Structural design and analysis of a launcher payload system under high inertial loading.

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Abstract

This paper presents a preliminary design and analysis for a sample return mission to the lunar South Pole aiming to bring lunar volatiles back to Earth, an engineering facet of high scientific interest nowadays. The objectives of the current work are focussed on the configuration design, manufacture and assembly of an entire spacecraft composite and conduct static/dynamic load analysis, impact and shock studies, earth launch and re-entry, moon soft landing and modal and frequency response analysis that are representative of the respective mission phases and operational modes. Intensive computational work is done for 'Phase A' of the overall project planning and implementation process, to articulate feasibility studies for such a mission. Finite Element Analysis for each sub-system operational mode during all mission phases were undertaken along with CFD work to determine dynamic failure modes. The task was conducted using design tools of CREO and CATIA while the dynamic/modal/thermal response analyses were carried out in ANSYS along with NASTRAN/PATRAN too. The overall spacecraft composite mass for such a mission considered is 2.5 metric tonnes and a Delta IV medium launch vehicle is selected for the payload fairing attachments and launch load studies. The inertial load experienced during the launch phase is 6.0g, which includes a margin of 10%. The maximum equivalent von-mises stress in the truss structure of the spacecraft composite is obtained to be 530 MPa, while the aluminium alloy 7XXX that is selected as the material has a maximum yield stress allowance of 625 MPa. The total deformation experienced by the composite shows 3.2 mm maximum value under the extreme loading. The modal analysis aimed at conducting a frequency response of the entire composite showed that the first lateral and longitudinal modes were not excited by the launcher. The lower limits for the established system were 8 and 25 Hz (for lateral and longitudinal frequencies respectively) while the actual computed values were 47.3 and 40.7 Hz respectively. The structure experiences a total lateral and longitudinal deformation of 9.7 and 21.7 cm respectively under the most exaggerated launch conditions. Criticalities for the design and analysis of the structural components included manufacture and assembly of the appendages to the main composite that have multiple translational/rotational degrees of freedom with respect to fixed contact points. The solar panels, lander legs, external propulsion tanks, externally fixed RTG for power supply, earth-relay antennas, returning rocket launch system are all the additional semi-fixed fittings that were integrated together with the rest of the system and contributed as technical drivers of the analysis input variables.

1. Introduction

1.1 Project Requirements

One of the primary design concerns during background research was the effect of the lunar environment on structures. It is known that radiation and extreme temperatures pose a serious potential damage to structural materials. The first project requirement was the development of substructure designs that satisfy the spatial and equipment layout concepts. Substructures include vertical supports, horizontal supports, and structural connections. During the design of the substructures, several construction materials were investigated. The next requirement was development of an assembly plan for constructing the substructures.

1.2 Design Criteria

To satisfy the project requirements, several design criteria for evaluating alternate designs were identified and weighed.

1.3 Material Considerations

Material mass and volume must be minimized to reduce transportation costs. Material packages must fit within the cargo areas of existing transporting vehicle. The material must also withstand structural loading without yielding in tension, compression, or shear. In the deep space conditions, it must withstand exposure to radiation, plasma and magnetic belts and extreme temperature fluctuations.

1.4 Structural Considerations

The structure must be designed to provide a safety factor on load bearing members and at the same time be compatible to various geometries and sizes. The support structures should accommodate all piping and ventilation systems (EPS, TPS etc). For instance, the structure should provide adequate space and strength for the placement of ventilation ducts and radiators to avoid excess heat accumulation in any sub-assembly. The design must provide structural redundancy in case of collapse too. Each level of the structure must be able to support 1 kPa load for landing on Moon, which corresponds to an equivalent vertical drop height computed based on the mission analysis. The platforms must accommodate various equipment arrangements too.

1.5 Maintenance Considerations

The design of the internal support structure system was selected with emphasis on maximizing use of available space, minimizing structural weight, and minimizing structure assembly time.

1.6 Support structures

Support structures must support all static and dynamic loads placed on the structure. To fulfil the design criteria for support structures, the support structures have been grouped into three categories, including vertical supports, horizontal supports, and structural connections. Each performs its restricted localised function and critical load bearing parts are identified by their free body analysis.

1.7 Manufacturing

One of the core concepts of *Phase A* feasibility studies is that the conceived design is done for both manufacture and assembly. For this purpose, and keeping in mind that the transfer from Phase A to Phase B involves rigorous checks in concept implementation as well as ease of practical validation, a checklist (Table 1) is devised to reflect the completeness of the current design and manufacture for each individual sub-system that is included in the entire configuration composite. This thereby provides an essential tool to proceed onto the corresponding Phase B stages of design development.

Table 1 – Checklist for design and manufacture

CHECKLIST [Part I] DESIGN	
The subsystem or component has been modelled and the design validated at assembly level.	Yes
Relevant calculations and a brief design methodology have been cross-checked.	Yes
The subsystem or component has undergone a material selection exercise.	Yes
All drawings are complete, i.e. all dimensions and any other required information is present.	Yes
All sub-system drawings have been scrutinised and authorised by the sub-system expert.	Yes
Appropriate assembly drawings have been included for clarity.	Yes
The design of the subsystem or component has been checked by the team.	Yes
CHECKLIST [Part II] MANUFACTURE	
The general manufacture of the subsystem or component has been researched.	Yes
The feasibility of manufacturing the current version of the subsystem or component has been confirmed.	Yes
The manufacturing methods have been identified and considered within the design methodology.	Yes
The total estimated number of man hours to manufacture (all components including multiple. quantities if any).	200 hrs
The total estimated material cost (all components including multiple quantities).	$ 4500
Material needs to be ordered specifically for the subsystem or component to be manufactured.	Yes
The manufacture of the subsystem or component has been checked/authorised by the team.	Yes

2. Materials Selection

Material selection is one of the most important aspects of engineering science. The properties of the product are determined by the materials that the engineers choose. It is obvious that spacecraft must have a high standard of safety which means high standards of material selection to avoid structural failure. In this project, the target is to build a spacecraft that has a negligible impact upon its environment, low cost is important and component parts must be designed for manufacture and assembly. Before the material is chosen, its properties are examined: for example, their mechanical properties (strength, youngs modulus etc.), physical properties (density, melting point etc.), electrical properties (conductivity, resistivity etc.), aesthetic properties (appearance, texture, colour etc.) and the cost of the material.

A matrix has been made and it has been found which properties to be considered most important; from that matrix, it can be produced this scoreboard (5 is the highest), in Table 2.

Table 2- Material selection parameter and their importance

Mechanical Property	4
Physical Property	3
Electrical Property	2
Aesthetic Property	1
Cost of the Material	5

2.1 Aluminium Alloys

Aluminium alloys are popular in space applications for several reasons. The major Reason for their popularity is the high strength-to-density ratio compared to other metal alloys (Figure 1). The density of aluminium can be as little as 1/3 the density of structural steel. Manufacturers of aluminium increase the strength-to-density ratio of the metal by adding lithium. The substitutional atoms of lithium increase the strength and decrease the density of the aluminium alloy structure. Adding just 1% lithium decreases the density of the metal by 6%. Other reasons for the popularity of aluminium alloys include lower cost, better machinability, and better weldability than structural steel. Heat treatable alloys are useful in structural applications because they have good manufacturing characteristics ([1]).

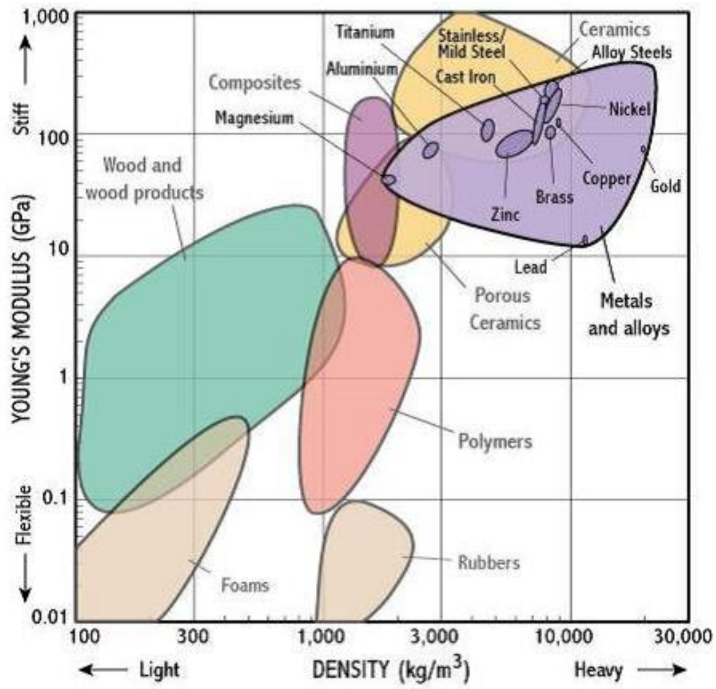

Figure 1- Material young modulus vs. density

7XXX Series The 7XXX series aluminium are high strength alloys. The yield strengths range from 95 to 625 MPa. Heat treatable alloys include 7075, 7079, and 7178 alloys. The team only considered the 7075 and 7178 alloys as candidates because the weldability and formability of the 7079 alloy is lower. The main alloying element in the 7XXX series aluminium is zinc, which is a well-known element for solid solution strengthening of materials ([1]).

3. Structural Analysis

3.1 Engineering Science

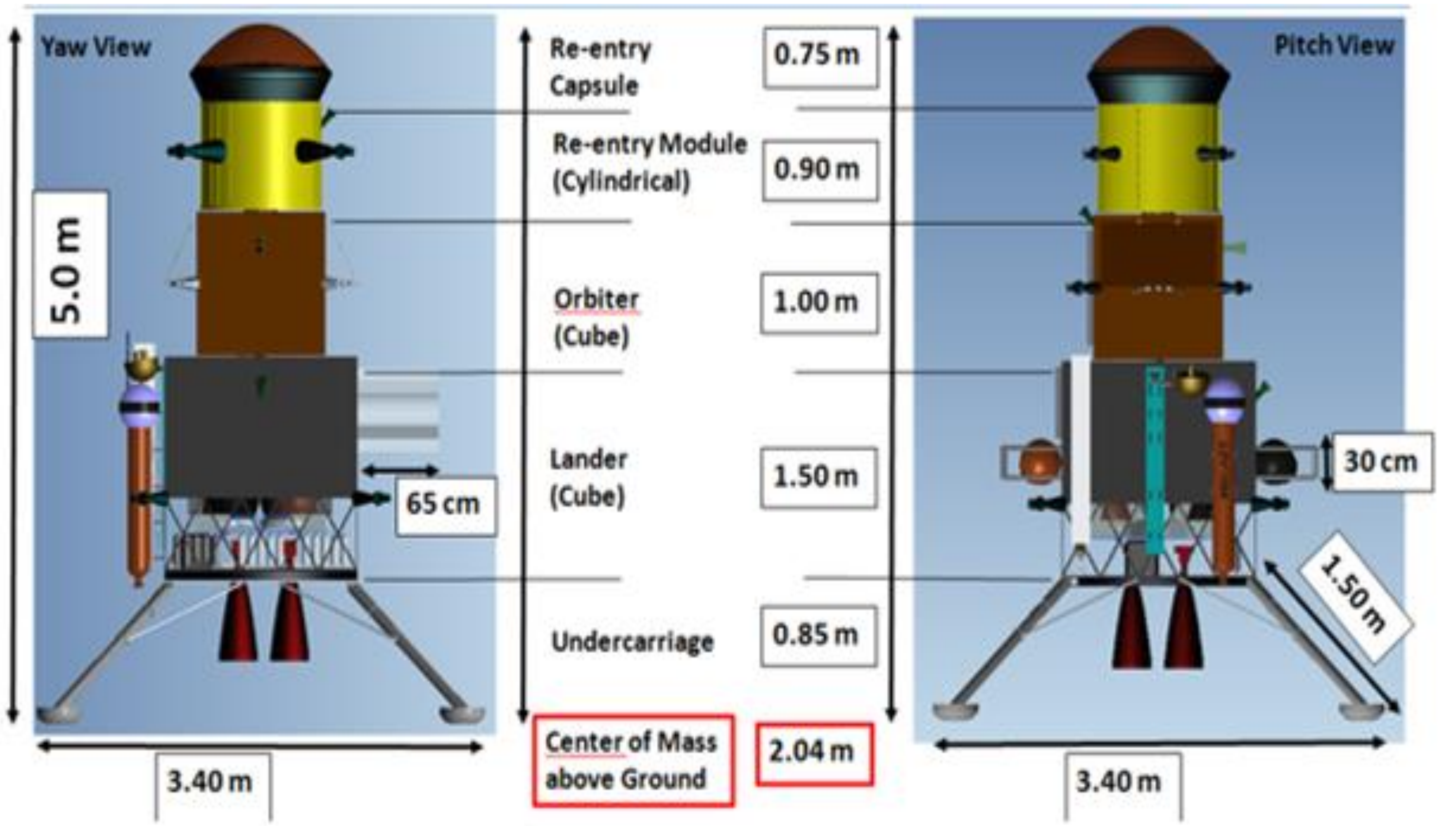

Figure 2- Complete configuration of the structure

This is an important part of the testing stage and plays its role after the manufacturing of individual parts and hence the assembly is complete. It precisely determines the extent to which each component would take the load of forces acting on it while in real conditions. Since certain external conditions and patterns are sometimes difficult to predict, it is always wise to calibrate the total forces on the parts slightly more than the maximum possible. This ensures margin of safety and also provides with an insight of certain areas that might fail or are vulnerable to adverse stresses ([4]).

Testing is normally done at a later stage of the design process and can be expensive and time consuming causing delays if modification is required at this late stage. With the constant increase in shock levels in launchers due to the decreasing amount of damping materials used in order to reduce weight, shocks and pyro-shocks are getting more severe in s/c. In addition to the increasing customer qualification requirements for such design capabilities, and with the advancement of computational methods, the development of an efficient method for load simulation using Finite Element Methods (FEM) is essential. Therefore the need for an efficient simulation method with accurate predictions to ensure sufficient dimensioning of equipment in order to avoid serious failure during tests and launch is paramount ([4]).

3.2 Individual module configuration

The configuration of individual modules comprising of the sub-systems assemblies are driven by the functionalities they serve during the different operational modes of the mission phases. It is essential to articulate these sub-system functionalities and their corresponding effect on the module designs.

A table to enable this is produced (Table 3) which gives a general description of the nature of the function that needs to be performed and its relative level of importance pertaining to the current design intended. The final design of the composite is directly influenced and inspired by these properties.

Table 3- Functionalities of the composite performance specifications

Title	Description/Design considerations	Importance (high-low: 5-1)	Intended Design
Capacity / Robustness	The inner capacity must be maximised for payload and vital components	5	($>$ 5.5, m^3)Lander contains most crucial payloads
Efficiency and effectiveness	Must be resistant to radiation and deep space particles; Must be able to operate in all environmental temperature conditions.	4	Relevant protection and shield employed; Able to sustain temperature range of -230°C to 50°C.
Lifespan	Maintenance should be minimal to allow long storage life and for immediate use; Components should not be made out of material which will begin to degrade in few months.	3	$>$ 6 months
Mass	Mass of the spacecraft should be kept as low as possible without compromising the effectiveness of the s/c to allow a greater weight of payload; Number of electronics and control systems should be minimal in order to keep the mass and costs down.	3	Dry mass $<$ 950kg Wet mass 2650 kg
Size and Shape	The general size of the s/c should be dictated by factors such as drilling required to be carried out and planned scientific payloads; The general shape should be optimised for ease of manufacture and transportation.	5	Height 5 m; Surface footprint 3.4, m^2; Lander cubic with each side 1.5 m
Strenght	The composite must be sufficiently strong to withstand launch conditions without damaging the payload or components	4	Structural analysis indicative s/c capable of worst load condition with pessimistic margin
Mechanisms	The s/c interface mechanisms must have quick response and be easy to operate, without seriously affecting the primary module performance	5	High TRL mechanisms employed only

In the big picture, the underlining study covers the following categories:

- Material review and literature study.
- Understanding loads, stresses, strains and their qualification requirements.
- Survey of applicable simulation methods.
- Applications of FEM software in similar analysis and understanding their capabilities.
- Applying different simulation methods to a simple model and comparing their simulation predictions with test measurements.
- Results comparison and discussion.
- Selection of the most accurate and the most appropriate simulation results.

3.3 Composite interfaces and separation mechanisms

As understood earlier, in order to provide for the vast requirements and functionalities for each phase of the mission and during different operational modes, the composite configuration is needed to be composed of several constituent modules and assemblies. Broadly, four distinct modules are identified to solve the varied purposes for the entire mission lifetime. These are namely the lander, orbiter, re-entry module and the re-entry capsule. Each individual module is further categorised into different components that require a mechanical attachment/detachment constraint, but as far as the mission criticality goes, these four remain at the forefront. Considering the high dependability of the mission success on these individual modules, the interface and deployment mechanisms undoubtedly play a key role in determining checkpoints that are listed on the mission timeline. Yet again, a table is produced (Table 4) to highlight the most important facets governing the science of module interfaces and their relevant application to the intended design.

Table 4 – Interface drivers and desired parameters

Title	Description/Design considerations	Importance (high-low: 5-1)	Intended Design
Accessibility	Immediate response of the servo and actuator motor control system for deployment purposes	5	Mechanism of are standardised and easy to access
Compatibility	Components should be standardised wherever possible and be driven by simple design	5	The design interlinks accommodate for possible generic components and attachments
Configuration	The configuration depends on what best accommodates the requirements of the design	5	Key driving factor for design at sub-system and assembly levels
Debris/ Emissions	The product itself must not produce emissions in the way; separations must be securely conducted to avoid part breaking off.	3	Protective layers and shielding employed
Heat input and output	It must be able to operate in all environments known with varying temperatures	4	Use of MLI; radiators for ventilation
Inter-changeability	Were possible the design should use standard parts for ease of assembly and manufacture. This also reduces production costs.	4	Components such as latches, hinges and actuators with high TRL and deployment mechanisms tested/used in literature
Redundancy	Redundancy should not increase cost unnecessarily; however it must have a high success rate	4	Appropriate backups included within the mass and power margins of the mission budget
Size and shape	Must have enough capacity for the purpose needed. Shape should ideally blend in with the structural components it is attached with	5	Occupying a volume with optimisation between the link connections mechanisms and the standardised component
Tolerance	Interface tolerance should not become a limiting factor.	3	Modal, Stress and frequency responses define the maximum tolerance limits that the composite sustains

3.4 Launcher Payload

The launcher adapter provides the interface between s/c composite and the launch fairing (figure 3). Delta IV M offers four main types of adapters, varying in sizes, shapes, interface attachments and separation mechanisms. Specific to the composite configuration developed in this case, the following Delta adapter is the best fit due to the constraints in lander and leg dimensions, footprint area and the preferred separation techniques. It has 18 sets of bolts and clamping points where the bottom of the lander is fixed by having the legs included within too ([5]). Now since the legs for this design originate and remains fixed to the lander at all times, they have free ends protruded outwards at 45 angles from the face of the lander. This is crucial to understand the stiffness and vibration limits of the legs when exposed to various external loading ([5]).

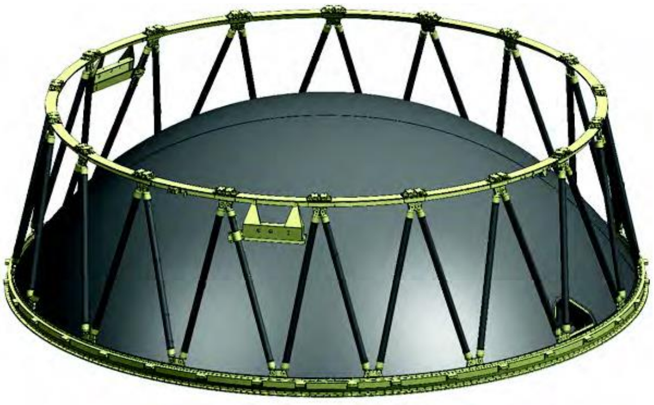

Figure 3 – Delta IV 4394mm Payload Attach Fitting (PAF)

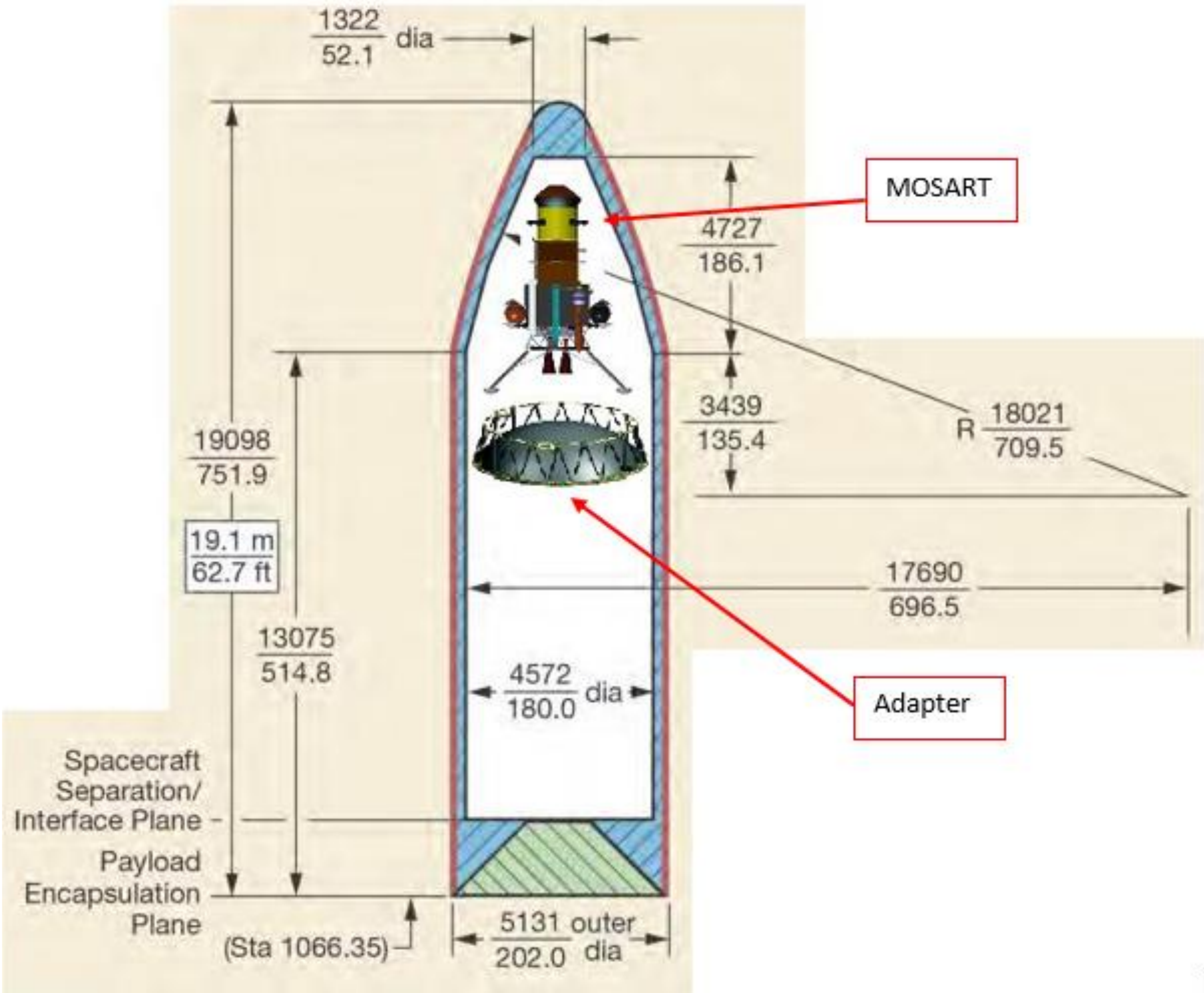

Figure 4 – composite as Delta IV M payload

3.5 Launch Analysis

The most important consideration taken into account for doing the structural work is the launch phase. It is necessary to replicate the conditions that will be experienced by the system during this initial phase since usually this will remain as the worst possible case for the entire duration of the mission from the structural point of view. For the launch, the s/c experiences a downward inertial load which is many times the gravitational acceleration. Apart from this, it also faces the masses carried by its components internally. These stresses act on the joints, interfaces, connective links, other edges and vertices with concentrated loads ([6]).

The critical point to incorporate however is the action on the appendages that are either fixed on some face of the configuration composite or are free to translate/rotate with restrictive DOF. The components that fall under such a bracket are:

- Solar panels.
- Legs.
- RCT units.
- Star sensors.
- External tanks.
- Driller.
- Launch rocket.
- Robotic arm translation unit.
- RTG.
- Antennas.

Being highly vulnerable to such loads, the results of the analysis will appropriately determine the exact areas of concern and identify the weakest positions within the entire composite matrix. The inertial load for the launch vehicle is 6.0g, including a margin of 10%. As well as these, there is likely to be considerable applied forces on the internal components such as the power units, data handling system, propulsion units, scientific payload etc. but since there is better provision for cladding and support frames within, these components may be assumed to show minimal movement and deformation relative to the outer ones.

One significant challenge at this point of the design and analysis programme was to be able to construct a simplified analysis pathway to minimise the code runtime, yet keeping in mind the vitality of each components material, structural individuality. Assemblies and sub-assemblies within the composite of utmost structural analysis interest have been inserted into the analysis model as in the real design while the rest that are considered to remain fixed and integrated along the internal composite structure are represented as point masses instead. Appendages have been reduced as point mass as well. This greatly simplifies the final entity that is run in the FEA code, at the same time not ignoring anyone detail either ([6]).

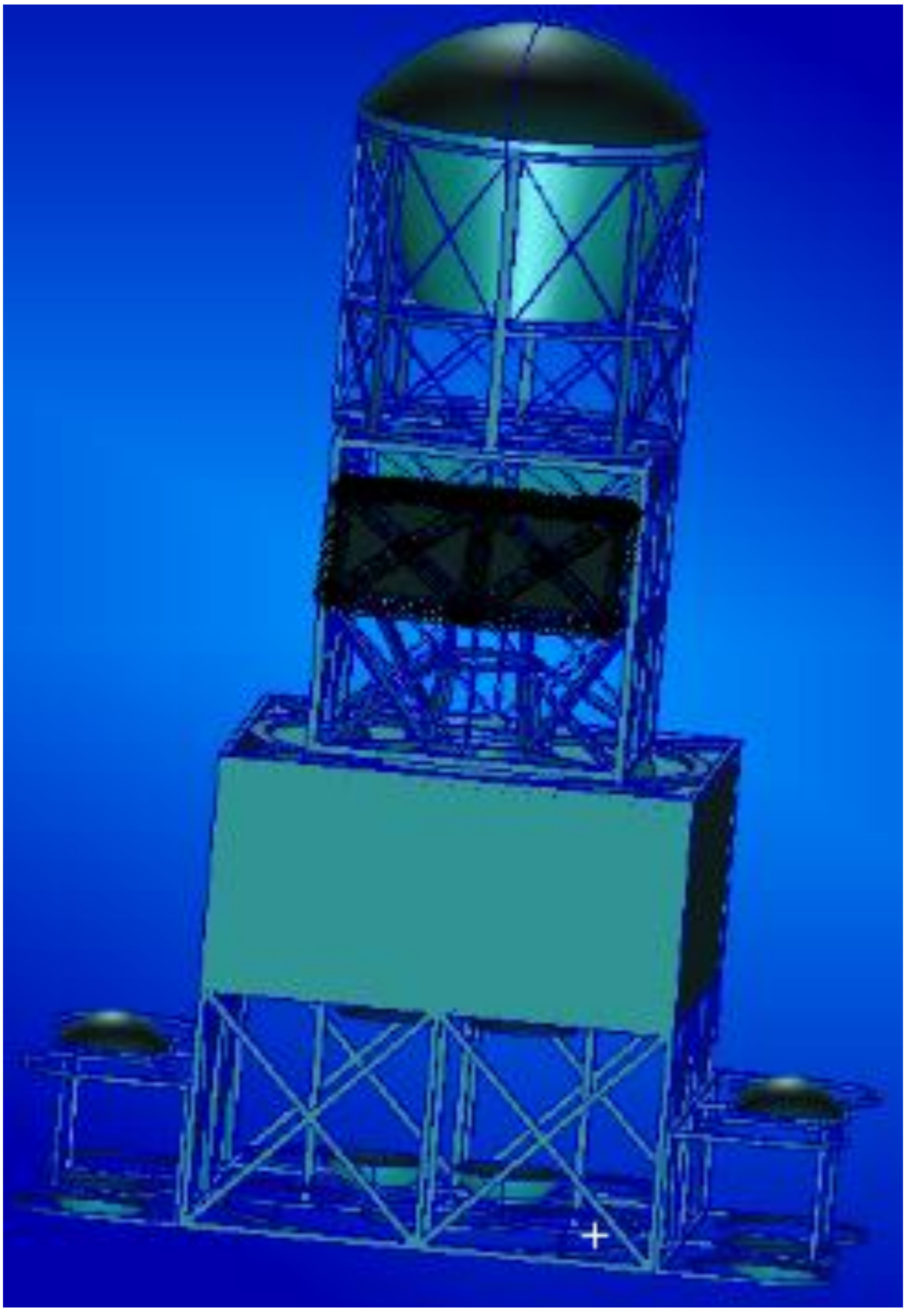
Figure 5 – Composite structure

STATIC ANALYSIS- From the following figures 5 and 6 it can be seen the results of the static analysis. In particular it can be noticed that the maximum equivalent stress is well beneath the yield stress of the chosen series of aluminium alloy.

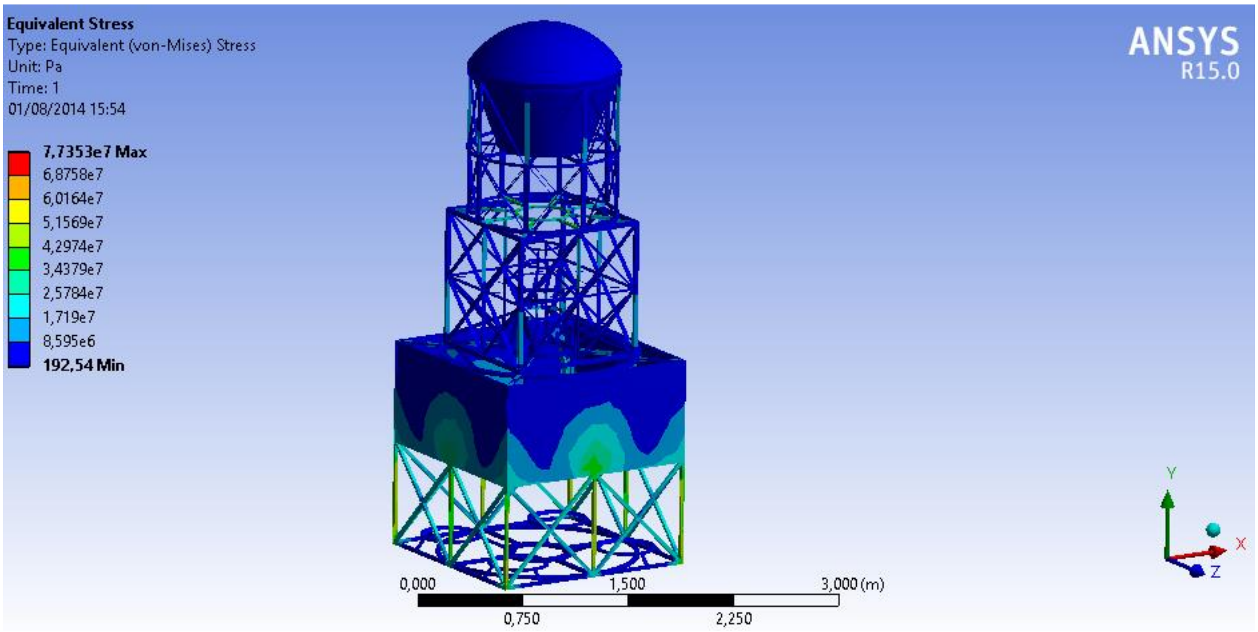

Figure 6 – Equivalent von-misses stress

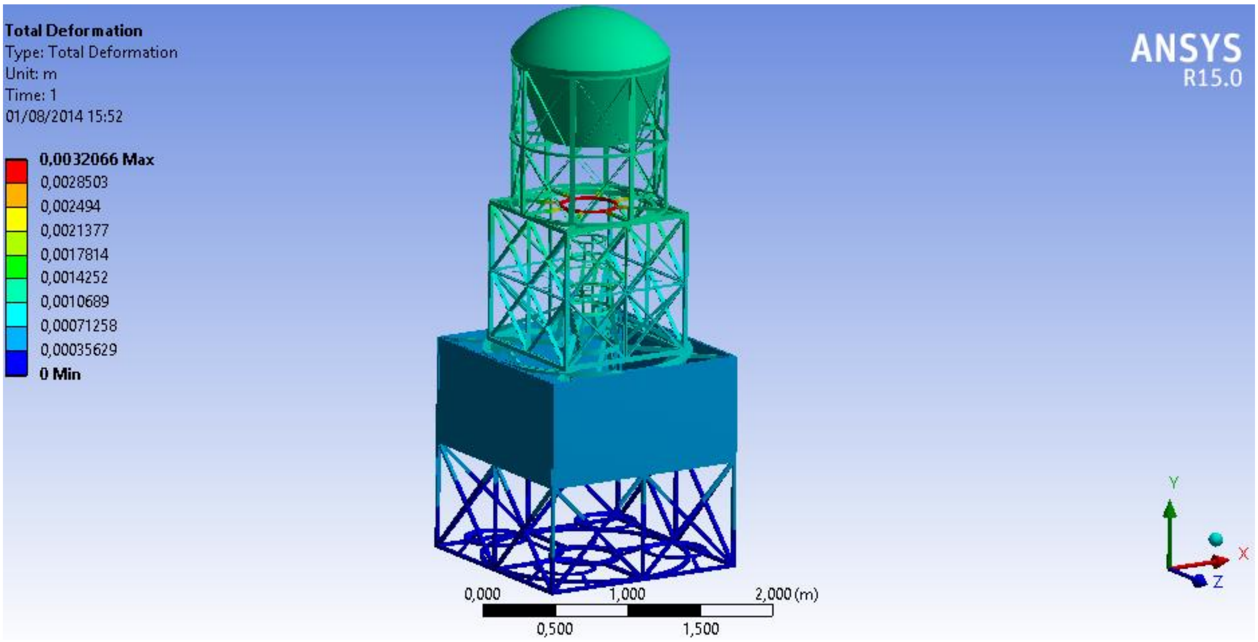

Figure 7 – total deformation

MODAL ANALYSIS- The modal analysis aimed at checking that the first lateral and longitudinal modes were not excited by the launcher selected. In table 5 the frequencies lower limit together with the evaluated ones frequencies of composite are reported, to show they are well beyond the limits.

Table 5 -1st lateral and longitudinal frequencies

	Lower limit	Computed
Lateral	8 Hz	47.29 Hz
Longitudinal	25 Hz	40.65 Hz

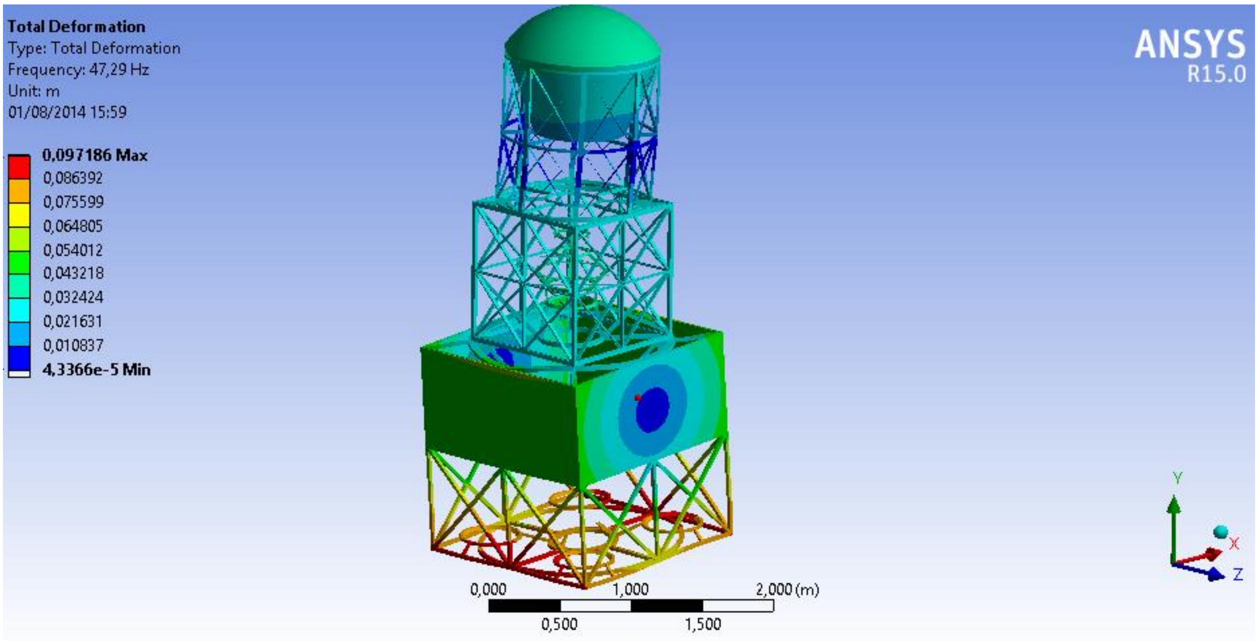

Figure 8 – 1st lateral (total deformation)

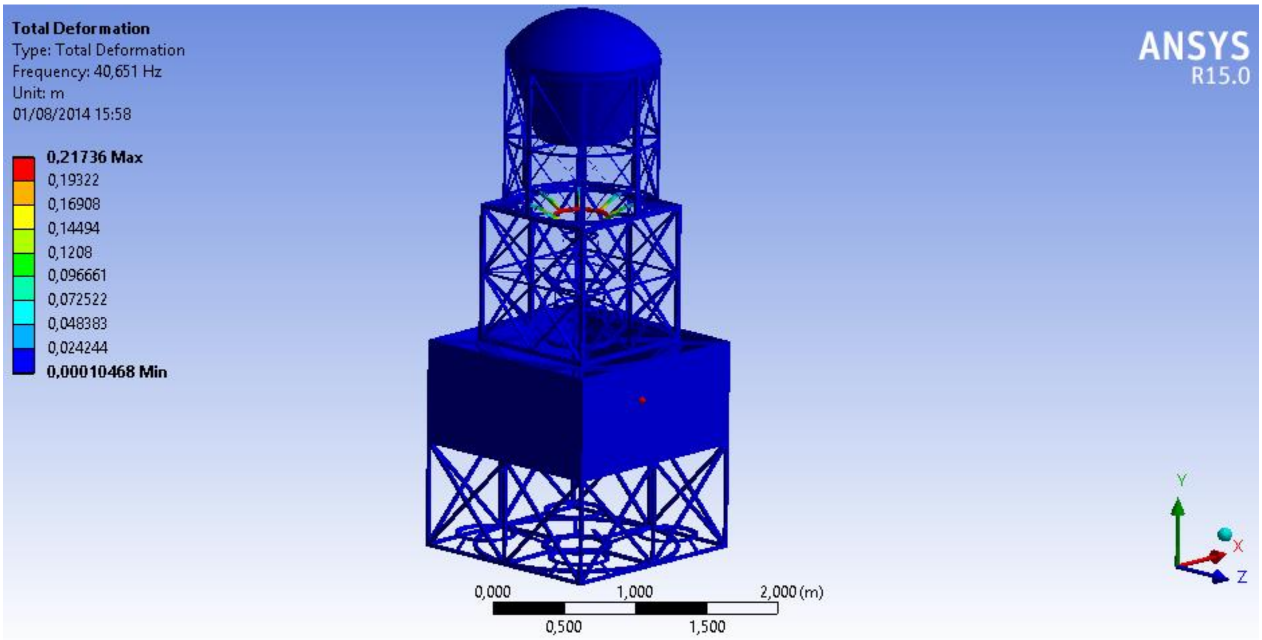

Figure 9- 1st longitudinal (total deformation)

Table 6 – structural mass budget

Vehicle	Mass [kg]	% margin	Total margined [kg]
Lander	123	30	160
Orbiter	16.2	30	21
Re-entry module	16.2	30	21

References

[1] CES (Cambridge Engineering Selector) programme

[2] Chuck Lazansky, Refinement of a Low-Shock Separation System, Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, May 16-18 2012

[3] Wigbert Fehse, Automated Rendezvous and Docking of Spacecraft, Cambridge University Press, 2003

[4] J.D. Carpenter, R. Fisackerly, D. De Rosa, B. Houdou, Scientific Preparations for Lunar Exploration with the European Lunar Lander, Planetary and Space Science

[5] Delta IV Launch Services Users Guide, United Launch Alliance, LLC/United Launch Services, LLC

[6] Andrew J Ball, James R C Garry, Planetary Landers and Entry Probes, Cambridge University Press, 2007

[7] C. R. Stroker, The scientific rationale and technical approach for drilling on the moon and mars, NASA Ames Research Center