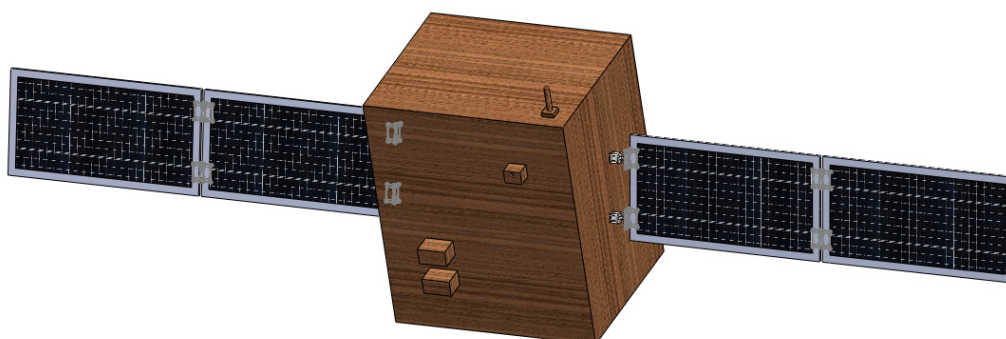


Figure 2. Final CAD assembly of the OceanSat-3-inspired bus, opposing solar-panel frames, and motorized tracking mechanism.

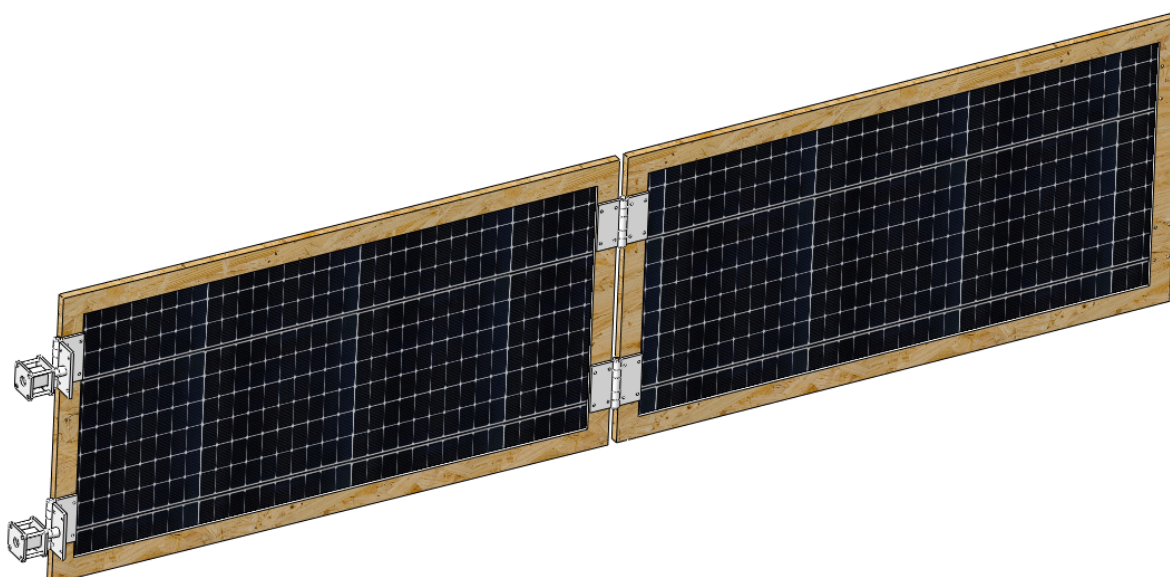


Figure 3. Solar Panel Frame with MFHB Material along with motorized mechanism

B. Compared simulation configurations

The source reports were treated as two configurations rather than three verified materials. Configuration A is clearly identified as an all-FFRP study. Configuration B has an FFRP model name but an MFHB-60/40 study name; its material table assigns MFHB-60/40 to two solid bodies. Configuration C uses an MFHB model name and the same MFHB-60/40 property set. The filename for Configuration B implies an FFRP/MFHB combination, but the report does not document separate body-level material assignments. It is therefore described as a mixed-label configuration, not as a proven hybrid-material assembly.

Table 2. Material properties exactly as exported in the reports

Property	A: FFRP	B: MFHB 60/40
Material name in report	Flax fiber reinforced epoxy	MFHB-60/40
Constitutive model	Linear elastic isotropic	Linear elastic isotropic
Elastic modulus, E	2.256×10^7 Pa (22.56 MPa)	1.600×10^{10} Pa (16.0 GPa)

Poisson ratio	0.300	0.318
Shear modulus, G	8.677×10^6 Pa	8.740×10^8 Pa
Density	1254 kg/m ³	16,000 kg/m ³
Yield strength	58 MPa	39 MPa
Tensile strength	145 MPa	5 MPa
Compressive strength	90 MPa	39 MPa
Thermal expansion coefficient	3.0×10^{-5} K ⁻¹	3.8×10^{-6} K ⁻¹

C. Study settings, loads, and constraints

All two reports use a linear-static solid study with thermal effects enabled, the FFEPlus solver, bonded global contact, small-displacement kinematics, and no friction, soft spring, or inertial relief. The zero-strain temperature is 298 K. A temperature of 125 degrees C (398.15 K) corresponds to a nominal increase of approximately 100.15 K. Gravity is applied in the global negative Z direction with a magnitude of 9.81 m/s². Three faces are fixed. The reports list a normal force but do not list a separate pressure load, despite pressure being part of the broader project description.

Table 3. Boundary-condition comparison

Setting	A: FFRP	B: MFHB 60/40
Solver / study	Static, FFEPlus	Static, FFEPlus
Contact	Global bonded	Global bonded
Fixture	Fixed geometry; 3 faces	Fixed geometry; 3 faces
Gravity	0, 0, -9.81 m/s ²	0, 0, -9.81 m/s ²
Normal force	0.001 N on 3 faces	0.0001 N on 3 faces
Temperature	125 C on 58 faces	125 C on 58 faces
Zero-strain temperature	298 K	298 K
Large displacement	Off	Off
Pressure load	Not listed	Not listed

Dynamic and modal analysis scope

The current study is linear-static and does not model angular acceleration, rotational inertia, transient solar-tracking loads, or natural frequencies. Consequently, it cannot quantify motor-start or reversal transients, array-mode excitation, or vibration transfer to the satellite bus. The next-stage study should include modal analysis and an appropriate frequency-response or transient-dynamic analysis using the actual array mass and rotational inertia, motor torque/acceleration history, joint stiffness, and representative tracking conditions.

D. Mesh generation and solution

A standard solid mesh with four Jacobian points and automatic transition disabled was used. Configuration A used a nominal element size of 142.214 mm and tolerance of 7.11069 mm; Configurations B used 147.118 mm and 7.35589 mm. No distorted elements were reported by the Jacobian check. However, 65.5-66.6% of elements had aspect ratio greater than 10, and no h- or p-convergence study was documented. The reported maxima must therefore be treated as mesh-dependent preliminary values, particularly near fixed faces, geometric discontinuities, and bonded interfaces.

Table 4. Mesh comparison

Metric	A: FFRP	B: MFHB 60/40
Element size	142.214 mm	147.118 mm
Tolerance	7.11069 mm	7.35589 mm
Nodes	30,992	29,382
Elements	15,453	14,785
Maximum aspect ratio	51.849	51.757

Elements with aspect ratio < 3	7.99%	7.58%
Elements with aspect ratio > 10	66.6%	65.5%
Distorted elements	0%	0%

E. Response and derived metrics

The primary outputs were maximum von Mises stress, resultant displacement, and equivalent strain. A nominal safety factor was calculated as entered yield strength divided by maximum von Mises stress. Stress utilization was calculated as maximum stress divided by entered yield strength. These quantities are convenient for screening isotropic ductile materials, but they are incomplete for laminates, wood-containing hybrids, adhesives, or joints. Orthotropic stress components and criteria such as maximum stress/strain, Tsai-Hill, Tsai-Wu, or Hashin should be selected after the laminate and failure modes are defined.

Buckling and stability assessment status

No eigenvalue or nonlinear buckling analysis is present in the supplied studies; therefore, no numerical buckling factor can be reported from the current dataset. This is an important limitation for a lightweight solar-array frame because instability may govern even when static von Mises stress is below the entered yield strength. The controlled rerun should first use eigenvalue buckling as a screening assessment and, where instability is relevant, follow with nonlinear buckling using realistic geometric imperfections, joint/contact behavior, and boundary conditions. Buckling load factors should be reported separately from the yield-based safety factor.

F. Comparative validity checks

Before ranking the results, four checks were applied: (i) dimensional plausibility of material properties, (ii) equivalence of geometry and body assignment, (iii) equivalence of loads and thermal selections, and (iv) mesh convergence. For an isotropic material, E, Poisson ratio, and G should satisfy $G = E / [2(1 + \nu)]$. The FFRP entries satisfy this relationship, but their magnitudes appear to have been entered in MPa where the software expected Pa or in g/cm³ where it expected kg/m³. For MFHB, E = 16 GPa and $\nu = 0.318$ imply G approximately 6.07 GPa, not the reported 0.874 GPa.

G. Validation status

The checks in Section 3.6 test internal consistency of the supplied inputs and outputs, but they do not independently establish that the calculated structural response is physically accurate. The current stress, displacement, strain, and reaction-force results should therefore be treated as preliminary numerical outputs. At least one representative configuration should be validated in the next stage using a hand or analytical model, an independently implemented finite-element model/solver, or a physical coupon/subassembly test, with the comparison reported quantitatively.

IV. RESULTS

A. Mass and reaction force

The total geometric volume is approximately 0.95231 m³ in all reports. Configuration A has a reported total mass of 1.19420 kg, whereas Configurations B have 15,236.98 kg. The corresponding resultant reactions are 11.7065 N and approximately 149,458-149,459 N. These values closely track the respective gravitational weights and show that gravity dominates the nominal 0.001 or 0.0001 N applied forces. Consequently, the density entries directly control the comparison.

Using $W = mg$ with $g = 9.81 \text{ m/s}^2$ gives $1.1942 \times 9.81 =$ approximately 11.715 N for Configuration A, compared with the reported 11.7065 N, and $15,236.98 \times 9.81 =$ approximately 149,474.7 N for Configuration B, compared with the reported 149,458-149,459 N. The differences are small (about 0.07% and 0.01%, respectively), so the reaction-force values are approximately consistent with gravitational weight. This arithmetic check is a verification rather than a new error and does not validate the physical plausibility of the entered density values.

Table 5. Reported and derived structural comparison

Metric	A: FFRP	B: MFHB 60/40
Total mass	1.1942 kg	15,236.98 kg

Resultant reaction force	11.7065 N	149,458 N
Maximum von Mises stress	0.1012 MPa	38.29 MPa
Maximum displacement	4.367 mm	60.68 mm
Maximum equivalent strain	2.157×10^{-3}	1.640×10^{-3}
Entered yield strength	58 MPa	39 MPa
Nominal safety factor	573.1	1.019
Stress utilization	0.174%	98.18%

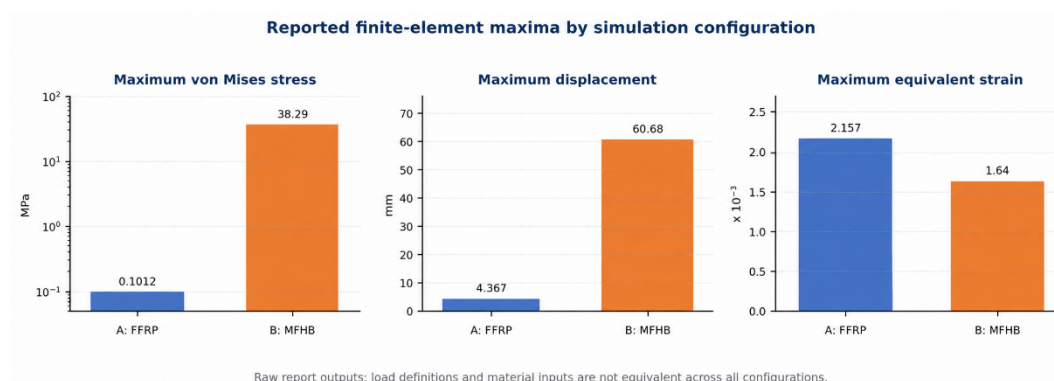


Figure 4. Comparison of reported stress, displacement, and strain maxima. The stress panel uses a logarithmic scale.

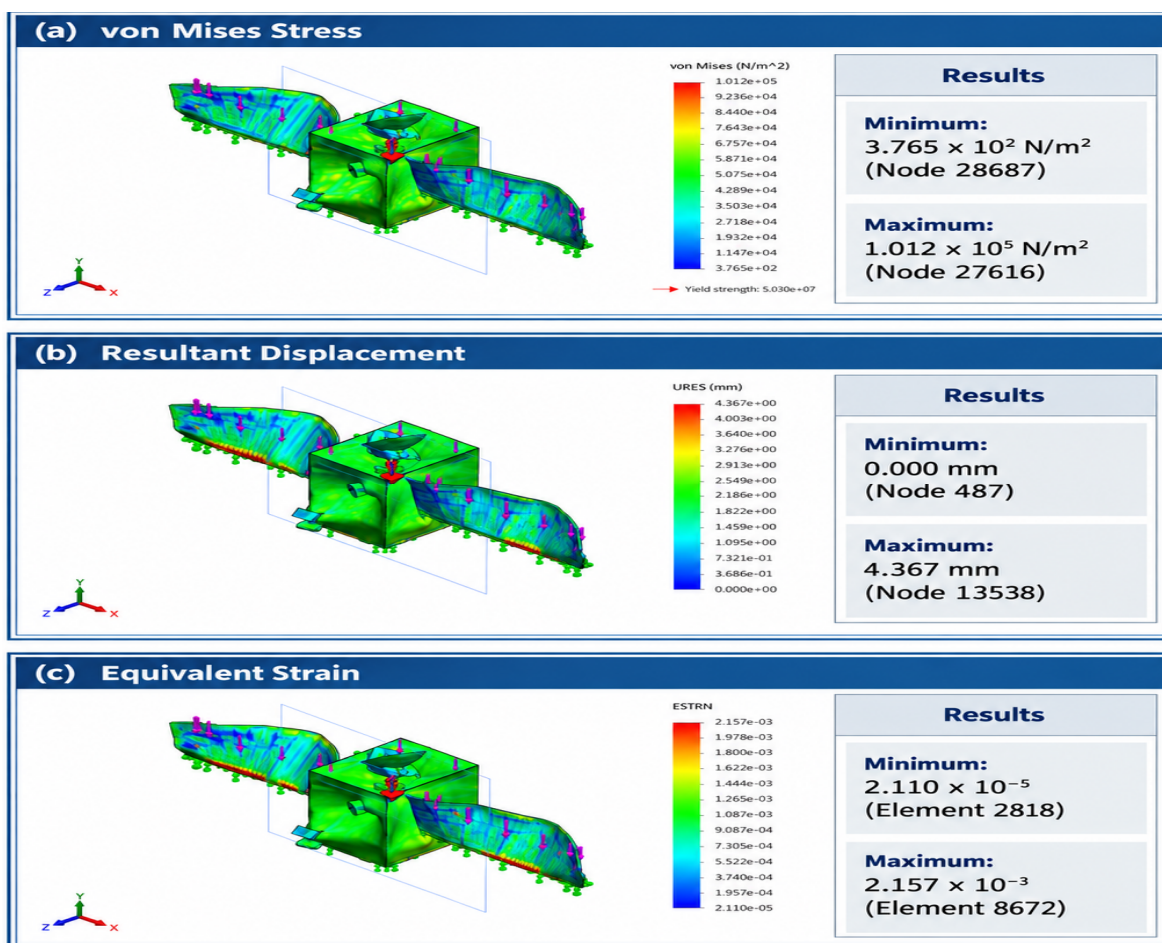


Figure 5:- FEA Results for the FFRP Configuration

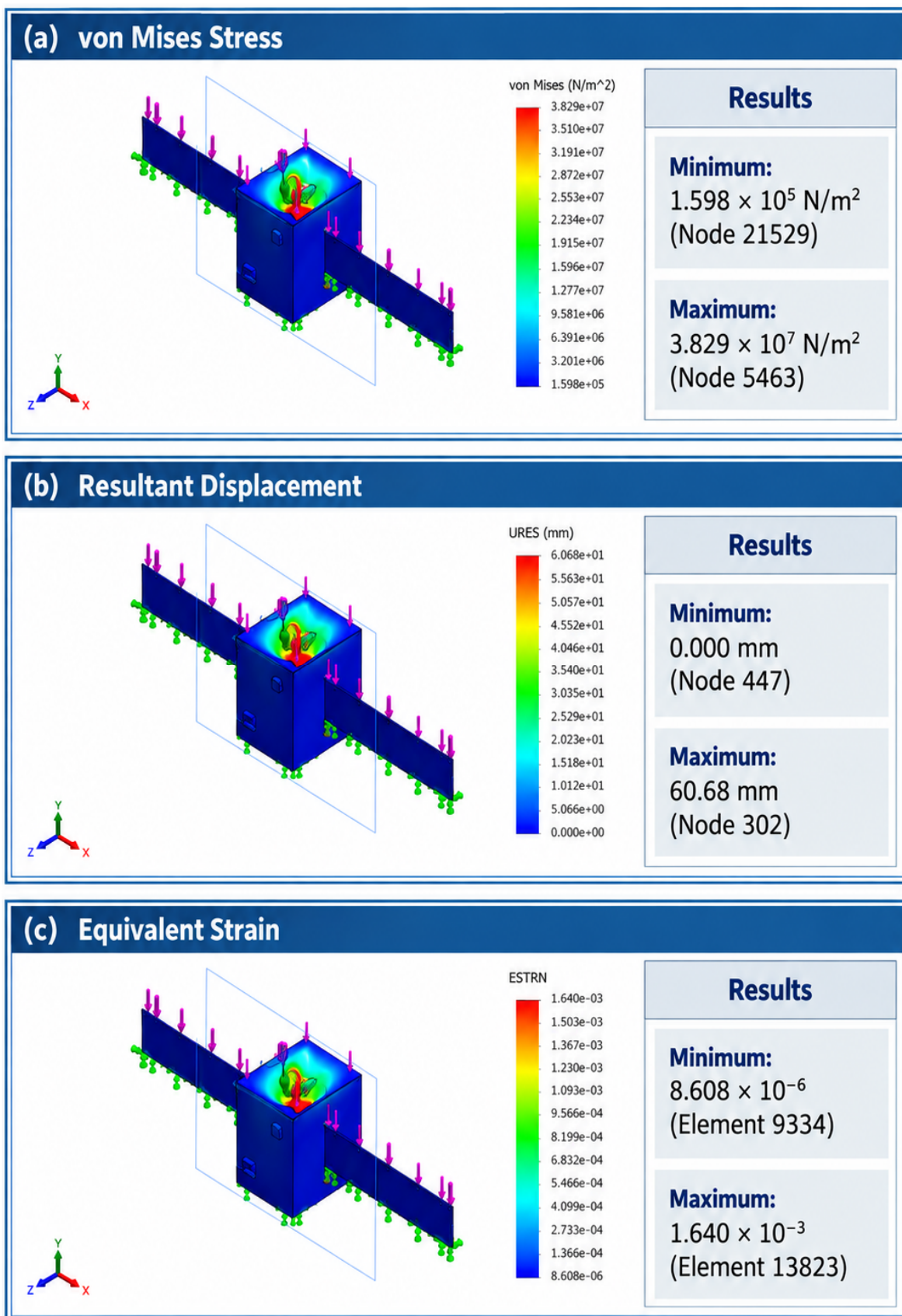


Figure 6:- FEA Results of MFHB 60 / 40 Configurations

V. DISCUSSION

A. Structural strength and stiffness

If the reported MFHB values are accepted literally, Configurations B operate close to the entered yield strength and have a maximum displacement of 60.68 mm. Such a small nominal stress margin and large deformation would be undesirable for an optical Earth-observation platform because flexible-array motion can couple into attitude control and payload pointing. Configuration A appears to have low stress but retains 4.367 mm displacement despite its extremely small gravitational mass. This combination is consistent with the very low entered elastic modulus and demonstrates why stress and displacement must be interpreted together.

A corrected comparison may change the ranking substantially. For gravity-dominated loading, stress scales strongly with density, while deflection depends on both load and stiffness. If the FFRP density and modulus were both understated by the same factor, gravity-induced displacement could remain of similar order while stress would not. Thermal stress responds to modulus, coefficient of thermal expansion, constraint, and the temperature field.

B. Suitability of the failure model

Both flax-fiber composites and wood-containing hybrids are direction-dependent. Modelling them as isotropic materials suppresses the distinction between longitudinal, transverse, and through-thickness stiffness and does not represent fiber-dominated, matrix-dominated, or interlinear failure. The next model should define the frame as a laminate or orthotropic solid with experimentally measured E_1 , E_2 , E_3 , G_{12} , G_{23} , G_{13} , Poisson ratios, thermal-expansion coefficients, tensile/compressive strengths, and shear strengths. The selected failure criterion must match the available allowable and laminate architecture.

C. Service life in low Earth orbit

Service life cannot be inferred from a one-time safety factor. A rotating frame experiences repeated motor starts, reversals, orbital thermal cycles, launch vibration, deployment shock, and long-duration material ageing. Polymer surfaces in LEO may be eroded by atomic oxygen and altered by UV and ionizing radiation [5]-[7]. Natural fibers add moisture sensitivity and possible vacuum-outgassing concerns. The qualification route should therefore include thermal-vacuum cycling, atomic-oxygen fluence, UV/radiation exposure, outgassing screening, retained-property tests, joint fatigue, bearing life, modal survey, sine/random vibration, and deployment or tracking endurance.

D. Carbon footprint and responsible sustainability claims

Published life-cycle studies show that flax-based composites can lower climate impacts in particular terrestrial applications [12]-[14], but the benefit depends on agriculture, resin chemistry, electricity mix, processing yield, transport, protective coatings, and end-of-life assumptions. For spacecraft, launch mass and mission replacement frequency may also be influential. A defensible study should define a functional unit such as one flight-qualified solar-array frame delivering the required stiffness and service life, then compare cradle-to-gate and mission-normalized impacts. Until that analysis is complete, the correct conclusion is that MFHB and FFRP are sustainability candidates, not demonstrated low-carbon spacecraft materials.

E. Preliminary material decision

Configuration B has the lowest reported strain among the MFHB-based studies, but also the highest stress utilization and essentially no reserve against the entered yield strength. Configuration A has the best nominal safety factor, yet its density and modulus appear to contain unit errors. The responsible outcome is a conditional shortlist: retain FFRP and MFHB-60/40 for a controlled rerun, add a conventional aerospace aluminum or CFRP baseline, and make selection only after the same geometry, loading, mesh-convergence target, and qualification criteria are applied.

VI. CONCLUSIONS

This study developed a coherent research framework around an OceanSat-3-inspired satellite bus, a motorized solar-array tracking mechanism, and sustainable frame-material screening. The three supplied reports show that the CAD assembly can be meshed and solved under combined gravity, force, constraint, and thermal inputs. Their reported maxima provide a useful starting dataset: 0.1012-38.29 MPa stress, 4.367-60.68 mm displacement, and $1.640\text{-}2.157 \times 10^{-3}$ equivalent strain.

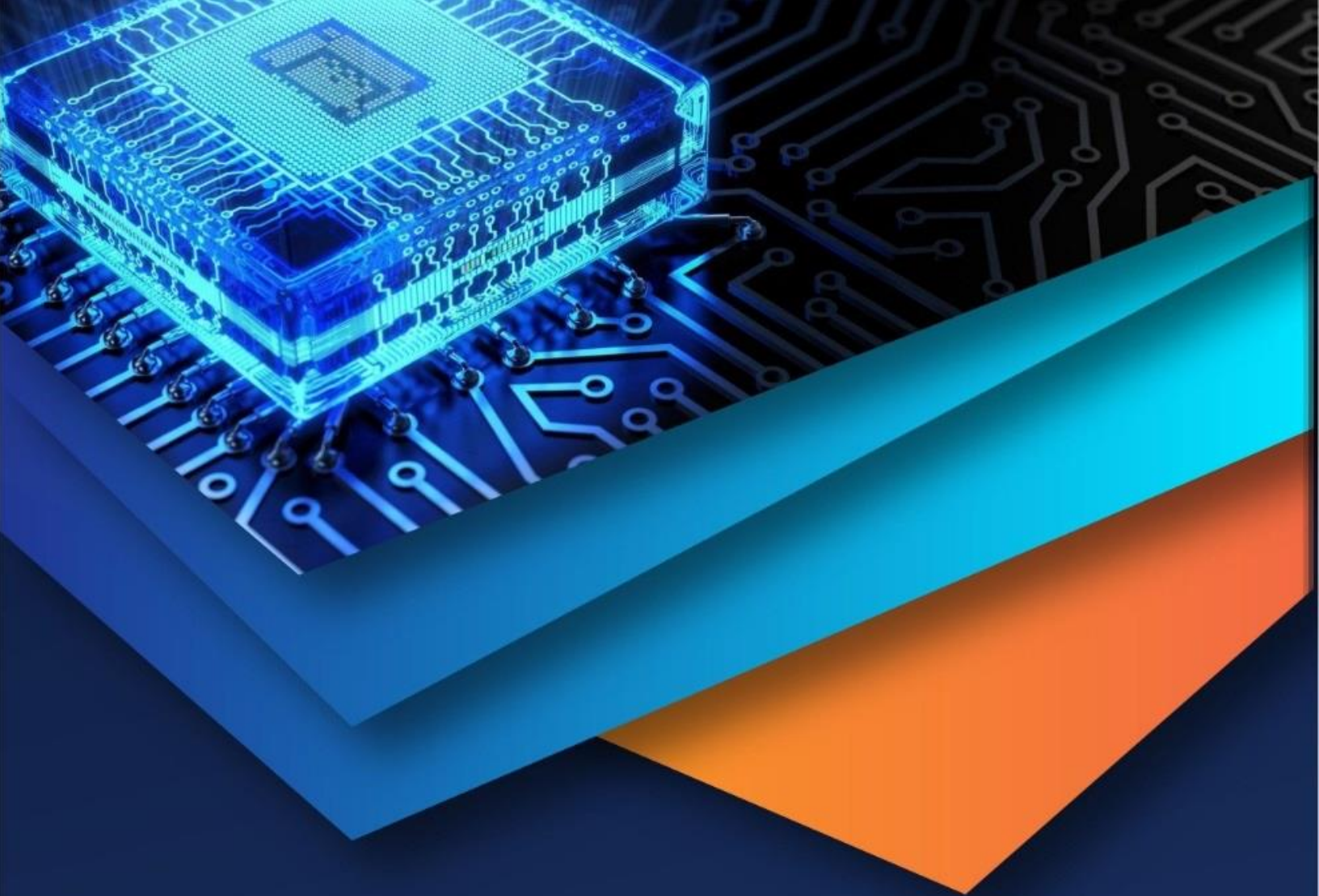
The comparison also reveals that the current simulations are not controlled material experiments.

FFRP density and modulus appear to contain unit-scale errors; MFHB density is physically implausible; the MFHB elastic and shear moduli are inconsistent under an isotropic model; the nominal force and thermal selections differ; the mixed configuration is not documented at body level; and mesh convergence is absent. The two MFHB-based configurations have nominal safety factors near unity, while the very high FFRP factor is driven by the entered data and should not be interpreted as a flight margin.

Accordingly, the project supports a publishable preliminary conclusion: bio-derived composites are credible candidates for continued investigation, and motorized tracking is a rational architecture for improving solar incidence, but neither structural superiority nor gains in accuracy, energy, life, or carbon footprint have yet been demonstrated. A corrected, identical-condition orthotropic rerun followed by joint/contact characterization, modal and transient-dynamic analysis, buckling assessment, independent structural validation, environmental qualification, fatigue, control, and life-cycle validation is the necessary next stage. This evidence-led framing preserves the originality of the project while making its claims technically defensible.

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