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Exploration Planetary Surface Structural Systems: Design Requirements and Compliance

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Abstract

The Lunar Surface Systems Project developed system concepts that would be necessary to establish and maintain a permanent human presence on the Lunar surface. A variety of specific system implementations were generated as a part of the scenarios, some level of system definition was completed, and masses estimated for each system. Because the architecture studies generally spawned a large number of system concepts and the studies were executed in a short amount of time, the resulting system definitions had very low design fidelity. This paper describes the development sequence required to field a particular structural system: 1) Define Requirements, 2) Develop the Design and 3) Demonstrate Compliance of the Design to all Requirements. This paper also outlines and describes in detail the information and data that are required to establish structural design requirements and outlines the information that would comprise a planetary surface system Structures Requirements document; provides a status of the data sets needed to establish requirements (most are currently incomplete or missing); and proposes an approach for developing the necessary data and information. The resulting plan is intended to serve as the framework for implementing a planetary surface structural systems technology development process to support exploration efforts.

Introduction and Objectives

The Lunar Surface Systems (LSS) Project, within the NASA Constellation Program, was responsible for defining and developing system concepts that would be necessary to establish and maintain a permanent human presence on the Lunar surface. Examples of potential system concepts include Habitats, Surface Mobility Devices, Robotic Manipulators, and Surface Power Generation and Storage. The lunar architecture studies investigated a wide variety of implementation scenarios that met overall Vision for Space Exploration (VSE) objectives, with different scenarios emphasizing meeting those objectives in different sequences. A variety of specific system implementations were generated as a part of the scenarios, some level of system definition was completed, and masses estimated for each system. Because the architecture studies generally spawned a large number of system concepts and the studies were executed in a short amount of time, the resulting system definitions had very low design fidelity. Many different mass estimation techniques were used to generate subsystem (such as structures, power, environmental and life support, avionics, etc.) definitions and masses. Reference 1 gives an overview of the methods used to define and estimate the mass of habitation structures, as well as a summary of the limitations of those methods. In Reference 1, an important demarcation is made between the structural concept definition that was being performed in LSS to support the architecture studies, and structural design. This distinction is critical because only a very limited amount of information can be inferred from concept definitions. In particular, technology development requirements cannot be inferred from concept definitions because those requirements are particular to and change with a given system implementation, and that implementation depends on, at a minimum, a conceptual design.

The development steps that are required to field a particular structural system can be categorized (at a broad level) into: 1) Define Requirements, 2) Develop the Design and 3) Demonstrate Compliance of the Design to all requirements. Currently, a comprehensive set of Structural Design Requirements (SDRs) does not exist for systems that must survive and operate on the lunar and other planetary surfaces (including smaller bodies such as Near Earth Objects). As a result, it is very difficult to perform even a conceptual structural design with any degree of confidence since compliance to major (undefined at this point) requirements may be lacking in the system. However, in order to meet any future exploration program mission goals, it is clear that the design process for planetary surface systems needs to begin immediately if the required systems are to be delivered in a timely manner to meet exploration flight manifests. The objectives of this paper are to; 1) outline and describe in detail the information and data that are required to establish structural design requirements, 2) outline the information that would comprise a planetary surface system Structures Requirements document, 3) provide examples and a status of the data sets needed to establish requirements (most are currently incomplete or missing) and, 4) propose an approach for developing the necessary data and information.

Design Requirements and Supporting Information

The full suite of Exploration Planetary Surface Systems will incorporate a wide variety of structural and material concepts and systems. Some of the structures will be pressurized (habitat for example) while many others will be unpressurized (rover chassis, solar arrays, etc.). Some of the structures will house people, transport people, or interact with people, while others will transport and handle critical flight hardware. The requirements developed to design the structural systems must be comprehensive and account for the unique environments (on a particular planetary surface, as well as transportation to the surface) that the systems will be exposed to. Decisions will have to be made as to the applicability and potential to incorporate Earth-based requirements as they might apply to the planetary outpost (OSHA safety for example) as well as transporting and handling flight critical and human payloads (NASA Critical Lift requirements, reference 2).

Overview

The purpose of having a set of SDRs is to ensure a minimum level of safety in any structural system developed under the auspices of a particular regulating authority. Thus, the requirements represent a general set of standards that are independent of any particular material/structural system design and implementation, and every system that is to be operated must show that it complies with all of the applicable requirements. In general, an evaluation of the structural system under typical load and environmental spectra must show how catastrophic failure due to any degrading environments (temperature, radiation, vacuum, for example), material specific response to loads (creep, fatigue, fracture, for example) or accidental damage can be avoided throughout the operational life of the structural system. Generally, this can only be assured when there is an adequate inspection program, so the evaluation must also result in an inspection and maintenance procedure. The evaluation must be applied to each Principle Structural Element (PSE) in the system whose failure, if it remained undetected, would lead to loss of the system.

In general, two different structural design categories (damage tolerance and safe life) exist and the evaluation must show compliance to whichever philosophy is chosen for the system. In the first category, damage tolerant structure, multiple paths exist for redistributing loads around a damage site. The evaluation must show that any damage (initiated by fatigue or accident for example) will never propagate to failure prior to detection. The evaluation may use a combination of test and analyses. Damage propagation must take into account the expected spectrum of loading (and resulting stress) and environmental exposure expected in service. Inspection frequencies must be determined based on damage propagation life from a detectable size to a critical size at limit load. The ability to repair damage is inherent in the damage tolerance approach and repair techniques must be developed and validated to be compatible with the planetary surface environment. For planetary surface structures, detectable damage will have to be repaired in the field for the structure to remain in service. The second category, safe life, applies to single load path structure where it can be shown that damage tolerance is impracticable (from inspection, not economic considerations, with landing gear and engine mounts being two examples for commercial transports). Safe life structure is defined as that in which any initial flaws can propagate and become critical before they are detectable in service. Substantiation is required by test, and based on those tests, a "safe life" is established for the structural element and the element must be replaced at the end of its life.

The broad categories of information and data that are required to perform structural design consist of the following; natural environments, threat environment, design loads, material properties, structural design requirements and design compliance. In general, all of the categories except Design Requirements and Design Compliance are independent of a particular structural/material design implementation. Within the realm of Design Requirements, many will also be independent of material/structural implementation and apply to all structural systems. The degree and depth to which data and information exist for each category will determine whether or not, and to what level of fidelity, structural design can be performed. In general, there is a minimum amount of information and data that will be required to cross the demarcation line from conceptual definition to conceptual design. In the following sections, each information category will be described along with examples of data required to perform such a design.

Natural Environments

The natural environments are the complete set of environments that the structural system will be exposed to during its entire life cycle. This includes exposure to Earth environments during the periods of storage before flight, transportation to the launch site, storage at the launch site, integration with lander and launch vehicle and waiting for launch on the pad. It also includes exposure to the in-space environment in low Earth orbit, planetary transit and planetary orbit; and exposure to the plantary surface environment. Examples of environments to consider for each phase are listed in Table 1.

Table 1. Natural Environment Examples by Mission Phase.

Mission Phase	Environment Definition Required
Earth storage, transportation, launch pad, launch	- Temperature (maximum and minimum) - Temperature cycle, time at temperature - Humidity - Ultra-violet (UV) radiation exposure - Rain, hail, lightning - Acoustic - Fluid exposure - Etc.
In-Space	- Temperature (maximum and minimum) - Temperature cycle, time at temperature - Radiation (UV, Galactic Cosmic Radiation [GCR], Solar Particle Events [SPE]) - On-orbit debris - Micro-meteoroid - Vacuum - Fluid exposure - Etc.
Planetary Surface	- Temperature (maximum and minimum) - Temperature cycle, time at temperature - Radiation (UV, GCR, SPE) - Micro-meteoroid - Lander induced ejecta - Vacuum - Fluid exposure - Gravity value - Etc.

The natural environments are very important and will impact many design factors. Absolute temperatures must be known and matched with loading history to define design load cases. Temperature cycling, vacuum and radiation environments can all influence the performance and degradation of certain materials. Micro-meteoroid and lander exhaust-induced debris environments will impact shielding design.

Natural Environment Knowledge Current Status: Good

Threat Environment

The threat environment refers to those external events that can cause damage to the structural system and pose a threat to structural safety. Threats to the structure will occur from the time of manufacturing through the end of operations (and end of life) on the planetary surface. A comprehensive set of threats must be compiled for each structural system, the probability of each threat occurring quantified, and the structural response and damage tolerance to each threat assessed. The desired level of safety, or acceptable level of risk, must be used in conjunction with the probability of occurrence and potential consequence (level of acceptable damage) to determine which threats will result in specific design requirements. Examples of possible threats for various time phases are listed in Table 2.

Table 2. Threat Examples by Mission Phase.

Manufacturing	- Manufacturing defect (non-detectable by inspection) - Tool drop, foreign object damage - Etc.
Preparation and Transportation to Launch Site	- Handling damage (dropping, fork lift, tool drop, etc.) - Foreign object damage - Accident (transporter) - Restraint failure - Rain, hail, lightning, etc. - Etc.
Integration with lander and launch vehicle and time on launch pad	- Handling damage (dropping, fork lift, tool drop, etc.) - Foreign object damage - Collision damage - Restraint failure - Rain, hail, lightning strike, etc. - Etc.
Launch, In-Space	- Rain, hail, lightning strike, bird strike, etc. on ascent - Foreign object damage on ascent - Collision (between stages) - On-orbit debris - Micro-meteoroid - Lander restraint failure - Etc.
Planetary Surface	- Handling damage (manipulators, EVA, mobility chassis, robotic assistant, etc.) during unloading - Restraint failure (mobility, handling) - Micro-meteoroid - Lander ejecta - Foreign object damage - Fire - Collision (between mobility devices, between mobility device and fixed device) - Roll over (mobility device) - Collision (between manipulator and other device) - Etc.

Threat Environment Knowledge Current Status:

Launch, In-Space, Planetary Surface: Poor
All Others: Good

Design Loads

The purpose of structure is to safely react and transfer loads within a system during its operation. To ensure a safe structure, the externally applied loads must be compiled for all mission phases, from the time the system is manufactured through the end of mission life. The applied loads are matched with consistent environments to define the design load cases. One example of an important interaction that must be captured when defining a load case, is between extreme temperatures (both hot and cold) and the applied loads. Since the performance of materials can change significantly with temperature, and extreme temperatures are possible on planetary surfaces, it will be especially important to include temperature conditions in each load case. Also, any stresses induced by environmental exposure (temperature for example) should be combined with the externally applied loads to define load cases.

Design loads fall into two major categories, limit and ultimate. Limit load is the maximum value expected to occur once in service during the life of the structural system. The structure must be able to sustain limit loads without any detrimental permanent deformation to the structure. At any load up to limit, deformation may not interfere with safe operation. Ultimate loads are obtained by multiplying limit loads by an appropriate factor of safety. The structure must be able to support ultimate loads without failure for a specified amount of time. Note that the factor of safety (FS) can be load dependant; FS = 1.5 is specified for mechanical loads, and FS = 2.0 is specified for pressure loads for example. However, FS is not intended to vary for different material/structural concepts or designs. Examples of possible external design loads to consider during typical life time phases are listed in Table 3.

Table 3. External design load examples by mission phases.

Test and Evaluation	- Static proof loads - pressure - Static proof loads – mechanical - Vibration loads - Acoustic loads - Thermal loads - Outfitting loads - Combined loads - Etc.
Preparation and Transportation to Launch Site	- Gravity (1-g) at specified orientation - Transportation loads (induced by truck, aircraft, etc.) - Handling loads (cranes, fork lifts, etc.) - Etc.
Integration with lander and launch vehicle and time on launch pad	- Gravity (1-g) at specified orientation - Handling loads (cranes, fork lift, etc.)

	- Outfitting loads - Etc.
Launch, In-Space	- Static mechanical loads (x-g's) at specified orientations (launch vehicle) - Acoustic loads - Vibration loads - Stage separation loads - Thermal loads - Pressure loads - Cyclic/fatigue loads - Etc.
Planetary Surface	- Static mechanical loads (at appropriate g level) in specified orientation - Thermal loads - Static pressure loads - Handling loads - Transportation loads - Docking/Berthing loads - Crash loads - Vibration loads - Etc.

Design Load Knowledge Current Status: Poor

Material Properties

A wide variety of materials are likely to be used for lunar surface structural systems. The major categories include metallic, polymer matrix composite (PMC) and structural soft goods (used in expandable or inflatable structures). Adhesives are considered a subset of PMC materials since most adhesives in a PMC system are derivatives of the matrix material. Structural soft goods can be divided into two major classes of material-product forms: bladders (which are two-dimensional tension membranes), and restraint layers (uni-directional tension straps). The material properties required for design vary by material type, with examples listed in Table 4.

Table 4. Material property typical examples (used in design). (Note: should be end-of-life.)

Metals	- Tension/compression moduli - Shear modulus - Tension/compression ultimate strength - Yield strength - Ultimate shear strength - Bearing strength - Fracture toughness - Creep strength (temperature dependent) - Density - Poisson's ratio

	- Coefficient of thermal expansion
PMCs Note, because of their orthotropic nature, polymeric composite laminate values must be determined for both the x and y directions, with orientation of the laminate in the structural application accounted for in verifying compliance.)	- Open hole compression strain (strength) - Open hole tension strain (strength) - Compression-after-impact strain (strength) - Bearing strength - Tension/compression moduli - Shear modulus - Shear strength - Poisson's ratio - Creep Strength (temperature dependent) - Density - Coefficient of thermal expansion (including through the thickness) - Interlaminar shear strength
Structural Soft-goods (polymeric materials)	- Bladder tension modulus - Bladder ultimate strength - Bladder tear strength - Bladder creep strength (temperature dependent) - Bladder density - Bladder Poisson's ratio - Bladder coefficient of thermal expansion - Strap tension modulus - Strap ultimate strength - Strap creep strength (temperature dependent) - Strap density - Strap coefficient of thermal expansion

In order to demonstrate design compliance it is required that the material properties, as they exist at the end of the system's lifetime, be used in the evaluation. The natural environments the materials are exposed to, along with exposure duration are important factors that can cause degradation to the beginning-of-life properties. Different materials will be more or less susceptible to degradation when exposed to the full spectrum of environments. Lunar and Mars environments are within the experience base of most metallic materials. PMCs can be susceptible to degradation of properties when exposed to radiation, and their strength properties are likely to vary within the operational range of temperatures expected on a planetary surface. Since polymeric materials are also used for structural soft-goods, radiation exposure and temperature (at design loads) will also be important considerations for these materials. Creep at elevated temperatures might also be critical. In general, statistically based strength allowable values must be used when verifying design compliance, with the regulating authority specifying the use of A-basis, B-basis or S-basis allowables that are consistent with ensuring the required level of safety in the system. For PMCs, strength allowable values are both material and laminate dependent, and must be generated for each laminate used in the structure. Also, in general, notched allowables such as compression-after-impact, open-hole-tension, etc. are required for design. Unnotched values are generally acceptable for laminate properties unrelated to strength such as modulus, Poisson's ratio, and the coefficient of thermal expansion.

The details of a particular structural design will also impact the amount and types of exposures and must be determined for each specific design application. For example, if a composite structure is covered in multi-layer insulation, no degradation of the composite due to ultra-violet radiation exposure may occur. Similarly, if the pressure shell of a habitat is covered in layers made up of thermal insulation, radiation protection and micrometeoroid protection, the shell may be sufficiently insulated that it does not experience the extreme temperature excursions that can exist on the lunar surface.

Material Properties for Design Current Knowledge -

Metals: Good
Polymeric Composites: Fair
Structural Soft Goods: Poor

Structural Design Requirements

Structural design requirements are imposed on the structural system to ensure a desired level of safety. Requirements span a large number of categories and many or most of these requirements are generally independent of material/structural design implementation. That is, any design put forward must show compliance with the same set of requirements, ensuring that all proposed designs exhibit an equivalent level of safety. As new materials and structural concepts have been introduced, concept specific requirements have been developed. An example of a comprehensive set of structural design requirements is given in Table 5, taken from reference 3. The content of this table is meant to illustrate the broad scope of issues that must be addressed in a comprehensive set of structural design requirements. Obviously, many of the specific items will not apply to planetary surface structural systems. However, it is likely that many new requirements will have to be established that are particular to systems designed for a planetary surface and these requirements will parallel the intent of many of the items in the table. In the High Speed Research (HSR) Program, both metallic and PMC materials were evaluated. A wide variety of structural concepts that are not traditional (i.e. metallic, mechanically fastened stiffened skin) to commercial aircraft primary structure applications, were also considered. These included bonded PMC stiffened skin structure, bonded PMC sandwich structure, bonded metallic sandwich structure, and integrally machined/stiffened isogrid metallic structure, among others. Examples of material/structural concept specific requirements are also noted in the table.

Table 5. Structural Design Requirement Examples from sections in HSR document.

Section Heading	Subsection Headings
General Requirements	Design Service Objectives
	Material Design Values (Note, not the properties themselves.)
	Environmental Requirements
	Stiffness Requirements
Airplane Level Structural Design	Definitions: Limit Loads, Ultimate Loads,

Requirements	Deformations, Load and Temperature Redistribution, Transient Response
	Weights for Structural Design
	Design Airspeeds
	Symmetrical Maneuver Criteria
	Gust Criteria
	Rolling Maneuver Criteria
	Yawing Maneuver Criteria
	Engine Out Maneuver Criteria
	Engine Inlet Unstart Maneuver Criteria
	Ground Loads Criteria: Landing Impact, Ground Handling Conditions
	Nacelle Loads Criteria
	Fuselage Pressure Loads Criteria
	Fuel Tank Load Criteria
	Ditching and Crash Load Criteria
	Damage Tolerance Loads Criteria
	Fatigue Loads Criteria
Material and Structural Requirements	General Material and Structural Concept Requirements: - Polymer Matrix Composite Requirements - Metallic Materials Requirements - Hybrid Titanium/PMC Laminate Requirements - Skin-Stringer Requirements - Honeycomb Sandwich Requirements
	Strength Requirements
	Stability Requirements
	Bolted Joint Requirements
	Bonded Requirements
	Repair Requirements
	Handling Requirements, Metallic Structure
	Handling Requirements, Non-Metallic Structure
	Minimum Gage Requirements
	Thermal Insulation Requirements
Durability and Damage Tolerance Requirements	Durability Objectives: Metals Durability, Composite Durability, Hybrid Laminate Durability
	Sonic Fatigue Requirements
	Panel Flutter Requirements
	Damage Tolerance Requirements: - Metallic Structure - Composite Structure

	- Hybrid Laminate Structure
	Ground Hail Zone and Requirements
	Runway Debris Zones and Requirements
	Lightning Strike Zones and Requirements
	In-Flight Discrete Source Damage Requirements

The first two categories of requirements (General and System [Airplane] Level Structural Design) apply to all material/structural designs and a significant number of these requirements deal with design load cases. One can also see many potential parallels between the categories for aircraft structure and lunar surface structure. For example, instead of In-Flight discrete source damage, a planetary surface system must consider micrometeoroid and lander ejecta damage sources.

The item "Minimum Gage Requirement" is an example of one that may be especially important for exploration planetary surface structures. Current structural mass estimation that has been performed for the Lunar Habitat pressure shell (see reference 1) relied on a single load case (internal pressure), with isolated margin-of-safety checks performed for a launch load case. The structural strength sizing required for this single load case resulted in very thin sandwich facesheets. As a result, the minimum gage criteria from reference 3 was applied to the structure. Although sizing with a single load case cannot be considered valid, the fact that a minimum gage constraint had to be imposed can be used to argue that defining the minimum gage for lunar surface structural applications is extremely important, since minimum gage will dictate the absolute minimum mass possible. The minimum gage value (which is material and structural concept dependent) for a structure is based on a damage tolerance evaluation, which requires a comprehensive assessment of the threat environment, the natural environment, load cases and material properties.

Structural Design Requirements Knowledge Current Status -

Metals: Poor
Polymeric Composites: Poor
Structural Soft Goods: Poor

Design Compliance

An evaluation must be performed on the structural system to demonstrate compliance such that every design requirement is met at each critical loading condition. Compliance can be accomplished through a combination of test and analysis. Structural analysis may be used only if the structure conforms to that for which experience has shown the analysis method to be reliable. The regulating authority may require ultimate load tests in cases where limit load tests are inadequate. A Design Compliance document will detail the PSEs in the system, acceptable analysis methods and equations, and types and degree of testing required. A detailed test plan describing test specimens, boundary conditions, loading histories, pass/fail criteria, etc. would also be developed. Demonstrating (through analysis and test) successful compliance to all structural design requirements would result in acceptance of the structural system for service.

<u>Design Compliance Current Status of knowledge -</u>

Metals: Poor
Polymeric Composites: Poor
Structural Soft Goods: Poor

Approach For Creating Necessary Design Data

At the end of each of the sections in "Design Requirements and Supporting Information", an overall status has been estimated. This status represents the author's opinion of the state-of-the-art in each area. Successfully designing planetary surface structural systems requires that the knowledge in each category exist, be comprehensive, and have high integrity. Based on the author's assessment, planetary surface systems for human exploration lack much of the foundational information that is required to design these structural systems. In order to begin addressing this deficiency, two potential tasks were outlined and submitted during the Technology Prioritization Process completed by LSS in December 2008:

1. Long term durability for polymeric composite materials and damage tolerance for metallic and polymeric composite structures; and,
2. Long term durability and damage tolerance for materials/structures for Inflatable Structures.

A detailed description of information needs and the state of knowledge pertaining to these two technology tasks has been described in this document.

In order to begin designing exploration planetary surface structural systems, the information and data in each of the major areas outlined under the "Design Requirements and Supporting Information" section must be developed, beginning with those areas where current knowledge is deemed to be Poor. The approach would be executed in approximately the same order in which those areas are discussed in this paper, with some activities proceeding in parallel. Major activities during the first several years would include:

1. collecting information and data,
2. defining the system structural concepts for which design must be performed,
3. identifying missing data and developing plans to obtain that data (through analysis and/or test),
4. performing trade studies to identify major material/structural concepts that could be applied to each system concept,
5. reconciling trade study and data development plans to identify required detailed tests and analyses,
6. performing the detailed tests and analyses,
7. compiling the planetary surface structural systems requirements and compliance document.

Concluding Remarks

The Lunar Surface Systems Project developed system concepts that would be necessary to establish and maintain a permanent human presence on the Lunar surface. A variety of specific system implementations were generated as a part of the scenarios, some level of system definition was completed, and masses estimated for each system. Because the architecture studies generally spawned a large number of system concepts and the studies were executed in a short amount of time, the resulting system definitions had very low design fidelity. The results of these low fidelity studies were insufficient to identify critical material and structures technology development needs. In particular, technology development needs cannot be inferred from concept definitions because those needs are particular to a system implementation (and thus change with implementation concept), and that implementation is dependent on, at a minimum, a conceptual design. This paper describes the broad steps that are required to develop and field a particular structural system with the steps being: 1) Define Requirements, 2) Develop the Design and 3) Demonstrate Compliance of the Design with all requirements. Completing this process is important because a comprehensive set of Structural Design Requirements does not currently exist for systems that must survive and operate on the lunar and other planetary surfaces. This paper also: outlines and describes in detail the information and data that are required to establish structural design requirements; outlines the information that would comprise a planetary surface system Structures Requirements document; provides a status of the data sets needed to establish requirements (most are currently incomplete or missing), and; outlines an approach for developing the necessary data and information. The resulting plan is intended to serve as the framework for implementing an exploration planetary surface structural systems technology development process.

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The Lunar Surface Systems Project developed system concepts that would be necessary to establish and maintain a permanent human presence on the Lunar surface. A variety of specific system implementations were generated as a part of the scenarios, some level of system definition was completed, and masses estimated for each system. Because the architecture studies generally spawned a large number of system concepts and the studies were executed in a short amount of time, the resulting system definitions had very low design fidelity. This paper describes the development sequence required to field a particular structural system: 1) Define Requirements, 2) Develop the Design and 3) Demonstrate Compliance of the Design to all Requirements. This paper also outlines and describes in detail the information and data that are required to establish structural design requirements and outlines the information that would comprise a planetary surface system Structures Requirements document.

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