# Simulation of Lunar Habitat Structural Integrity Under Impact and Micrometeoroid Collision


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## ABSTRACT

Lunar habitat structures are critical for ensuring safe and sustainable living conditions on the Moon, capable of withstanding its harsh environment. This research employs ANSYS simulation software to evaluate and optimize the structural integrity of lunar habitats subjected to micrometeoroid impacts and other debris. A detailed three-dimensional finite element model of a lunar habitat is constructed, incorporating advanced materials such as regolith-based composites and polymers. These materials are selected based on their potential availability and suitability for lunar construction. The primary objective is to simulate realistic impact scenarios based on lunar micrometeoroid flux and collision velocities, providing crucial insights into the habitat's structural performance under lunar conditions. The analysis focuses on stress distribution, deformation, and damage propagation. Stress distribution analysis identifies potential weak points, deformation analysis examines the habitat's resilience under varying impact conditions, and damage propagation analysis predicts the spread of cracks and failures. Design modifications, such as energy-absorbing layers and impact-resistant coatings, are explored to enhance durability. Sensitivity analyses are conducted to identify optimal material choices and structural configurations. This research aims to develop highly resilient lunar habitats that ensure the safety and sustainability of human life on the Moon.



Keywords: Lunar habitat, structural integrity, ANSYS simulation, micrometeoroid impact, stress distribution, damage propagation, energy-absorbing layers

# 1. INTRODUCTION

## 1.1 Importance of Structural Integrity for Lunar Habitats

The Moon's surface presents a hostile environment, requiring lunar habitats to be robust against external forces that can compromise their structural integrity. One of the primary concerns is the impact of micrometeoroids, which are small meteoroids that can cause significant damage to the habitat's exterior and potentially penetrate the walls, leading to depressurization and loss of internal atmosphere (Lin, 1985). Additionally, the lunar surface offers little protection against harmful radiation from the sun and deep space, which can pose a significant threat to both the habitat's electronic systems and the health of astronauts (NASA, 2006).

Temperature fluctuations are another critical factor to consider, as the Moon's surface temperature can vary greatly between day and night, ranging from -243°C to 127°C (-405°F to 261°F) (NASA, 2006). This extreme temperature fluctuation can cause materials to expand and contract, leading to structural stress and potential failure.

Given the harsh conditions on the Moon's surface, structural integrity is essential for ensuring the safety of astronauts and maintaining internal life-support systems. A habitat's failure can lead to catastrophic consequences, including mission failure and loss of life (Francisco, 2021). Therefore, it is crucial to design and engineer lunar habitats with robust structures that can withstand the external forces and environmental stresses, ensuring a safe and reliable environment for astronauts to live and work in during extended lunar missions.

## 1.2 Overview of the Lunar Environment and Hazards

The lunar surface lacks an atmosphere to shield it from micrometeoroids, which travel at velocities of up to 70 km/s, making structural resilience critical (Ruess et al., 2006). In addition to micrometeoroids, lunar habitats must contend with extreme temperature fluctuations, with daytime temperatures reaching 107°C and nighttime temperatures plummeting to -233°C (Dorsey et al., 2008). These fluctuations induce significant stress in materials, leading to fatigue and potential failure over time (NASA, 2006).

## 1.3 Objectives of the Study

This study aims to simulate the structural integrity of lunar habitats subjected to micrometeoroid impacts using advanced finite element modeling. Key aspects of performance include stress distribution, deformation, damage propagation, and the effectiveness of design modifications like energy-absorbing layers and protective coatings.

# 2. LITERATURE REVIEW

## 2.1 Lunar Habitat Structural Design and Materials

Lunar habitat designs must incorporate materials that can endure the Moon's extreme conditions. Studies suggest using lunar-derived regolith-based composites and polymers as construction materials (Young, 1985). Dorsey et al. (2008) examined the structural efficiency of hard-shell and inflatable soft-shell habitats, highlighting the potential of hybrid designs.

## 2.2 Existing Simulation Studies on Impact and Collision Scenarios

Previous studies have simulated micrometeoroid impacts on lunar habitats, but gaps remain, particularly in dynamic load cases. NASA (2006) developed a habitat design tool incorporating meteoroid impact analysis. Francisco (2021) emphasized the need for more comprehensive simulations that incorporate lunar-specific environmental factors such as dust and radiation exposure.

## 2.3 Gaps in Current Knowledge

Many studies rely on simplified models or empirical equations that may not accurately represent material behavior under real lunar conditions (Francisco, 2021). This research aims to fill these gaps by conducting sensitivity analyses on various material choices and structural configurations, offering insights into improving lunar habitat designs.

# 3. METHODOLOGY

## 3.1. Material Selection

This study employs regolith-based composites and polymers for their availability on the Moon and suitability for construction. These materials are modeled in ANSYS, incorporating specific properties like density, thermal expansion coefficients, and tensile strength (NASA, 2008). We study the rate of stress distribution on the materials Ti-6Al-4V, Composite fibre reinforced polymer and the lunar regolith which we can further use to construct the lunar habitat biosphere to sustain various life forms.

### 3.2. Development of the 3D Finite Element Model

The lunar habitat is modeled in three dimensions using finite element analysis (FEA). Realistic micrometeoroid impact scenarios are defined based on lunar flux rates and velocities, simulating impacts at different angles and speeds. We designed a model of lunar dome but our simulation and calculations primarily depend upon a cuboid structure with the same material as that of the dome.

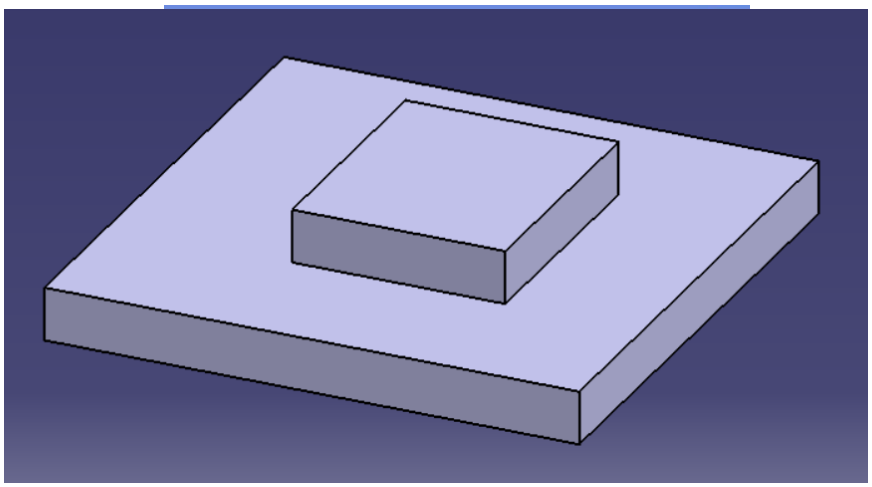


Fig. 2: Geometry for simulation

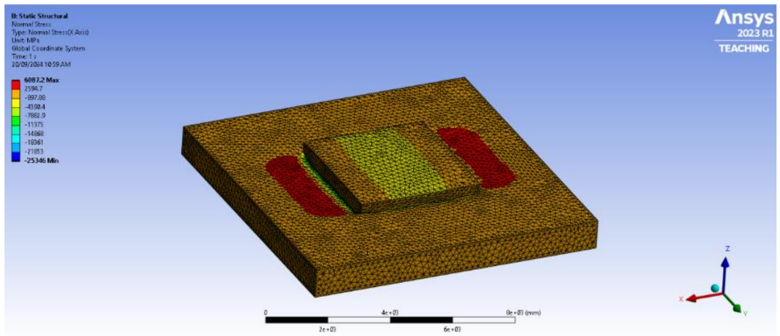
### 3.3. Impact Simulation

The simulation assesses the habitat's stress distribution, deformation, and damage propagation under micrometeoroid impacts. The goal is to identify stress concentrations, predict crack propagation, and evaluate deformation limits to ensure safety margins. A force of magnitude 7e+10 N is applied on the top surface of the smaller cuboid and a fixed support is kept on the bottom surface of the larger cuboid. We are applying this force as uniformly distributed load because we assume that the micrometeoroid come in group and every particle travel at the same speed, have same mass and density.

# 4. SIMULATION AND ANALYSIS

## 4.1. Stress Distribution Analysis

Stress concentrations are analyzed under impact loading, identifying potential weak points in the structure. These stress distributions provide a map of force dispersion throughout the habitat, pinpointing critical areas for structural reinforcements (Ruess et al., 2006)




. Fig. 3: Stress analysis on Carbon Fibre

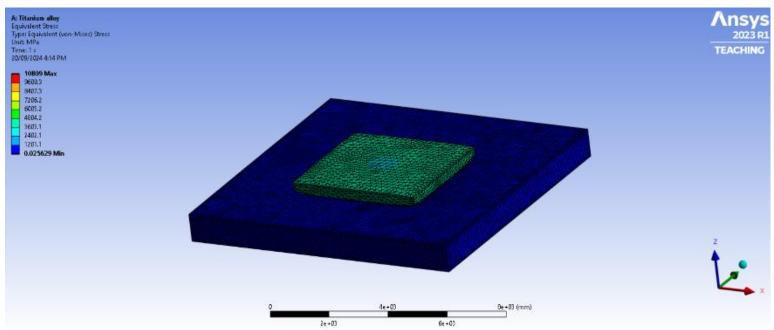



Fig. 4: Stress analysis on Titanium Alloy

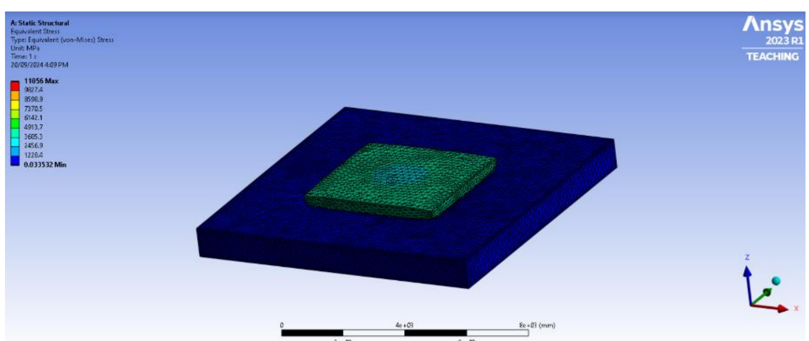



Fig. 5: Stress analysis on Ti-6Al-4V

### 4.2. Deformation Analysis

Deformation analysis evaluates the extent to which the structure bends or warps without compromising its integrity. The habitat must absorb impact energy while minimizing damage to critical areas (Francisco, 2021).

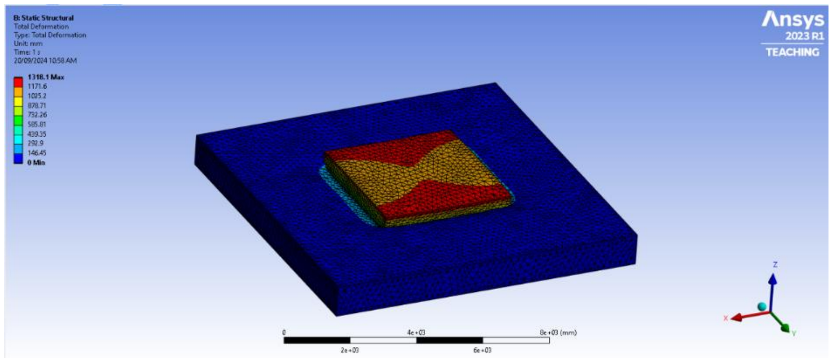



Fig. 6: Total Deformation on Carbon Fibre

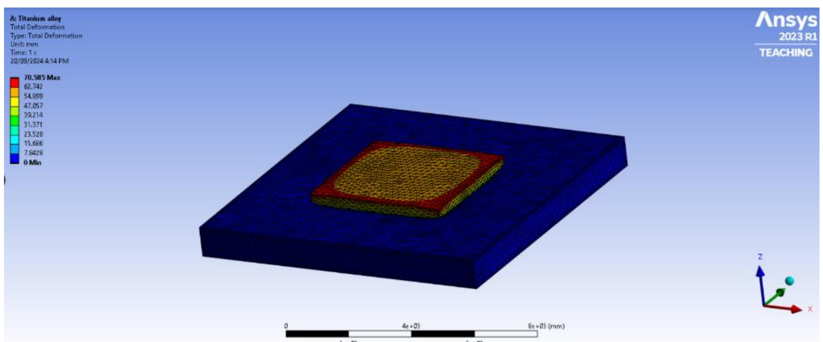



Fig. 6: Total Deformation on Titanium Alloy

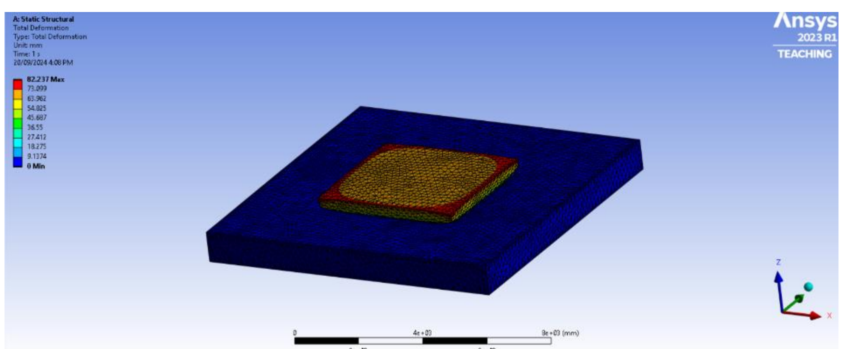



Fig. 8: Total Deformation on Ti-4Al-4V

### 4.3. Damage Propagation

This analysis predicts how cracks spread through materials under impact. It is vital for ensuring that local damage does not escalate into catastrophic failure (Dorsey et al., 2008).

The mechanical behavior of three materials—carbon fiber, Ti6Al4V, and titanium alloy—under micrometeoroid impact loading conditions was simulated using ANSYS software. The goal was to assess each material's total deformation and normal stress in order to decide which ones were suitable for building lunar habitats. The materials were modelled according to their mechanical characteristics; titanium alloy and Ti6Al4V were acknowledged for their remarkable rigidity and durability, while carbon fibre was valued for its high strength-to-weight ratio. These materials are excellent choices for lunar settings since they are frequently taken into consideration for structural, automotive, and aerospace applications. To ensure consistent stress distribution throughout the materials, meshing was utilized in conjunction with a finite element analysis (FEA) technique. To replicate micrometeoroid collisions and represent the hostile lunar environment, impact loads (7e+10 N) were included. Under the same loading conditions, the simulation examined the stress concentrations, deformation patterns, and failure locations of every material. Therefore, the goal to understand the response of these materials to external forces akin to those on the surface of the Moon was achieved.

# 5. DESIGN MODIFICATIONS AND OPTIMIZATION

Lunar habitats must endure extreme environmental conditions, such as micrometeoroid impacts and severe temperature fluctuations. To ensure the long-term viability of these habitats, design modifications aimed at enhancing structural resilience are critical. This includes integrating energy-absorbing layers, applying protective coatings, and using sensitivity analyses to optimize material selection and configuration.

One of the key design enhancements involves the integration of energy-absorbing layers into the structure of lunar habitats. These layers are designed to mitigate the damage caused by micrometeoroid impacts by dispersing kinetic energy across the habitat's surface. Materials such as regolith-based composites offer the dual benefit of reducing the habitat's weight and using locally sourced materials, minimizing the logistical challenges of transporting construction materials from Earth. By distributing impact forces more evenly, these layers help reduce stress concentrations, improving the overall durability of the habitat (Koenig, 2020).

Another critical design improvement is the application of impact-resistant coatings on the outer surface of the habitat. These coatings provide additional protection against micrometeoroids and help manage the habitat's exposure to extreme temperature variations. Materials such as ceramic-based coatings and metallic alloys are commonly used due to their high thermal resistance and durability. Research into self-healing coatings has also shown promise in extending the operational life of habitats, as these materials can autonomously repair minor damage, reducing the need for external maintenance (Kim & Lee, 2019).

To ensure the effectiveness of these modifications, sensitivity analyses are conducted. These analyses involve systematically adjusting design parameters, such as the thickness and material composition of both energy-absorbing layers and protective coatings. By using the Finite Element Method (FEM), engineers can simulate various impact and thermal scenarios to assess how different materials and configurations will perform under the harsh conditions of the lunar surface (Smith et al., 2020). This process allows for the identification of optimal material combinations that strike a balance between weight, cost, and durability.

# 6. RESULTS AND DISCUSSIONS

## 6.1. Key Findings

The simulation results reveal that stress concentrations occur around the habitat's joints and outer surfaces, making these areas critical for reinforcement. Design modifications such as energy-absorbing layers significantly improve the habitat's resilience.
For the total deformation, with a maximum value of 1318.1 MPa, carbon fiber showed the largest deformation, demonstrating its high flexibility. Because of this characteristic, carbon fiber can be utilized to absorb energy in non-load-bearing structures. The maximum deformation of Ti6Al4V and titanium alloy was found to be lower, 70.585 MPa and 82.237 MPa, respectively, indicating their greater stiffness and resistance to external forces. These alloys are more suited for applications requiring load bearing in lunar domes.

| **Total Deformation (mm)** | **Carbon Fiber** | **Ti-6Al-4V** | **Titanium alloy** |
|---|---|---|---|
| Maximum | 1318.1 | 70.585 | 82.237 |
| Average | 154.39 | 8.4077 | 9.7975 |
| Minimum | 0 | 0 | 0 |

Table 1: Total deformation of the materials in millimeters

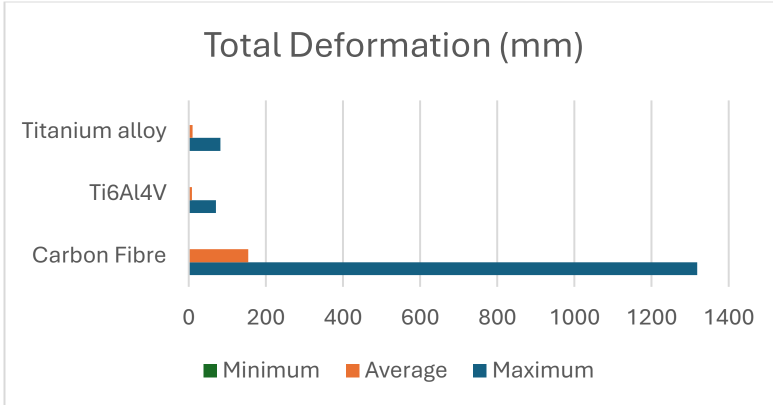



Fig.4: Total deformation of the materials in mm

Under the normal stress distribution, it is studied that carbon fiber demonstrated its resilience to significant impact loads by exhibiting the highest maximum stress value of 6087.2 MPa. Nonetheless, the carbon fiber's negative minimum stress of -25346 MPa and average stress -245.45 MPa imply that it may be subject to strong compressive pressures and may buckle under prolonged stress. More balanced stress values were shown by Ti6Al4V and titanium alloy, with maximum stresses of 2871.1 MPa and 3180.3 MPa, respectively. Both materials were more appropriate for structural stability because of their comparable average stress values 1014.7 MPa for Ti6Al4V and 1026.6 MPa for titanium alloy.

| Normal Stress (MPa) | Carbon fiber | Ti6Al4V | Titanium alloy |
|---|---|---|---|
| Maximum | 6087.2 | 2871.1 | 3180.3 |
| Average | -245.45 | 1014.7 | 1026.6 |
| Minimum | -25346 | -6598.5 | -7072.5 |

Table 2: Normal Stress of the materials in MPa

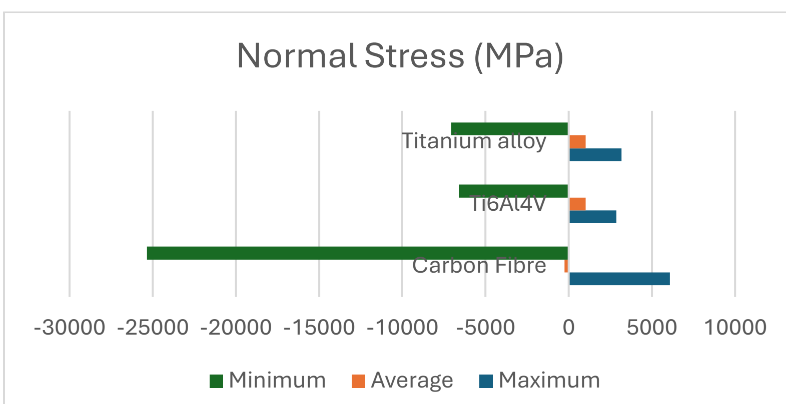



Fig.5 : Normal Stress of the materials in MPa

### 6.2. Design Modification Effectiveness

The integration of protective coatings and energy-absorbing layers reduces the spread of cracks and lowers deformation under impact loading, improving the habitat's structural integrity (Lin, 1985). By adding different materials for reinforcing the structure that has better load carrying capacity and trusses for better load distribution, the design can be optimized and further developed for optimum effectiveness. The material of choice has to be considered upon various factors like radiation resistant, should have slow crack growth rate and many other properties.

# 7. CONCLUSION

This study provides a comprehensive evaluation of lunar habitat structures using ANSYS simulation software. By testing innovative design modifications, the study offers crucial insights into developing resilient lunar habitats. The results of the ANSYS simulations show that titanium alloy, carbon fiber, and Ti-6Al-4V all have unique qualities that can be carefully used to improve the structural integrity of lunar domes. Ti-6Al-4V and titanium alloy give the essential rigidity for internal support structures, while carbon fiber's high flexibility and impact resistance make it appropriate for outside layers. While there are advantages that has to be noted there are also disadvantages that should be taken into account like the weight, material availability and others. Future research will concentrate on refining the application of these materials in multi-layered structures to enhance their resilience against micrometeoroid impacts and additional environmental strains on the Moon.

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