MAE 4291

Reusable Lunar Landing Gear

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1 Senior Design Content Summary Form

1. What are the functions of your design?
   The functions of this reusable lunar lander is to create a delivery payload system that would deliver cargo to the surface of the Moon. Its main purpose is to be a cargo rated lander that can be reused a minimum of ten times with the ability to absorb most of the energy from the impact on the surface of the Moon. The design itself must focus on low complexities in order to reduce maintenance need on the landing gear should it be required. A damper is used within the leg of lander that consists of nitinol columns that buckle in order to absorb the impact of the collision with the surface. This can be thought to be similar to the aluminum that was crushed during the Apollo Lunar Module landing impact.

2. What constraints related to the main functions must you design satisfy?
   The constraints to this design were to be able to land safely on the surface of the Moon by limiting the acceleration experienced by the payload, and be able to repeatedly land a minimum of 12,500 kg. The landing gear therefore must be reusable and encourage simplicity in order minimize risk and lower landing gear maintenance.

3. What are the performance objectives of your design? What must be optimized?
   The performance objectives of this design is to minimize mass for the landing gear, and absorbing the majority of the energy during impact with the lunar surface. The design of the nitinol column must also be optimized in order to calculate a critical buckling load and reduce mass.

4. What alternative design concepts were considered?
   The use of a hydraulic landing gear was considered in the initial stage of the design process. Different second moments of inertia were considered for the nitinol column.

5. What analyses were used to select among these alternative design concepts?
   The hydraulic landing gear was disregarded due to its complexities in nature, difficulty in modeling, and difficulty of maintenance in space. Hydraulics have also been investigated and published in papers regarding its reusability for space applications. Nitinol column design concepts were compared such as a pre-bent column, straight column, and I-beam column. These columns were then compared in ANSYS in a collision which resulted in different buckling forms and modes. A spring shaped column was also considered, but disregarded due to the minimal amount of stiffness it provided. Due

to the properties of nitinol, the pre-bent column was chosen in order to control the direction and amount of the strain experienced during buckling.

6. Which concepts or skills learned in your coursework were applied to the design?
   CS 1112: MATLAB
   MAE 2020, MAE 3270, MAE 3280: Solids Curriculum. Second moment of inertia, column buckling, and material analysis. ANSYS Finite Element Analysis
   MAE 4160: Spacecraft Technology and Systems Architecture. Constraints and requirements.

   Concepts and skills not learned in coursework:
   ANSYS FEA - Explicit/Collision Dynamics. Dynamic Column Buckling. Soil Impact Simulation.

7. What format did your design take?
   The design consisted of CAD drawings of the different components of the lander. These were were then imported into ANSYS for impact analysis with lunar regolith.

8. Briefly evaluate your design, relative to its functions, constraints, and objectives.
   The design was optimized to choose a column with an area moment of inertia that would allow for the nitinol material to buckle with a significant impact. The column buckled as expected during the landing on the lunar surface, and plates between the dampers demonstrated a decrease in velocity. Although the damper was effective, the entire design is inconclusive as the maximum payload acceleration was not able to be determined due to the small simulation time frame of 0.01 s.

9. Describe each student's role in the design project - Anthony Aguilar:
   Researched reusable landing gear designs.
   Researched nitinol material properties.
   Bought and tested nitinol specimen.
   Researched lunar regolith properties.
   Researched lunar landing gear impacts.
   Learned ANSYS's explicit dynamics functionality. (Meshing, Material Property Assignments, Contact Conditions)

2 Introduction

The lunar and cis-lunar space realm is becoming a more focused area of exploration as the industry seeks to commercialize space, and use the Moon as a "stepping stone" to Mars. This includes landing on the surface of the Moon in order to deliver a variety of payloads. In order to increase sustainability and decrease overall mission costs, it would be ideal to create a reusable lunar lander (RLL) that is able to repeatably land on the Moon. An RLL would require a landing subsystem that should encourage low complexity in order to reduce risk, but also encourage the number of times it can be reused. A complex design causes more uncertainties and risk within the system due the increased number in parts and complex simulations. Therefore, this design explores a proof-of-concept the uses a shape-memory alloy, nitinol, as a form of damper in a landing gear subsystem.

3 Design Requirements

Listed below are the design requirements that were considered during the development of the landing gear proof-of-concept. The full development of a landing gear subsystem would require an increased number of requirements that would involve thermal, mass, structural, and electrical constraints.

1. The landing gear shall provide sufficient energy-absorption capability and prevent a maximum acceleration experienced of 10g.
2. The lander shall land with a vertical velocity less than 2.5 m/s.
3. The lander shall be rated for cargo transportation.
4. The lander shall support a payload of 12,500 kg.
5. The lander shall land on the lunar surface multiple times.

4 Trade Studies

4.1 Hydraulics

One of the initial topics that was researched was the usage of hydraulics within the landing gear. This is due to the common use of hydraulics within the aviation industry and its effective energy dissipation. There have been several papers that have investigated the potential usage and landing performance of potential spacecraft which demonstrate its feasibility and effectiveness [2][3]. Yet, there may be other concerns when considering hydraulics such cavitation, thermal control, and excess maintenance. Thus, other novel forms of dampening were considered in order to explore new solutions, and determine if simpler methods existed.

4.2 Nitinol

The use of nitinol, or Nickel Titanium, can be used as an advantage compared to other reusable mechanisms due to its simplicity. Nitinol is a metal alloy that is composed of of nickel and titanium that have varying specimens with small variations such as Nitinol 55 or Nitinol 60. A nitinol specimen has the ability to return to its original shape after being deformed by heating the specimen above its transformation temperature. The specimen can therefore be in two states called the martensite stage, when it is below its transformation temperature, or austenite stage when it is above the transformation temperature, Fig.(2). This special property allows for work to be performed on a specimen in order to dissipate energy. For the purpose of this design, it was assumed that nitinol has a Young's modulus of 30 GPa, with a varying tangent modulus after 0.01 strain, and a Poisson's ratio of 0.33 [7].

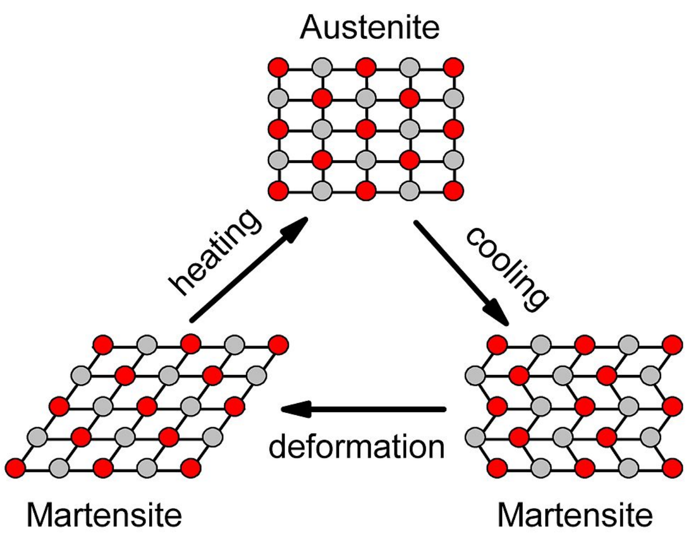

Figure 1: Apollo Lunar Module dimensions with extended landing gear. [4]

Nitinol also has its drawbacks in which it has a maximum amount of strain it is able to experience for its pseudoelastic property. After the first cycle between the martensite and austenite stage, the specimen begins to experience permanent plastic deformation that is unable to return to its original shape, even after passing the transformation temperature Fig.(2). A potential solution to this problem is to repeatedly submit the specimen to similar loads in order to "train" the specimen to a new shape. After a repeated number of cycles, the nitinol will begin to converge to a new shape, Fig.(3).This will then limit the amount of permanent deformations experienced for future loads [5] [6]. It is also encouraged that the deformation be limited in order to avoid potential fractures that may occur due to high stresses such as in Fig.(4).

Figure 2: Nitinol specimen transforming into its austenite stage and returning to its original shape. Since this specimen underwent large deformations, it did not return to its complete original shape.

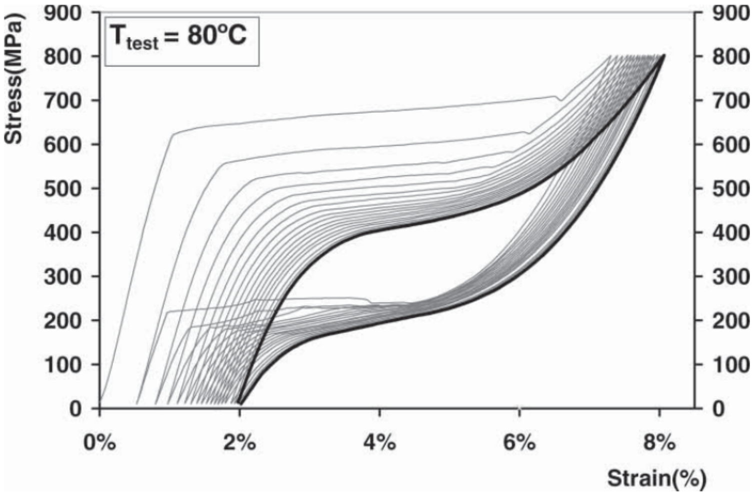

Figure 3: Nitinol specimen that underwent training via isothermal cycling. The last cycle is bolded. [6]

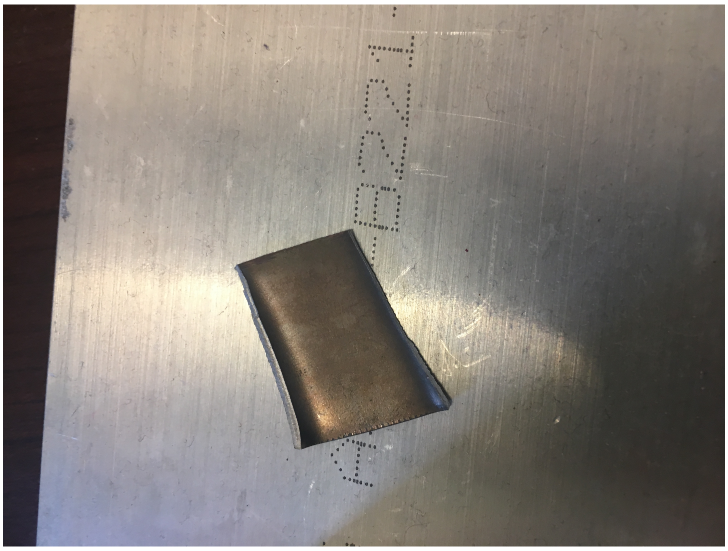

Figure 4: Nitinol also experiences fractures if it experiences large deformations and stresses.

5 Design Decisions

Inspiration was drawn from Apollo's method of dampening the lunar module (LM) by deforming a metal alloy to absorb the impact. The lunar module's crushable honeycomb aluminum is unable to regain its original shape after being used, and thus cannot be reused for future missions. Nitinol's ability to become "un-deformed" may allow the use of reusing a landing system that contains a deformable nitinol specimen. After consideration of nitinol's drawbacks, a list of design parameters were considered in the development of a damper in Table 2. Due to nitinol's ability to fracture, designing a nitinol replica of the honeycomb aluminum used in the LM would not function in this situation. Therefore, the concept of a buckling column was considered. During the collision, the column would begin to buckle as the force of the impact would go past its critical load.

Design Parameter	Variable given
Column shape	Straight, Pre-bent, Spring
Column height	L
Cross section	A, I
Number of columns per damper	n
Critical Load	P_{cr}
Number of dampers per leg	i
Height of lander leg	H

Table 1: Design parameters for damper and landing gear.

The RLL requirements were also based on some of the requirements that were implemented in the Apollo space program [1]. This is due to the similarity of potential future missions, such as landing humans on the Moon, and the its success in landing on the surface. Therefore, a number of design decisions were based on the Apollo LM, Fig.(5), that resulted in similar dimensions for the RLL.

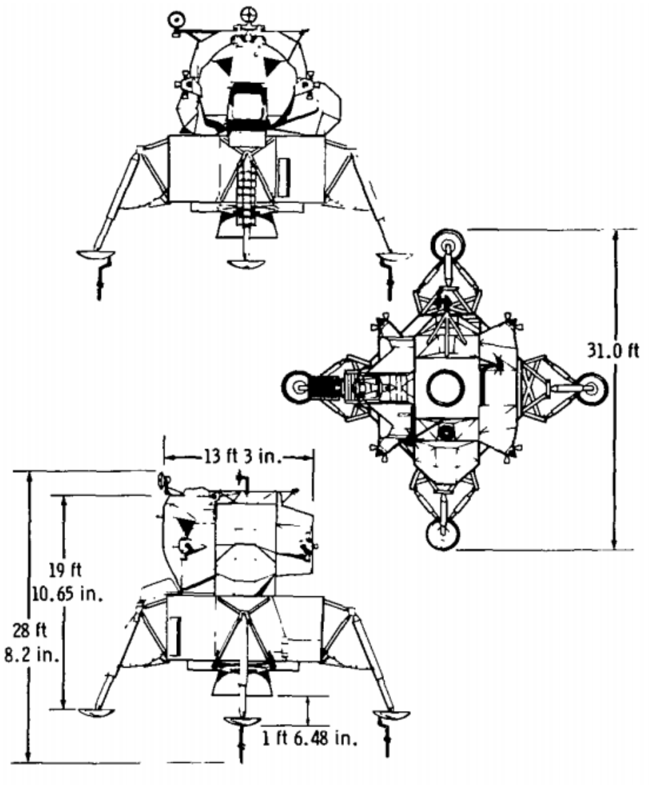

Figure 5: Apollo Lunar Module's dimensions. [1]

5.1 Damper Column

Different column shapes were considered for the development of the damper. Initially a straight column was modeled and tested in ANSYS. These results demonstrated that the column develops multiple bends during the impact, which is not favorable since the nitinol specimen would experience a fracture, Fig.(6). Thus, it was considered to create a "pre-bent" nitinol column that would allow for the column to buckle in a pre-determined manner. Simulations in ANSYS determined that this concept was feasible as the column underwent buckling as predicted in a $n = 1$ mode shape, Fig.(7). During these simulations, a rectangular cross-sectional area was chosen for the column. When then changed to an I-shaped cross section, the simulation resulted in buckling deformations that caused the column to move sideways rather than the direction, Fig.(8). Spring columns were also considered, but its stiffness property was not considered sufficient for the absorption of the impact energy.

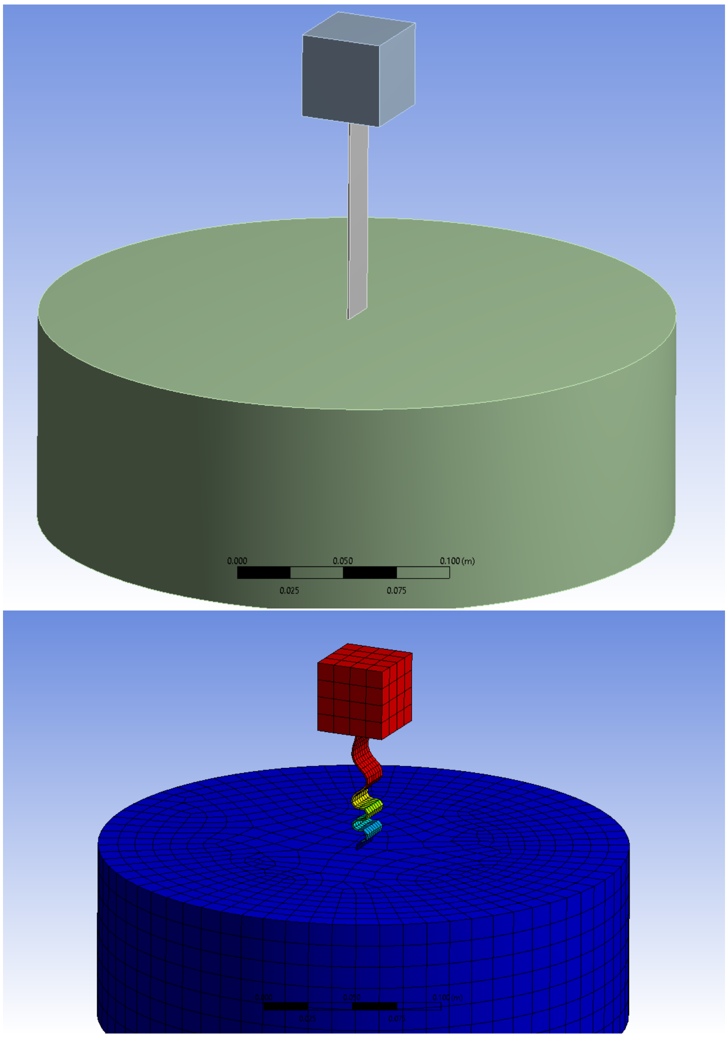

Figure 6: Straight nitinol column buckling into multiple deformations.

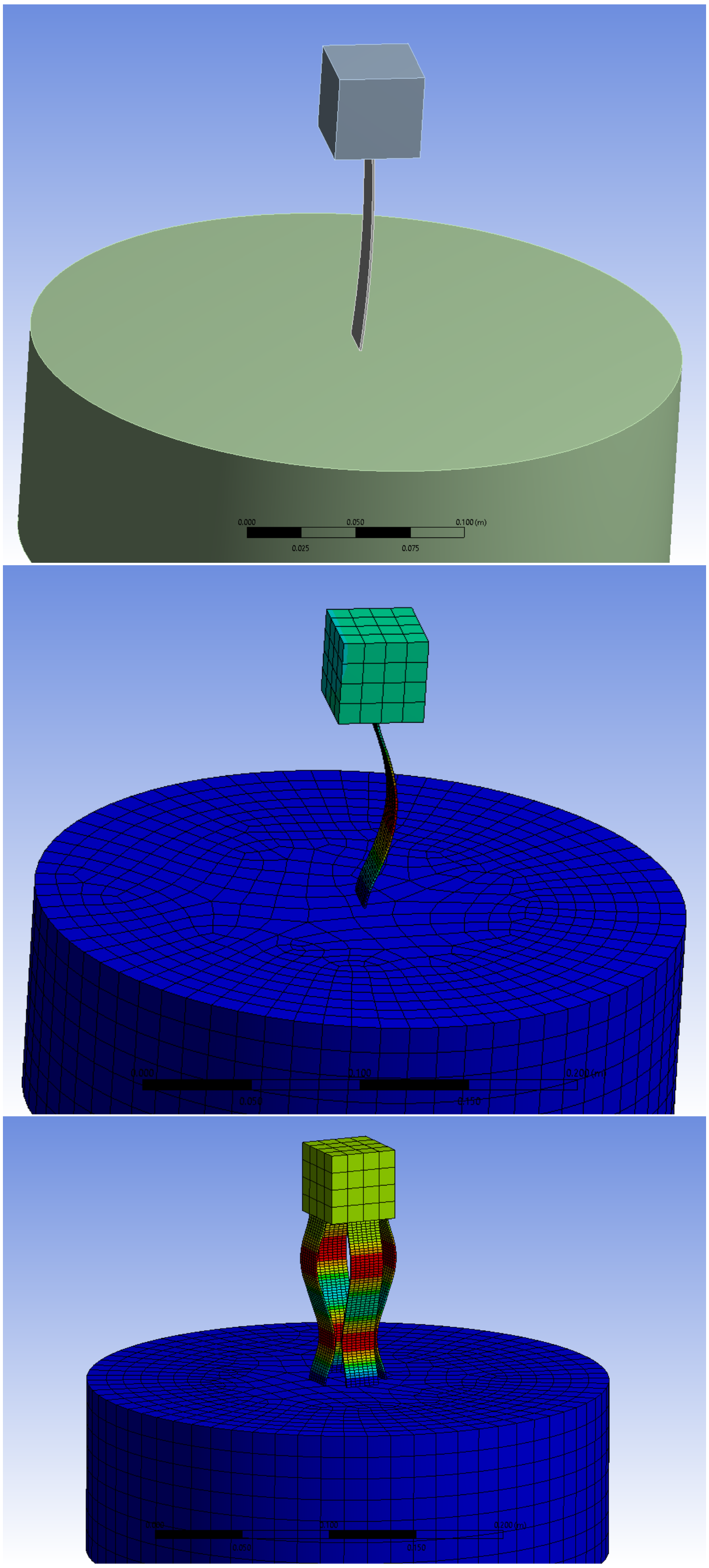

Figure 7: Pre-bent nitinol columns that buckle into the preferred mode of $n = 1$ or $n = 2$. The $n = 2$ mode of two pre-bent points did not result an increase in the deceleration experienced and was not pursued.

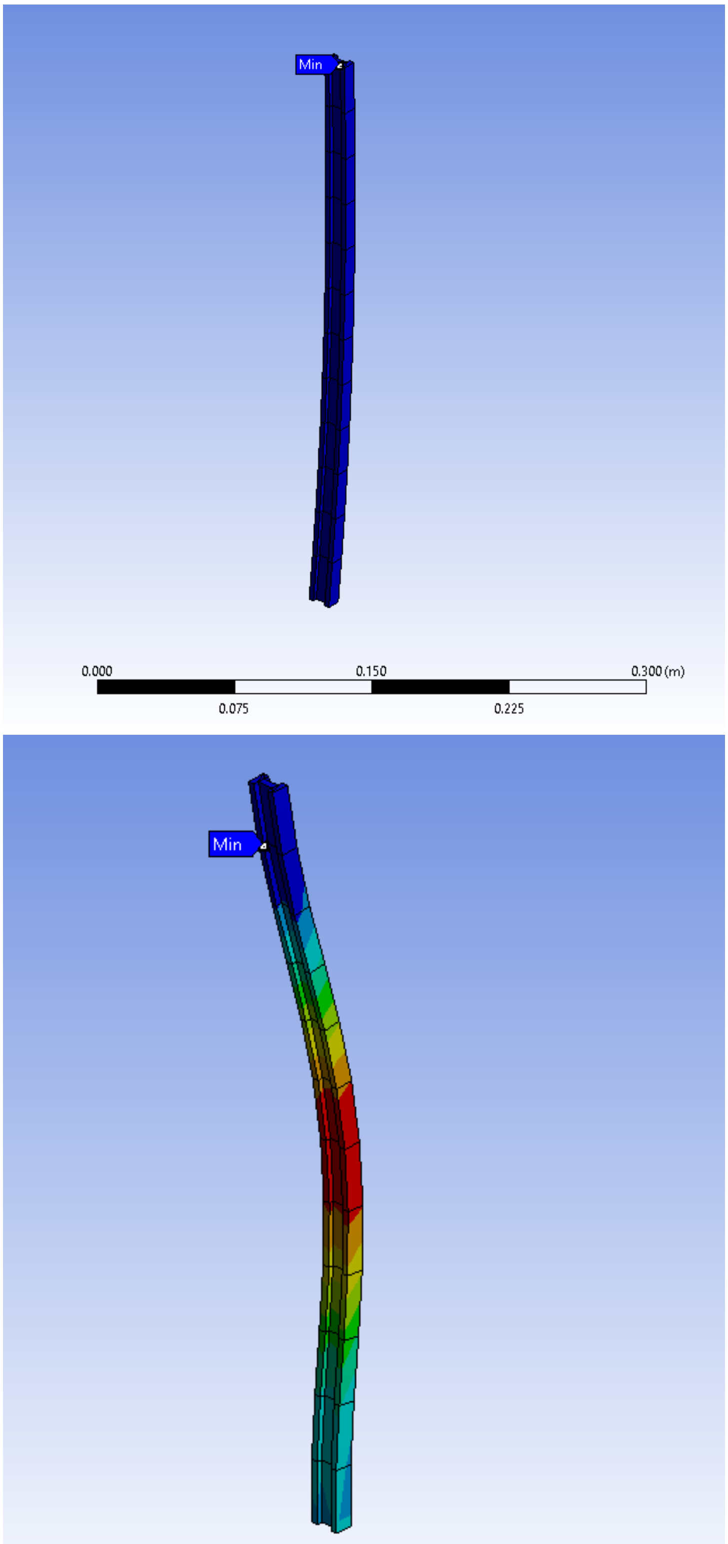

Figure 8: Pre-bent I-shape cross section resulted in a sideways deformation in an unwanted direction.

5.2 MATLAB

Using the design parameters (2) that were previously generated, and using the formula for P_{cr}, the following expressions were formed in order to determine the relationships between the parameters. This would then aid in determining an optimal design choice. It was assumed that the mass of the entire lander would be 15,625 kg with a vertical landing velocity of 2.50 m/s^2 that results in a kinetic energy (η) of approximately 48.8 kJ.

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}, K = 0.5, I = \frac{1}{12}b^4 \tag{1}$$

$$P_{cr} = \frac{\pi^2 E b^4}{3L^2} \tag{2}$$

$$P_{cr} = \frac{P_{\text{impact}}}{n} \tag{3}$$

$$H \approx L * i \tag{4}$$

$$\text{Total KE} = \text{constant} = \eta \approx i(P_{\text{impact}} * L) \tag{5}$$

$$P_{\text{impact}} \approx \frac{\eta}{i * L} \tag{6}$$

$$b = \frac{3L^2\eta}{n\pi^2 EH} \tag{7}$$

$$i = \eta\frac{Eb^2}{6nLP_{cr}^2} \tag{8}$$

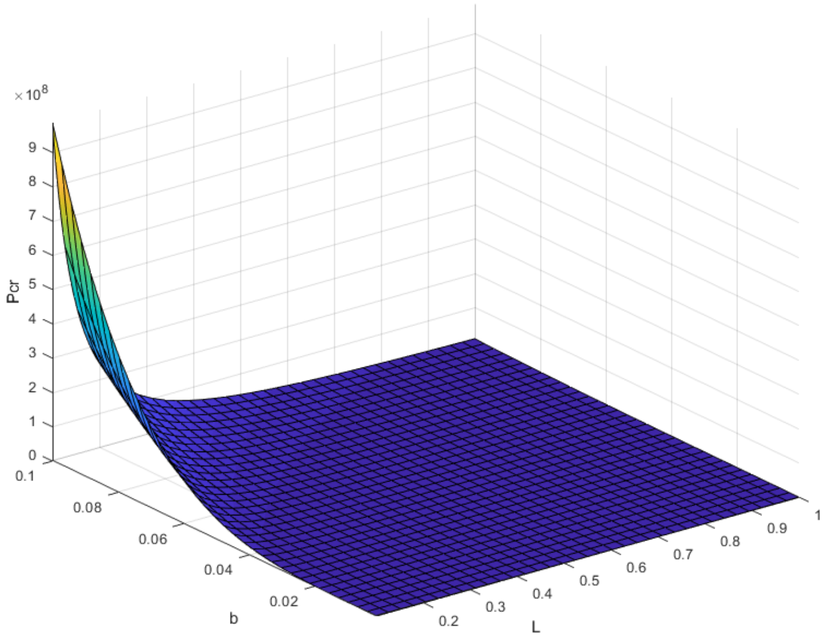

Figure 9: Surface graph comparing the critical load of the column with its the length of its square cross section and length of the column.

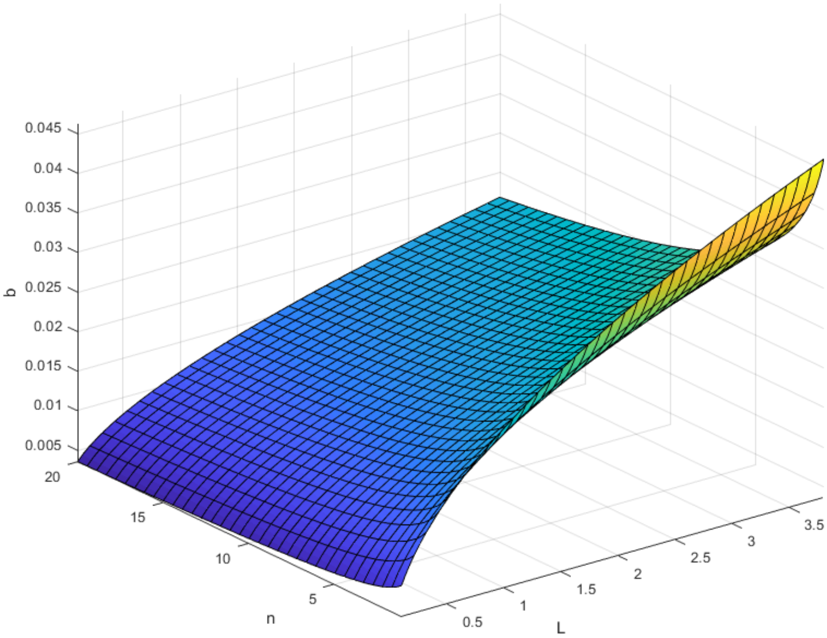

Figure 10: Surface graph comparing the length of its square cross section, number of columns per damper, and length of the column.

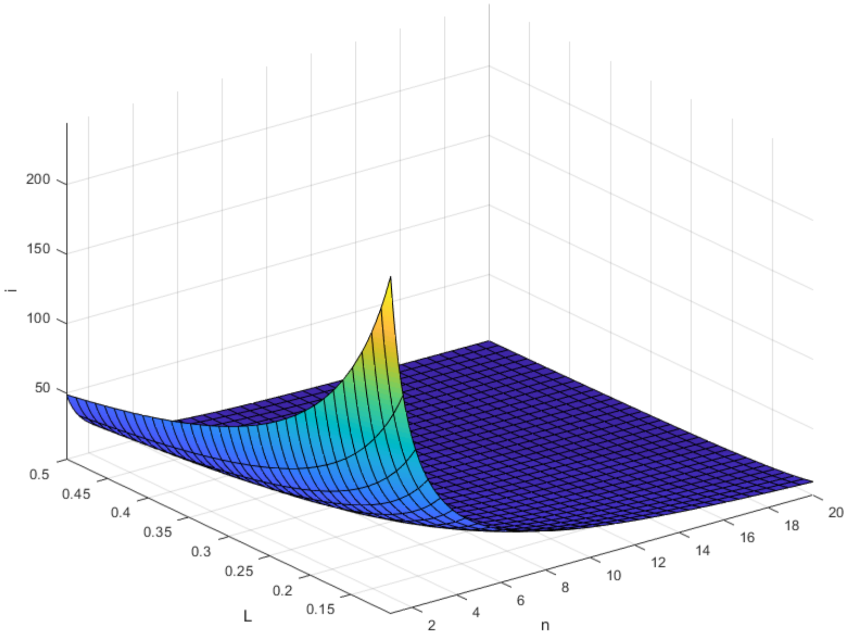

Figure 11: Surface graph comparing number of dampers per leg, length of column, and number of columns per damper.

6 Findings and Future Improvements

The chosen design input for the lander were:

Design Parameter	Decision Made
Column shape	mode n = 1, Pre-Bent
Column height	$L = 0.341$ m
Cross section	Square cross section, $b = 20$ mm
Number of columns per damper	$n = 6$
Critical Load	$P_{cr} = 135.8$ kN
Number of dampers per leg	$i = 10$
Height of lander leg	$H \approx 3.8m$
Lunar Regolith Bulk Modulus	4.5 MPa [9]

Table 2: Design decisions chosen for the design parameters and lunar regolith's bulk modulus.

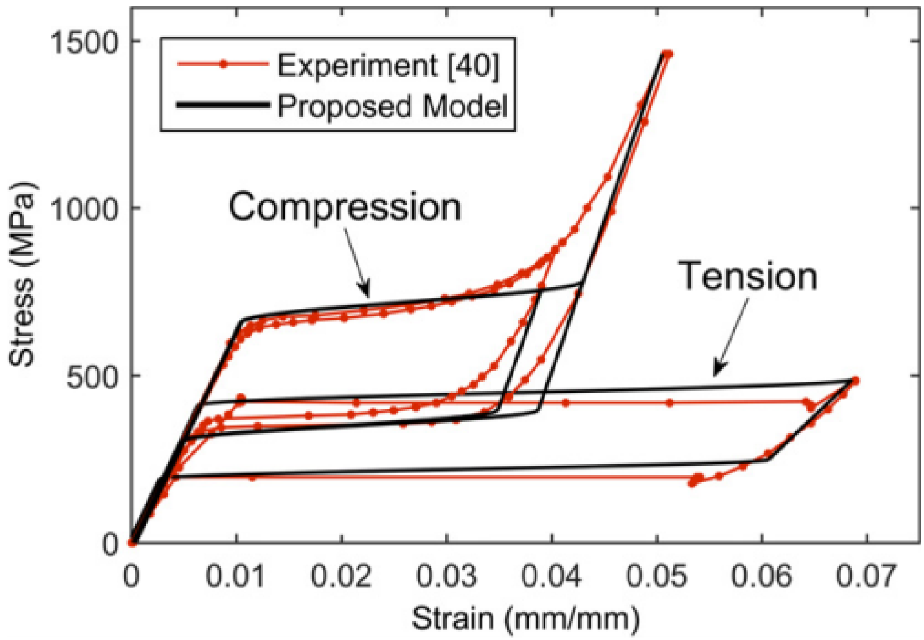

Figure 12: The nitinol stress-strain curve is non-linear and begins to increase as it passes a certain point of deformation. This advantageous to a nitinol column since its reactive force will increase as it continues to deform. [8]

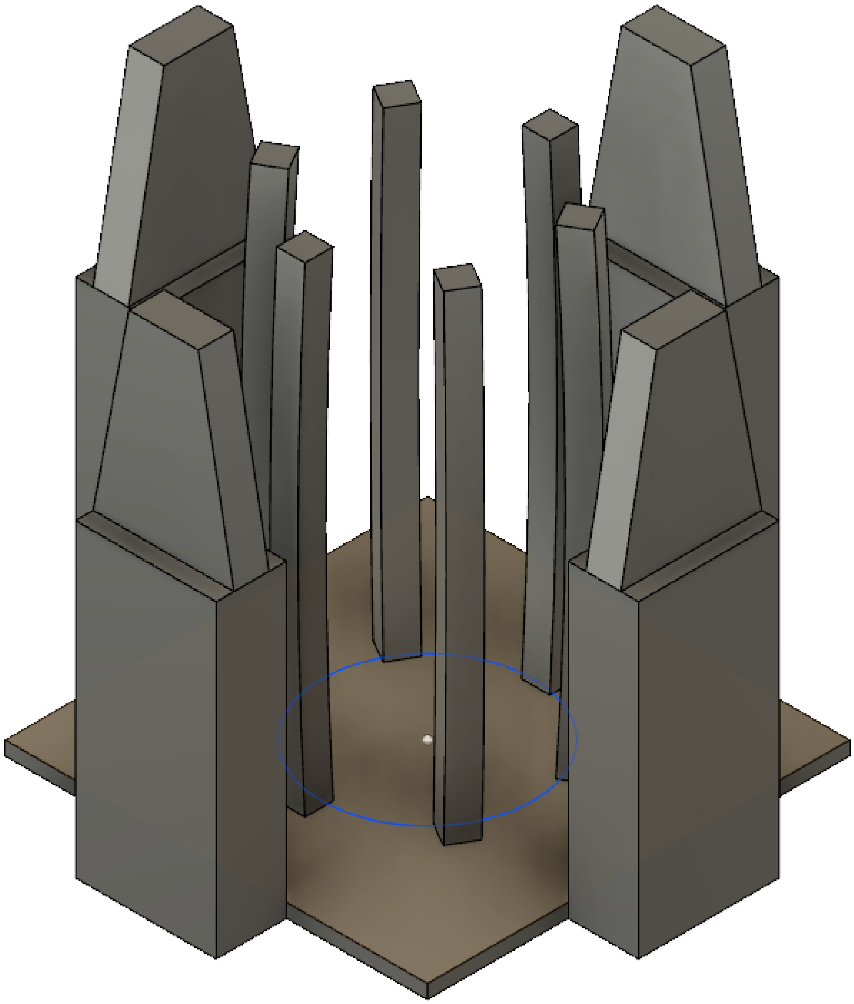

Figure 13: Damper unit assembly that makes up a landing gear leg. This damper contains six nitinol columns and four "telescope" holding structures in order to limit the amount of deformation.

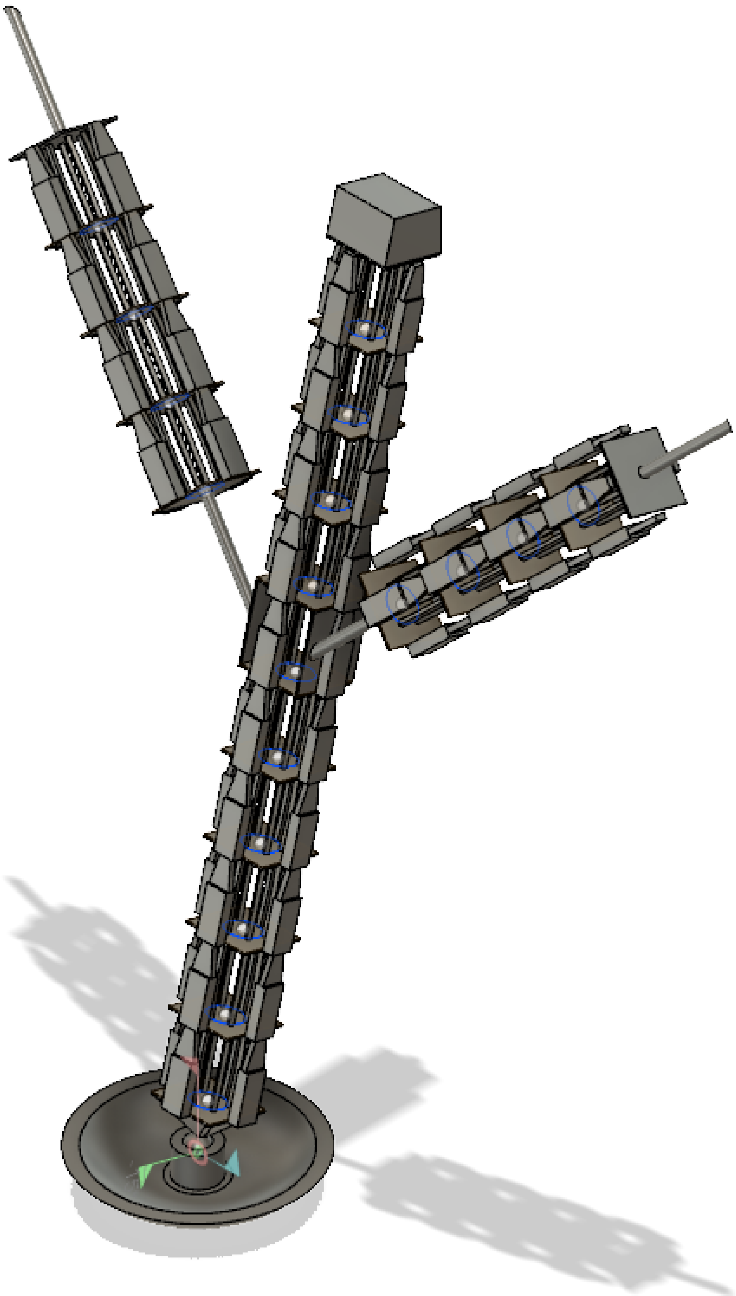

Figure 14: The leg assembly consist of ten dampers along the main structure with two secondary struts in order to absorb the kinetic energy from any horizontal velocities.

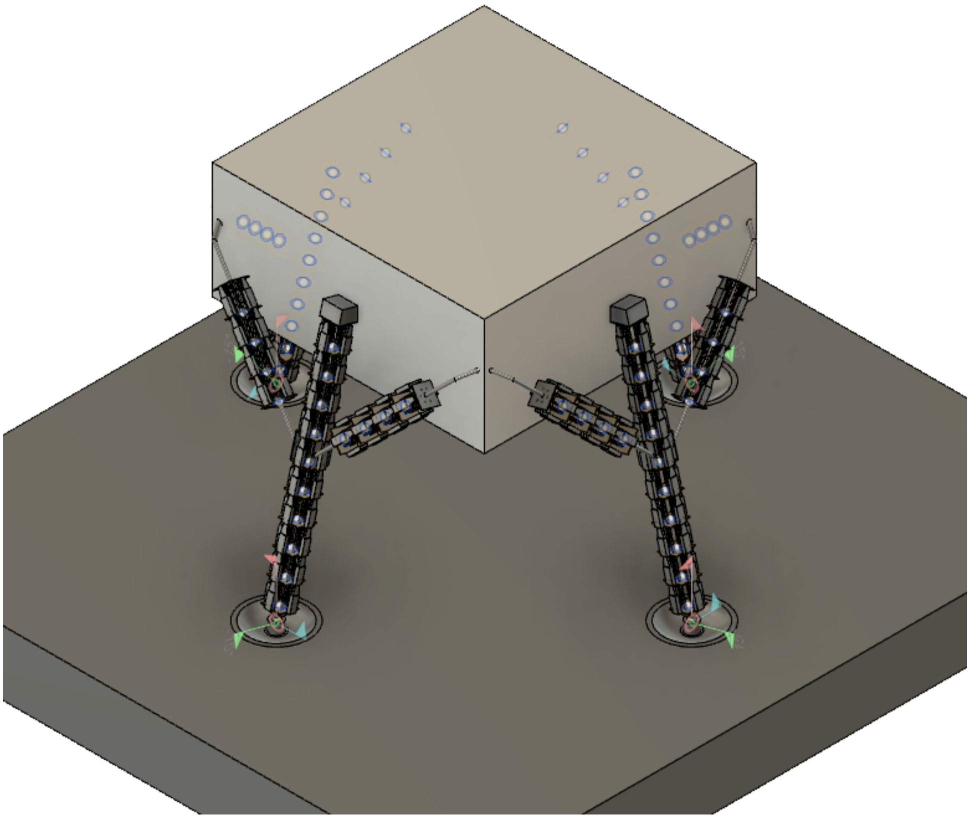

Figure 15: RLL assembly that consists of four landing legs.

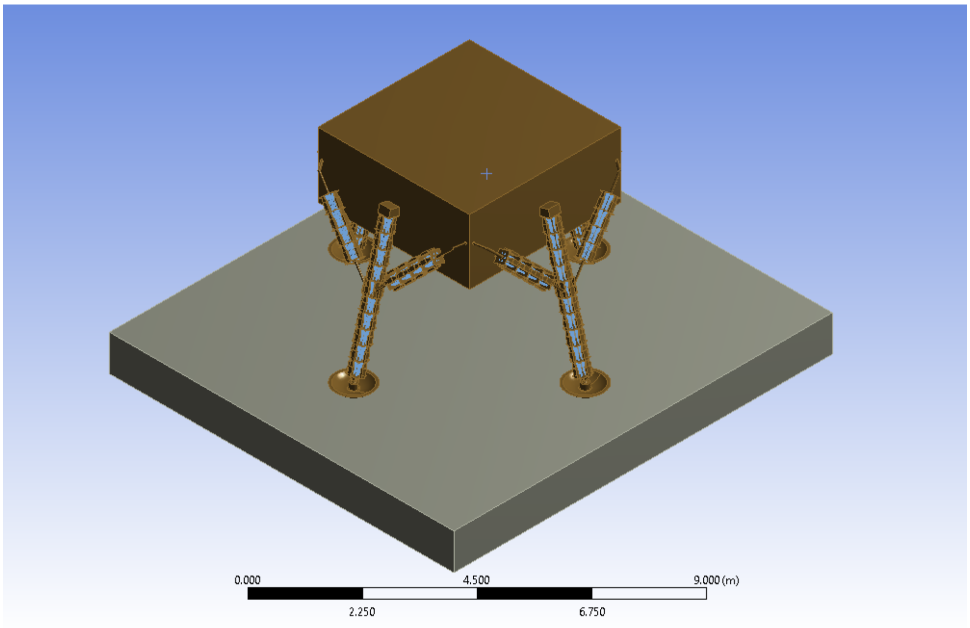

Figure 16: RLL assembly imported and set up in ANSYS.

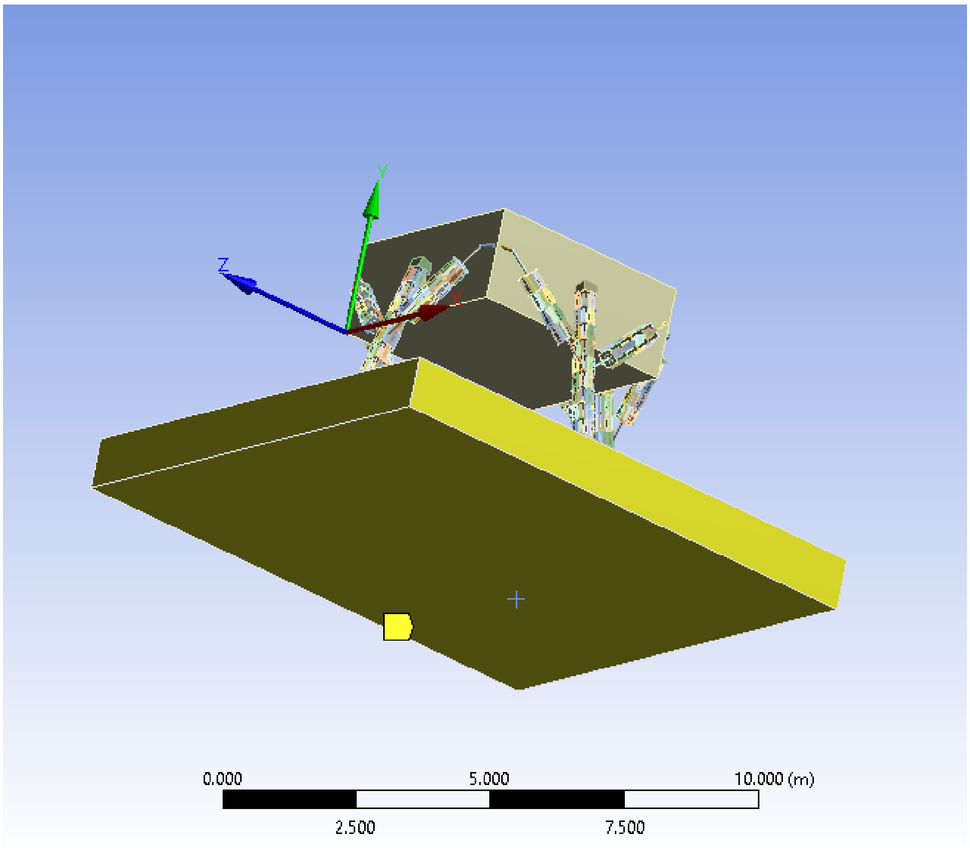

Figure 17: Displacement conditions of the exterior of the lunar regolith block is set to zero.

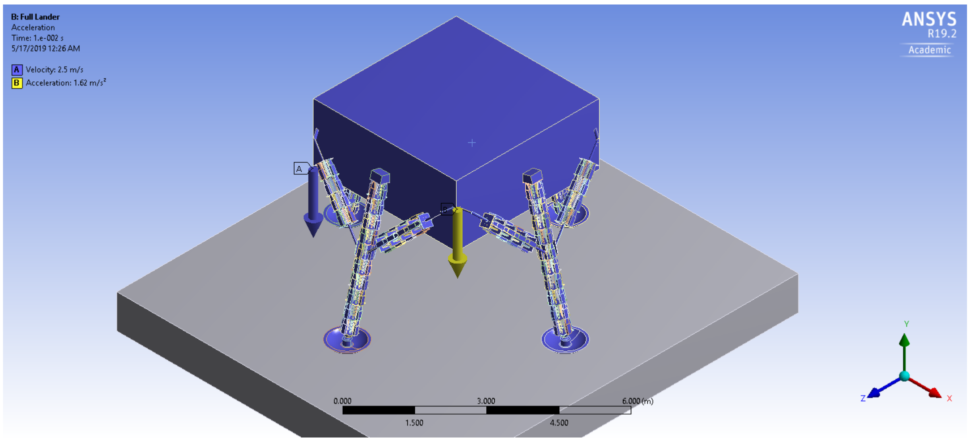

Figure 18: Velocity of -2.5 m/s and lunar acceleration of -1.62 m/s^2 is set to the entire lander.

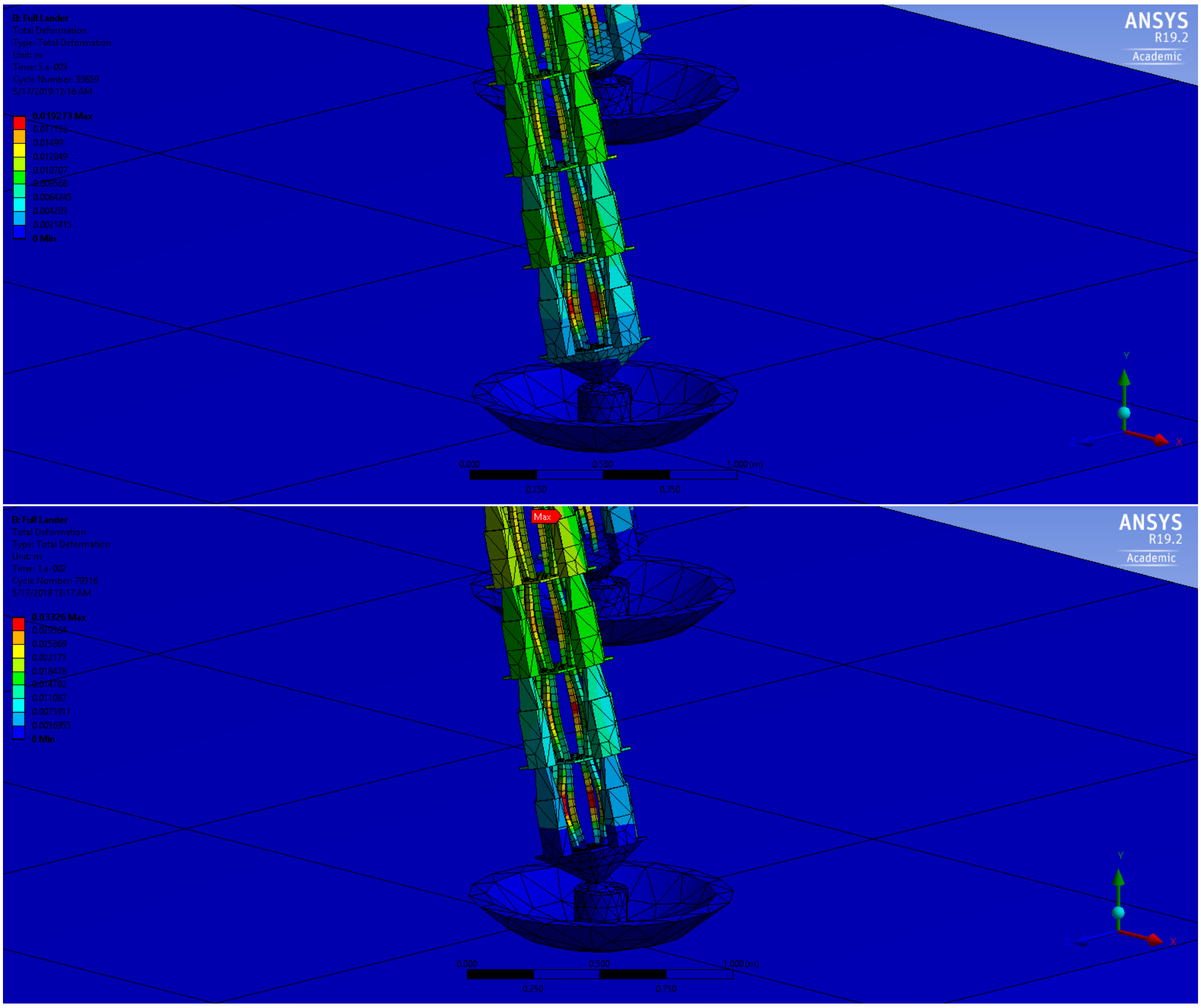

Figure 19: Deformations occurring near the footpad of the lander at 5e-3 s and 1e-2 s.

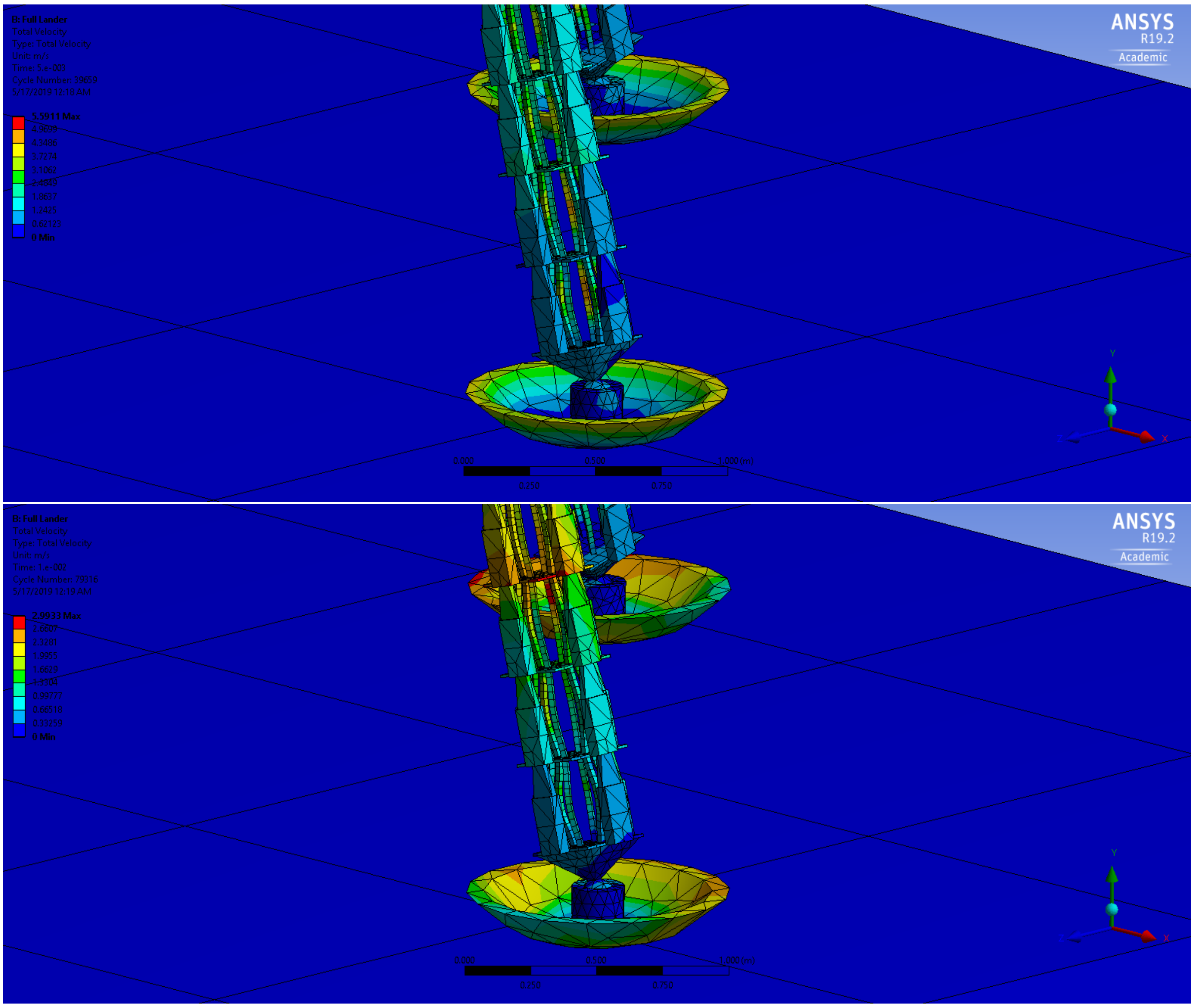

Figure 20: Velocity occurring near the footpad of the lander at 5e-3 s and 1e-2 s.

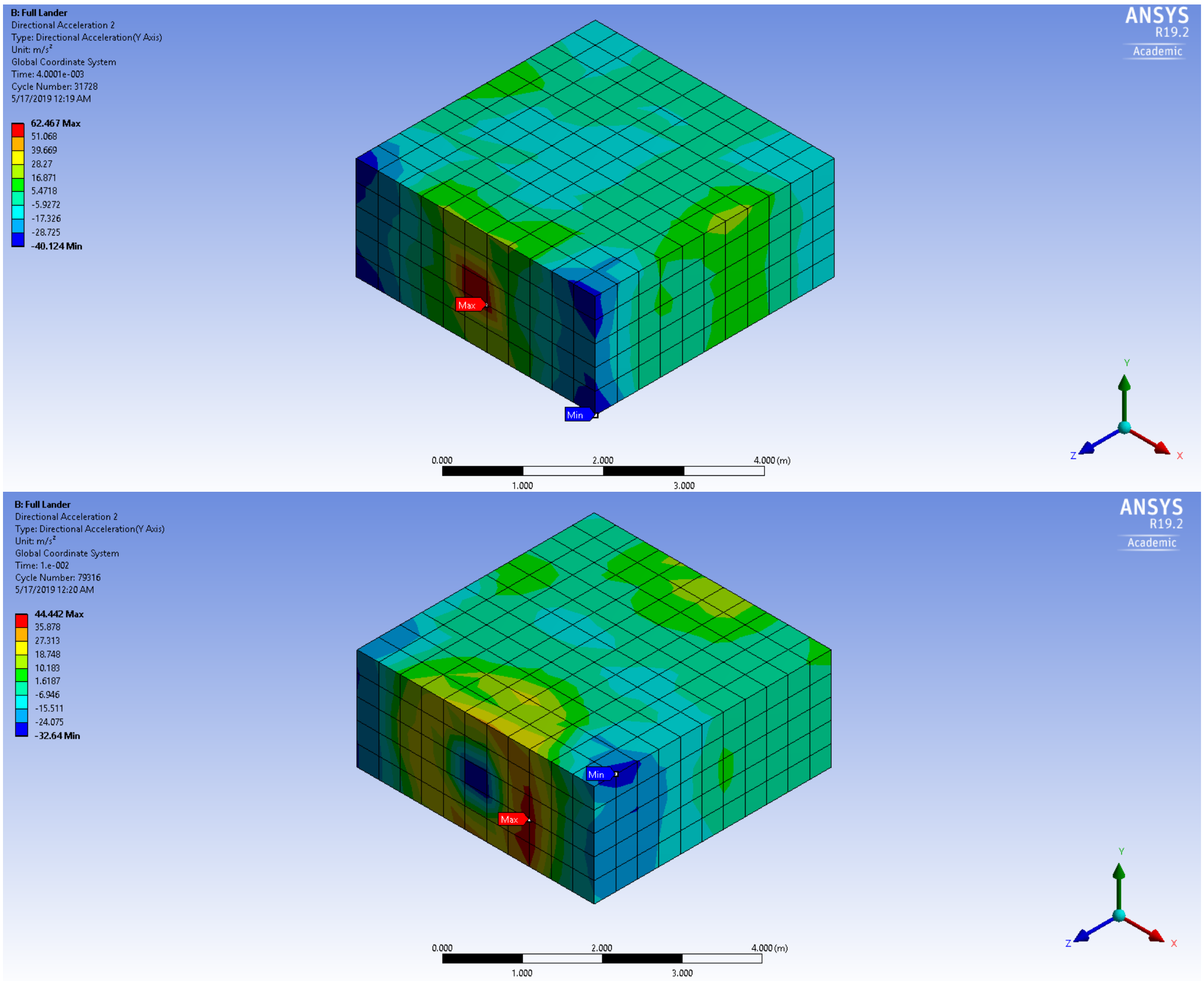

Figure 21: Accelerations experienced by the payload at 4e-3 s and 1e-2 s with an acceleration experienced of 62.467 m/s^2 and 44.442 m/s^2 respectively.

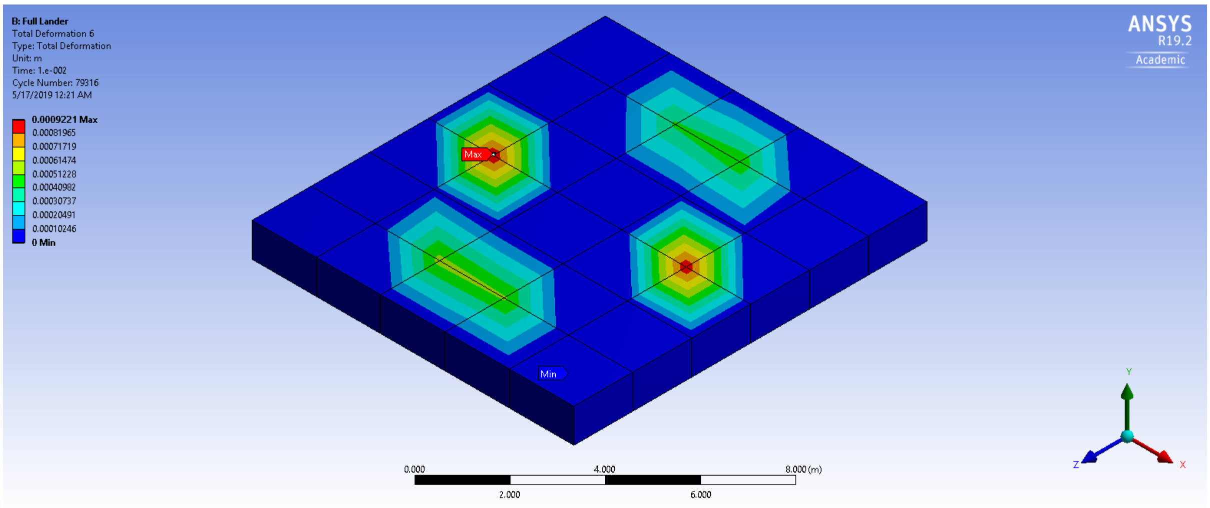

Figure 22: Deformation experienced by the lunar regolith at 1e-2 s.

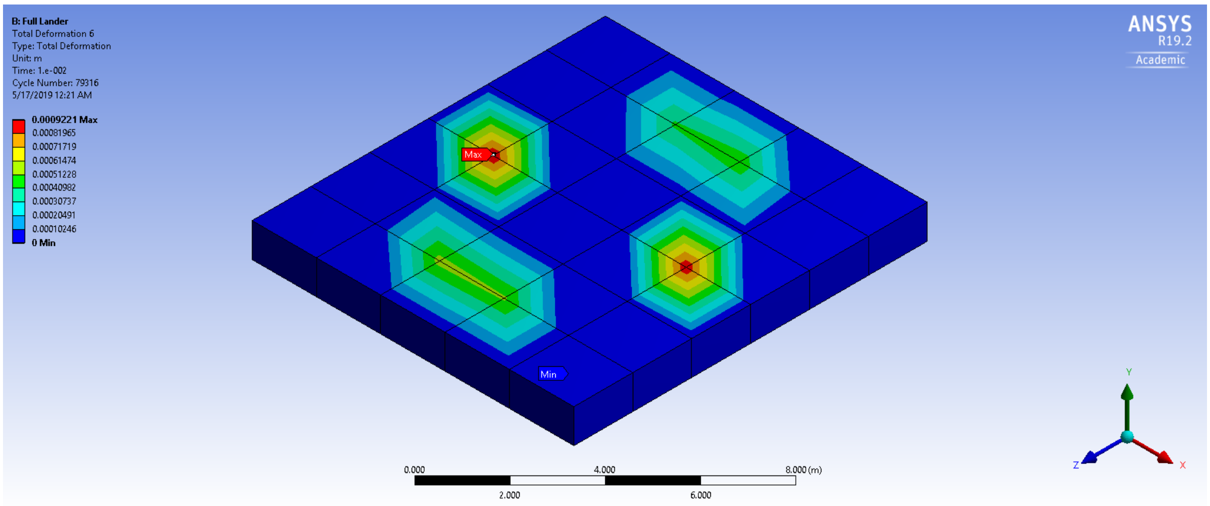

Figure 23: Deformation experienced by the lunar regolith at 1e-2 s.

Due to the small amount of time simulated of 0.01 seconds, the results of the ANSYS simulation are inconclusive. Within this time frame, it is unclear whether the damper has the ability to mitigate shocks during landing, or if the payload has experienced its maximum acceleration. Since explicit dynamics is computationally intensive, a longer simulation to achieve 1 second would have taken several days of run time for this setup. The simulation does provide an insight in the manner in which the buckling occurs within the damper of lander. The damper demonstrated that it absorbs the impact energy, since the velocities of the plate between the dampers begin to decrease as the nitinol columns continue to buckle, Fig.(25). Future methods to improve this design is to perform the simulation on a more powerful computer in order to reduce the computational time and increase the number of design iterations. It would also be useful to first determine the energy absorption characteristics of a nitinol column before moving on to the entire damper. Any mathematical methods that can be used prior to the ANSYS simulation would aid in determining the strains experienced during the impact. It would also be a point of comparison in order to validate the results of the ANSYS simulation.

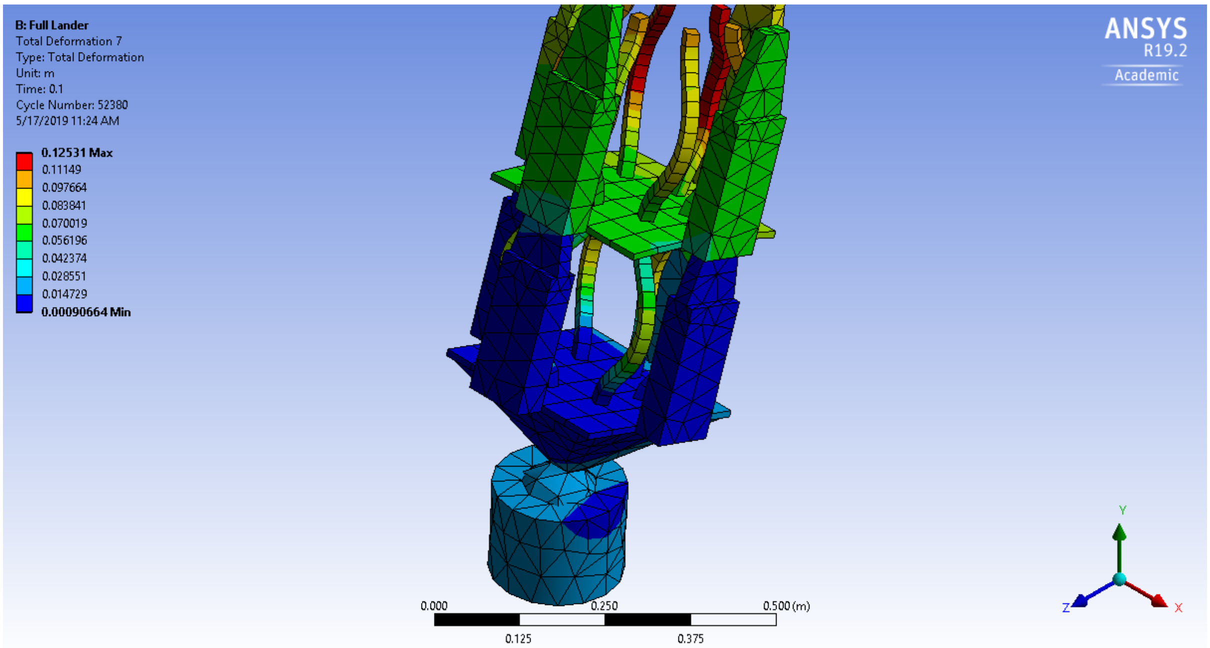

Figure 24: Damper deformation that was tested in ANSYS simulation that consisted of just the leg assembly and lunar regolith for 0.1 s.

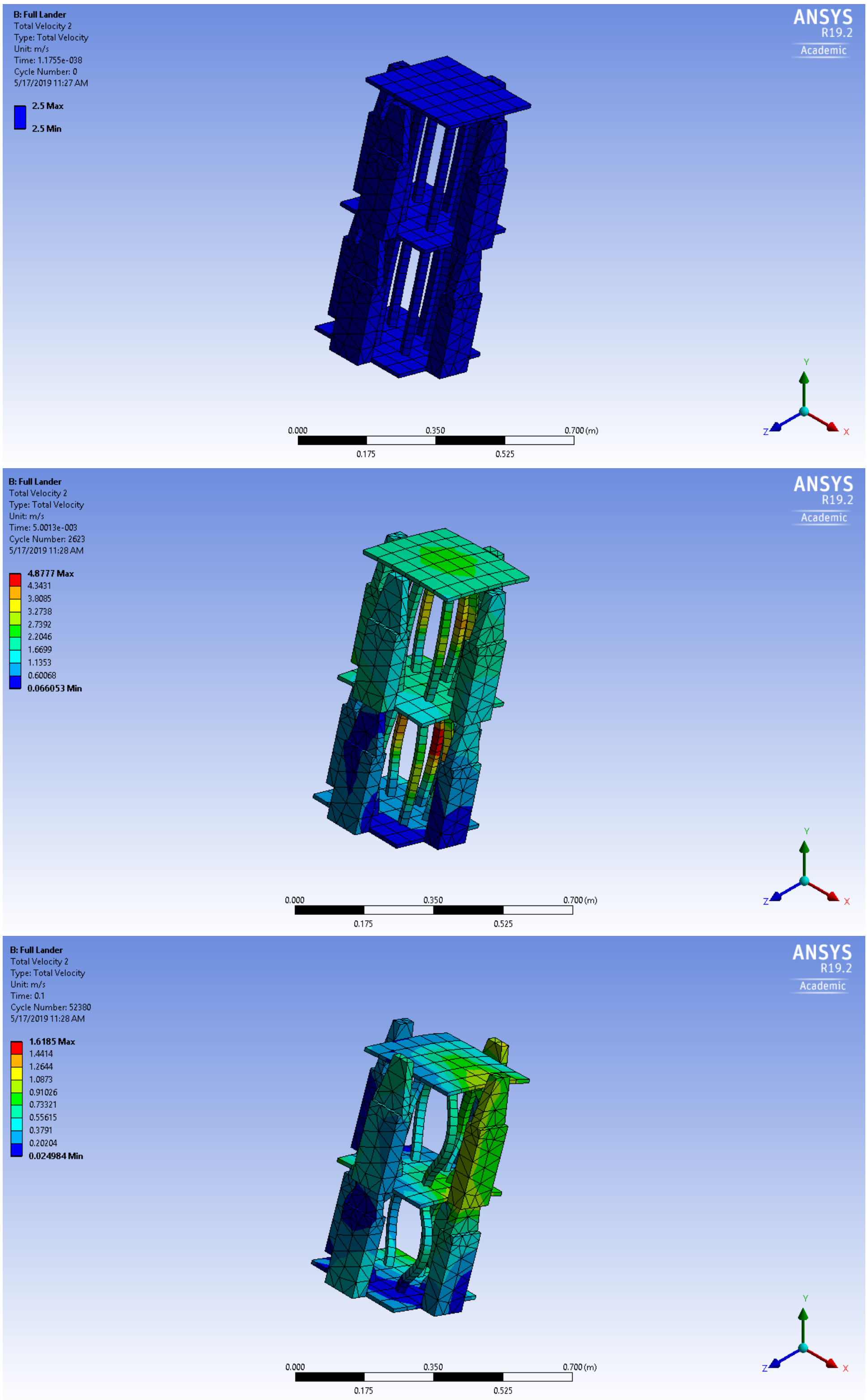

Figure 25: Velocities experienced during impact begin to decrease as the column continues to buckle which verify that the dampers are absorbing the impact energy.

References

[1] William F. Rogers. *Apollo Experience Report - Lunar Module Landing Gear Subsystem.* Manned Spacecraft Center. Houston, Texas. June 1972.

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