

Framework for Seismic Vulnerability Assessment of Nonstructural Elements Inside an Inflatable Lunar Habitat

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The pursuit of knowledge and curiosity are once again driving humanity to seek a human presence on extraterrestrial bodies. While numerous challenges must be overcome on the moon to achieve this goal, the moonquake hazard has often been overlooked. Using NASA's Moon to Mars Architecture requirements for surface habitation and accounting for the midterm/long-term mission duration, a framework for vulnerability assessment is developed for essential nonstructural elements (NSEs) inside an inflatable habitat subjected to moonquakes. The aim of this study is to develop an approach to assess the vulnerability of typical NSEs that support essential equipment, such as the environmental control and life support system, under a paucity of information related to the seismic hazard. We also emphasize that the launch dynamic environment and lunar seismic environment exhibit notable differences in their characteristics, which can lead to higher lateral acceleration levels than initially expected. This acceleration may be linked to high-occurrence seismic events. However, due to the lack of information regarding the frequency of these events, the risk of NSEs being subjected to unforeseen loads increases. It is imperative to equip future lunar habitats with seismic mitigation measures until additional seismometers are deployed near upcoming surface human outposts.

Nomenclature

g = gravitational acceleration on Earth (9.81 m/s^2)
 g_L = gravitational acceleration on the moon (1.63 m/s^2)

I. Introduction

IN RECENT years, there has been a resurgence of global interest in space exploration, a renewed passion reminiscent of the Apollo era. During the 1950s to the 1970s, lunar surface missions enjoyed their golden age, witnessing the launch of approximately 90 missions. However, in the decades following the Apollo era, lunar exploration came to a standstill, with zero missions conducted. Nevertheless, the trajectory has changed dramatically, with the annual number of missions steadily increasing. Presently, both NASA and various private entities are making substantial investments in returning to the moon, positioning it as a short-term objective in their broader goal of reaching Mars. Under NASA's Artemis program, plans are underway for a short-term surface mission by the end of this decade. Concurrently, in alignment with NASA's Moon to Mars Architecture, the imperative of contemplating long-term surface habitation becomes the logical next stride in the quest for sustainable lunar exploration.

To achieve these goals, it is essential to delve deeply into the concepts of surface habitats and the potential architectural options for lunar surface missions. Surface habitats can be categorized based on their construction methods, with Class I habitats being fabricated and certified on Earth before launch, Class II habitats requiring additional assembly or deployment on the lunar surface, and Class III habitats involving complete construction on the extraterrestrial body's surface. Furthermore, architectural designs are intrinsically linked to the overall mission design. Inflatable habitats possess a distinct advantage over other Class I designs because they can substantially increase

the payload volume of the launch vehicle once deployed on the lunar surface. The concept of space habitation in inflatable structures has been in existence for decades, but its practical application was first tested with the Bigelow Expandable Activity Module (BEAM) module on the International Space Station (ISS). The BEAM module occupied 3.6 m^3 on the launch vehicle and expanded to an operational volume of 16 m^3 [1,2]. Currently, Sierra Space is in the process of developing their Large Integrated Flexible Environment (LIFE) orbital habitat, positioned to serve as the next-generation space station after the retirement of the ISS, boasting a claimed operational volume of 270 m^3 [3]. Inherently, the current engineering workforce is predominantly focused on launch vehicle operations and the development of the next orbital habitat. However, the next logical step is to extrapolate these developed technologies for lunar surface missions. NASA, in its Moon to Mars Architecture definition document and various other NASA sources, has used the example of a surface habitat using an inflatable torus technology on top of a lander [4]. This design concept appears to be a promising solution that needs to address the myriad challenges presented by the lunar environment. One of the known challenges often overlooked are seismic motions. This is primarily due to a lack of understanding regarding the impact of such events on a lunar habitat and the perceived safety provided by designs optimized for launch environment vibrations.

Lunar seismic research had its origins with the Apollo passive seismic experiment (APSE) in the late 1970s [5]. The advancements in planetary seismology resulting from this instrumentation have been of immeasurable value to the scientific community. Among the numerous insights gained, several key conclusions have emerged regarding the seismic hazard on the moon. First, it has been established that the lunar interior remains tectonically active. However, to gain a comprehensive understanding of the source of these seismic motions, additional data is imperative [6]. Furthermore, the paucity of data hampers accurate estimations of the energy released during seismic events, making it challenging to assert with any degree of certainty that the largest event observed represents the upper limit. Notably, significant seismic events are anticipated to have low occurrence, with intervals possibly extending more than eight years [7]. The limited available data also obstructs the establishment of a seismic risk assessment for lunar bases and the evaluation of ground motion effects on lunar habitats [8]. Evidence gleaned from the proximity of recorded moonquakes to young thrust faults, along with satellite imagery, suggests ongoing tectonic activity on the moon [9]. Given these findings, it becomes evident that until a more substantial dataset becomes available to enhance our comprehension of shallow

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moonquakes, a conservative approach is needed in the design of Class I lunar habitats as opposed to ignoring the risk because of the need for more data. This raises a critical question: Given that a Class I lunar habitat designed for short-to-long-term missions is engineered to withstand the rigors of the launch environment, will shallow moonquakes pose a significant risk to its structural integrity? If so, how can we assess this vulnerability and its potential impact on the habitat's contents?

This paper is structured to address the aforementioned inquiries through the utilization of numerical evidence highlighting the differences in performance between launch-induced vibrations and shallow moonquakes. We delve into an illustrative example involving the design of a Class I lunar habitat, examining the habitat's performance under two scenarios: first, considering the effects of vibrations solely from the launch environment, and, second, factoring in a series of scaled shallow moonquakes. Subsequently, we apply the insights gained from this illustrative example to establish a framework for assessing the vulnerability of the habitat's contents relative to the mission duration. Finally, we conclude the study with a discussion of the results and a comprehensive summary of our findings.

II. Illustrative Example

In this study, the Class I habitat chosen for analysis comprises a torus-shaped inflatable structure mounted atop a lander housing the environmental control and life support system (ECLSS) universal pallet design from Collins Aerospace [10], along with a work desk and a storage rack. The torus stands at a height of 6 m and encompasses two floors, supported by a cantilever hydraulic jack system. The core of the torus consists of solid aluminum vertical members, leaving open spaces for equipment installation. The connection between the torus and the lander is assumed to be facilitated by an aluminum pedestal. For reference, the lander is assumed to have dimensions similar to those of the descent stage of the lunar module (LM) from the Apollo missions. Notably, the lunar habitat exhibits distinct dynamic configurations for both launch conditions and when fully deployed on the lunar surface (Fig. 1). Within the habitat, the ECLSS universal pallet, work desk, and storage rack are situated on the second floor.

The contents within the habitat are treated as components, each with its own distinct dynamic characteristics and its own response to the ground motion transferred through the main structure. The ECLSS universal pallet, for instance, is composed of a frame featuring four aluminum elements, incorporating lateral restraints both at

the supports and midheight points. The dimensions of the pallet are assumed as 0.60 m $\times$ 0.60 m $\times$ 1.80 m [25" $\times$ 25" $\times$ 70"] according to the suggestions in [10]. It is assumed that the pallet is supported at both its top and bottom via pin connections (Figs. 2a and 2b). In a similar fashion, the storage racks are assumed to possess dimensions of similar proportions, with the added assumption of a fixed bolted connection at their bases (Figs. 2c and 2d). Likewise, the desk is presumed to share comparable dimensions with a height of 0.75 m [30"], also featuring a fixed bolted connection for stability (Figs. 2e and 2f). Due to the inherent design of the habitat, in its undeployed state within the payload fairing, it is primarily containing the ECLSS among the other components that are assumed to be installed in the expanded volume on future missions.

The ECLSS universal pallet is assumed to be positioned within the aluminum core of the torus, as this space remains unchanged between deployment conditions. It is necessary to describe the physics-based model that describes the response of the structural elements due to the imposed vibrations.

The fundamental dynamic equation for the habitat, subjected to external dynamic forces in both the launch and lunar seismic environments, and referred to as the undeployed and deployed conditions, respectively, can be expressed in matrix form as

$$[M_i]\{\ddot{u}_i\} + [C_i]\{\dot{u}_i\} + [K_i]\{u_i\} = \{F_i\} \quad (1)$$

where $[M_i]$, $[C_i]$, and $[K_i]$ represent the mass, damping, and stiffness matrices, respectively; $\{\ddot{u}_i\}$, $\{\dot{u}_i\}$, and $\{u_i\}$ denote the displacement, velocity, and acceleration vectors; and $\{F_i\}$ signifies the external force vector. This is applicable for each i -structural model.

For the launch environment, $[M_{\text{undeployed}}]$ incorporates the mass contributions from the descent stage, including the associated propellant, the self-weight of structural materials, the softgoods mass, and the mass of the nonstructural elements (NSE) launched with habitat. Similarly, $[K_{\text{undeployed}}]$ encompasses the lateral pinned stiffness of the landing legs, the reinforcing plates of the descent stage, the aluminum transfer pedestal, and the columns of the torus core, in addition to the stiffness of the mechanical interface on top that supports the undeployed structure during launch. $\{F_{\text{undeployed}}\}$ in this context draws its values from the signals representing the launch dynamic environment (Fig. 3a).

In the lunar seismic context, it is assumed that the habitat is experiencing external forces after a minimum of 5 years has passed since deployment, time assumed for a short-term surface mission.

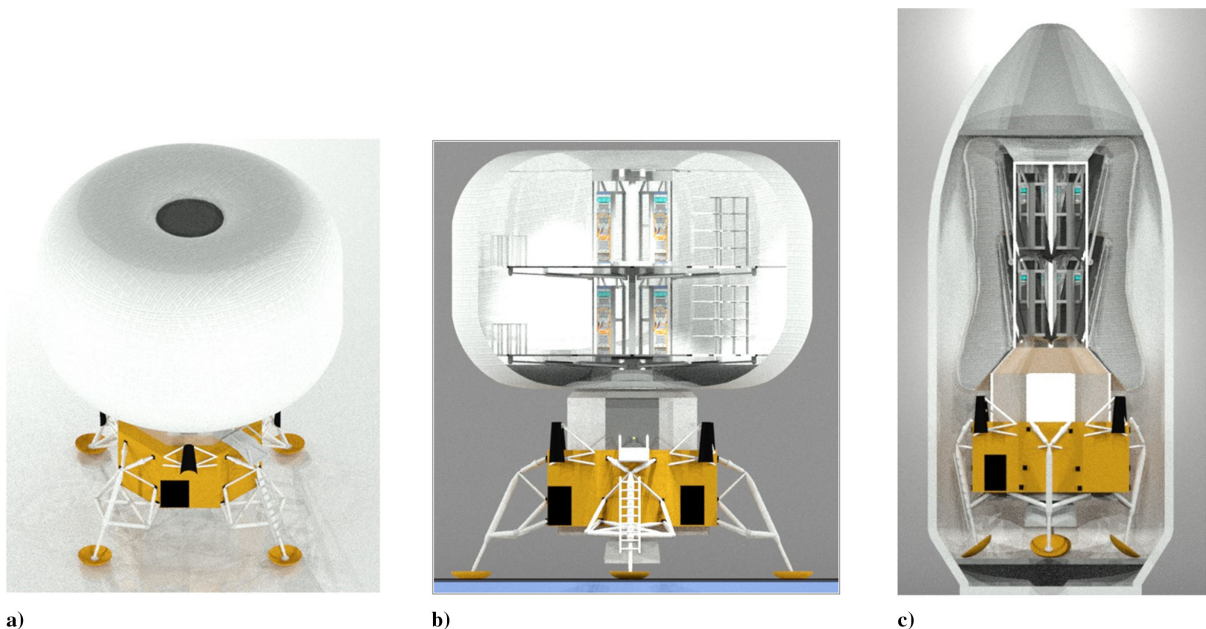


Fig. 1 Illustrative example conceptual views: a) isometric view deployed; b) section view deployed; c) section view undeployed.

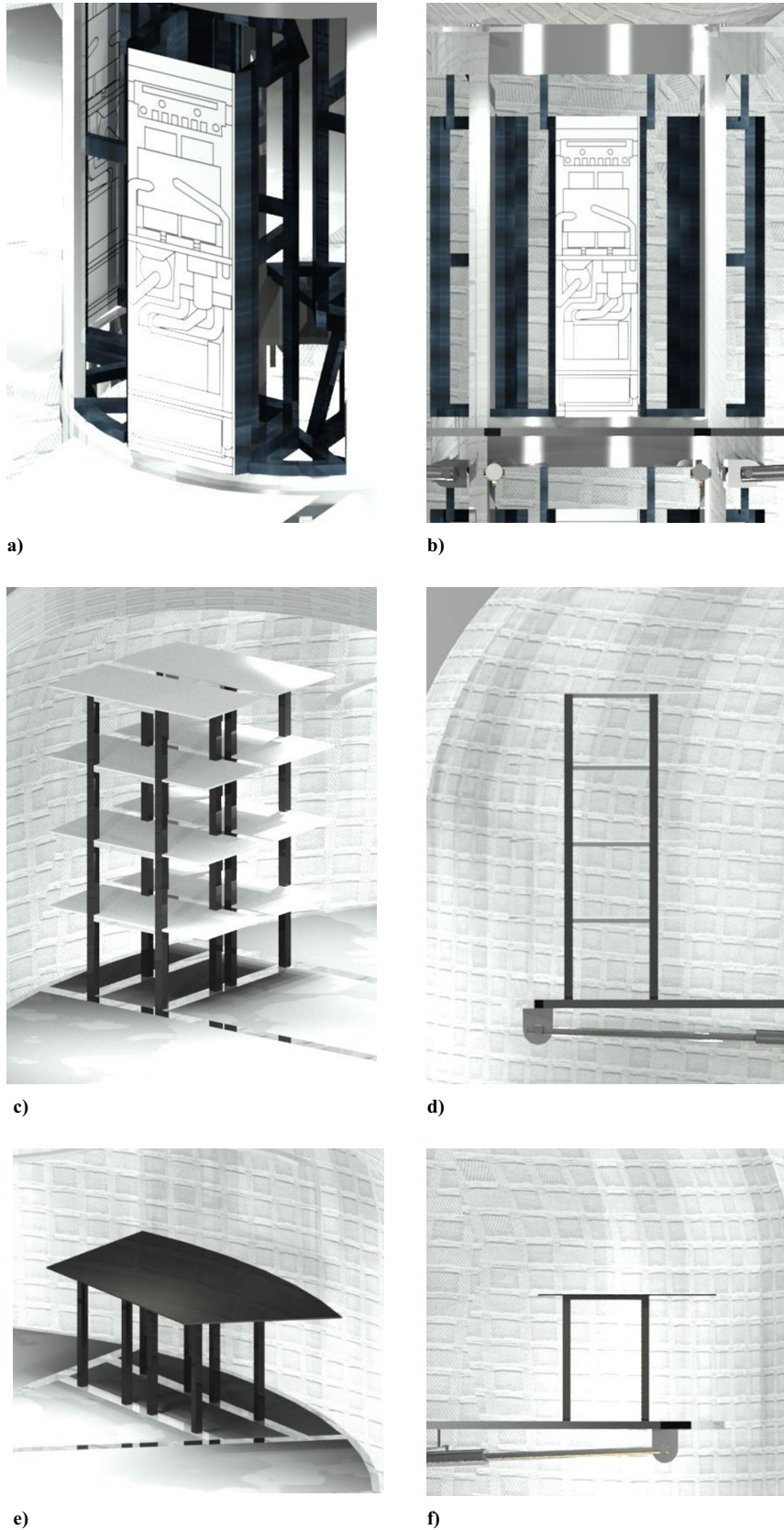


Fig. 2 Internal nonstructural elements 3-D and front view representation, respectively: a, b) ECLSS universal pallet; c, d) storage racks; e, f) work desk.

$[M_{\text{deployed}}]$ encompasses the mass of the descent stage without its propellant, the self-weight of the structural materials, the mass of the softgoods, and any additional mass added in future missions. Likewise, $[K_{\text{deployed}}]$ maintains the same stiffness characteristics as in previous cases, with the exception of the stiffness associated with the support

condition at the top due to the payload fairing, which is not considered. $\{F_{\text{deployed}}\}$ in this scenario draws its values from the signals representing the lunar seismic motion environment. These distinct parameters account for the unique dynamics experienced during lunar seismic events, differentiating them from the launch environment (Fig. 3b).

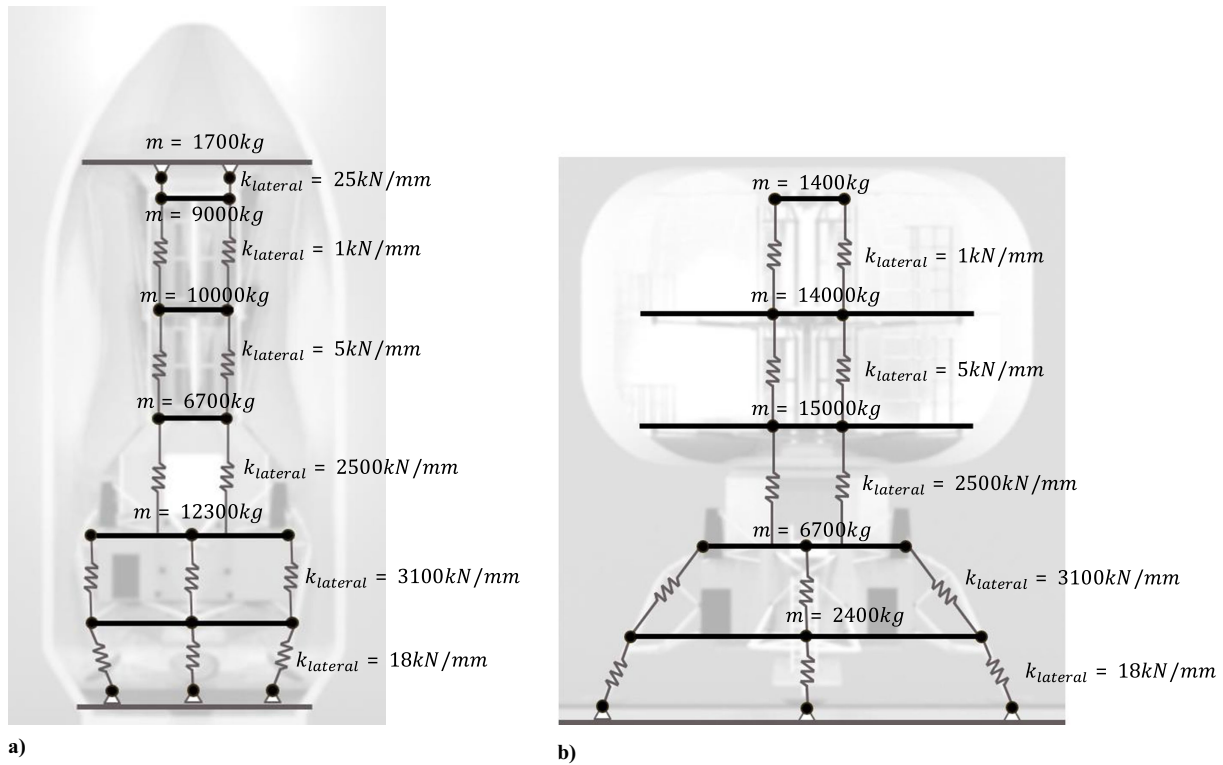


Fig. 3 Dynamic model input parameters' primary structure: a) deployed surface habitat; b) undeployed structure inside payload fairing.

In the case of the ECLSS, desk, and storage rack, $[M_{\text{ECLSS/desk/rack}}]$ accounts for the self-weight of the respective component plus an additional superimposed self-mass. $[K_{\text{ECLSS/desk/rack}}]$ encompasses the lateral stiffness of the aluminum elements, with the conceptual design of the transverse dimensions derived from [10]. $\{F_{\text{ECLSS/desk/rack}}\}$, in this scenario based on the acceleration response of the primary structure at the base of the NSE. It is important to note that this approximation neglects the influence of the dynamic coupled interaction between the primary structure and the NSE (Fig. 4).

A time-stepping technique with modal simplification using Newmark's method is employed to solve the aforementioned equations [11]. The damping matrix is constructed with the assumption of classical damping at 5% of the critical damping. Consequently, it becomes imperative to thoroughly examine the dynamic loads imposed by the launch environment that the universal pallet will

encounter. This step is crucial for establishing a reference point for assessing the structural integrity of the habitat toward seismic motions that may take place on the lunar surface after deployment.

III. Launch Dynamic Environment

The launch of a rocket subjects its payload to a multitude of dynamic loads, ranging from the ignition of the engines, the liftoff release loads, the aerodynamic pressures experienced during ascent, as well as maneuvering forces, among others. These loads are categorized based on their sources, which can include acoustic and vibratory excitations. It is imperative to thoroughly assess these loads to guarantee the structural integrity and proper functionality of the spacecraft and its payloads.

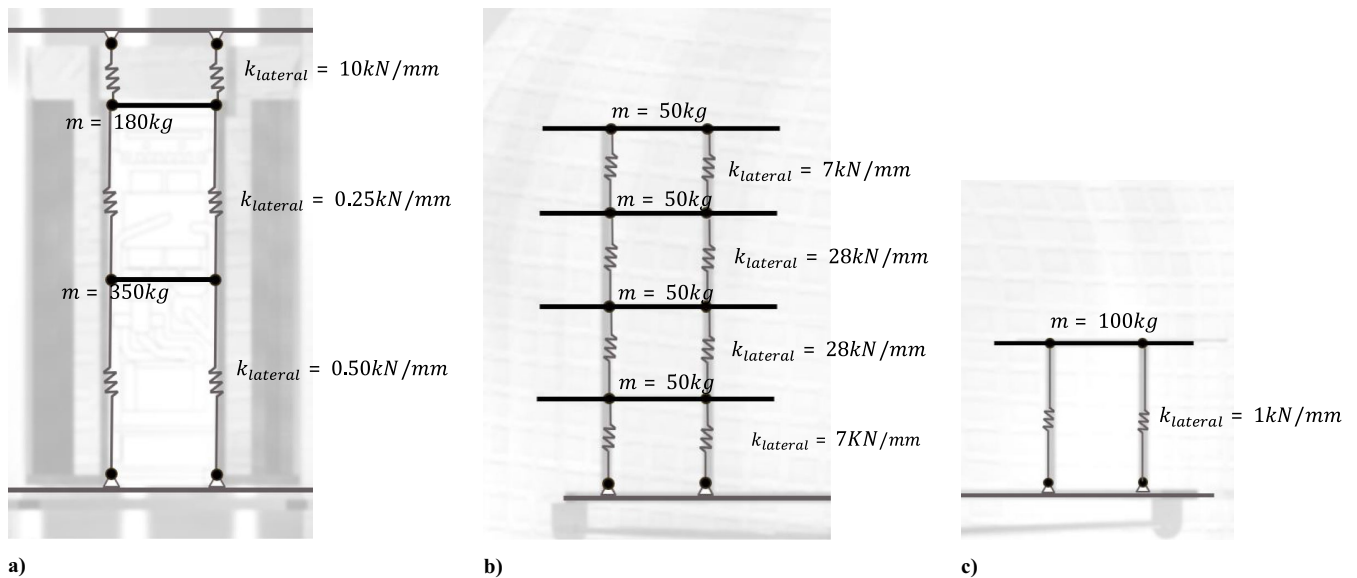


Fig. 4 Dynamic model input parameters' secondary structures: a) ECLSS; b) storage rack; c) work desk.

All of these loads are encapsulated in a set of test requirements that hinge on the specific characteristics of the payload [12]. Among other required vibration tests, the sine sweep test and the random vibration test are most common. The sine sweep test aims to replicate the low-frequency dynamic environment experienced by the payload, in accordance with the mission-specific coupled load analysis (CLA). The CLA serves the purpose of providing a reliable prediction of the coupled dynamic behavior between the vehicle and the payload. Once the final design of the structure has been reached, along with a dynamic model capable of accurately forecasting flight responses, it becomes necessary to conduct tests to validate each dynamic characteristic of the model. This validation process is essential for qualifying the payload for flight in alignment with their analytical solutions. In contrast, the random vibration test is employed to qualify components of the payload that are susceptible to high-frequency vibrations, including electrical, electronic, and electro-mechanical components [13–15]. For the purposes of this work, where a detailed CLA analysis is not the primary focus, recommendations provided by two aerospace companies are used as reference for the sine sweep input time history and for the input motion of random vibration test.

Commercial spacecraft such as the Atlas V and Falcon vehicles provide initial recommendations for the sine vibration test, which can later be refined through the use of CLA, and offer guidelines for high-frequency random vibration tests [16,17]. To generate the sine sweep time history, specifications for lateral loads from both companies are adhered to, with a duration matching the rate of 4 octaves per minute [18] (Fig. 5). Similarly, the synthesizing of a time history in accordance with the power spectral density (PSD) outlined in NASA's standard minimum workmanship criteria and Falcon vehicle recommendations is used, with a set duration of 2 minutes, following NASA's stipulated requirements [14] (Fig. 6). It is worth noting that accurately representing the dynamic forces experienced during launch is a complex task, and relying solely on these two signals serves as a foundational approach for designing the payload to withstand lateral loads. A Class I habitat situated within the payload fairing of such rockets will have to endure these forces without damage, but it is important to consider that their ultimate goal is an extended stay on the lunar surface, where seismic motions constitute another source of lateral loads. Therefore, it is important to describe these seismic signals in detail.

IV. Lunar Seismic Motion Environment

The seismic data collected by the APSE was initially recorded on analog tape. Over the years, the responsibility for preserving this valuable data has changed hands among various institutions, leading to potential errors in the original records. To ensure accuracy and reliability, we employed the raw seismic data from [19], which was formatted in the Standard for the Exchange of Earthquake Data (SEED). Furthermore, we adopted the data processing and refinement methodology outlined in their work for the purpose of cleaning and analyzing the seismic data. Among the extensive seismic dataset comprising approximately 12,000 events [6], the seismic motions of particular interest are the 28 shallow moonquakes, also known as high-frequency teleseismic events (HFTs). These events represent the most energetic seismic occurrences observed during the 8-year campaign.

We initiated the process by selecting seismic motions for our analysis. To achieve this, we followed the recommendation of using eleven distinct motions to capture various motion characteristics. Typically, in terrestrial habitats, this selection is performed using ground motions that share similar on-site seismic characteristics. However, since characterizing lunar sites lacks sufficient information, we opted to begin by choosing events with the highest recorded magnitude from the APSE dataset. Specifically, we selected events with the highest lunar HFT magnitude, as defined by [20]. It is important to note that this magnitude is primarily used for comparative purposes during the selection process and other magnitude definitions can characterize the motions better. There are alternative selection methods based on the frequency content of the seismic motions and the natural frequency of the structure. However, as choosing 11 motions already covers 40% of the available data, this additional consideration is not expected to significantly impact the final results. Subsequently, the selected events, referenced in Fig. 7, are meticulously reviewed at each of their recording stations and channels. This closer examination aimed to further refine our choices by identifying signals with minimal recording errors, spikes, and the highest amplitudes. In Fig. 8, is noticeable that the measured amplitudes are in the order of $1e-07 g_L$. This observation raises questions on the expectation that in view of those limited measurements of the lateral acceleration experienced from shallow moonquakes by a surface habitat launched from Earth, should already be well-protected since it is designed to handle the lateral acceleration induced during launch.

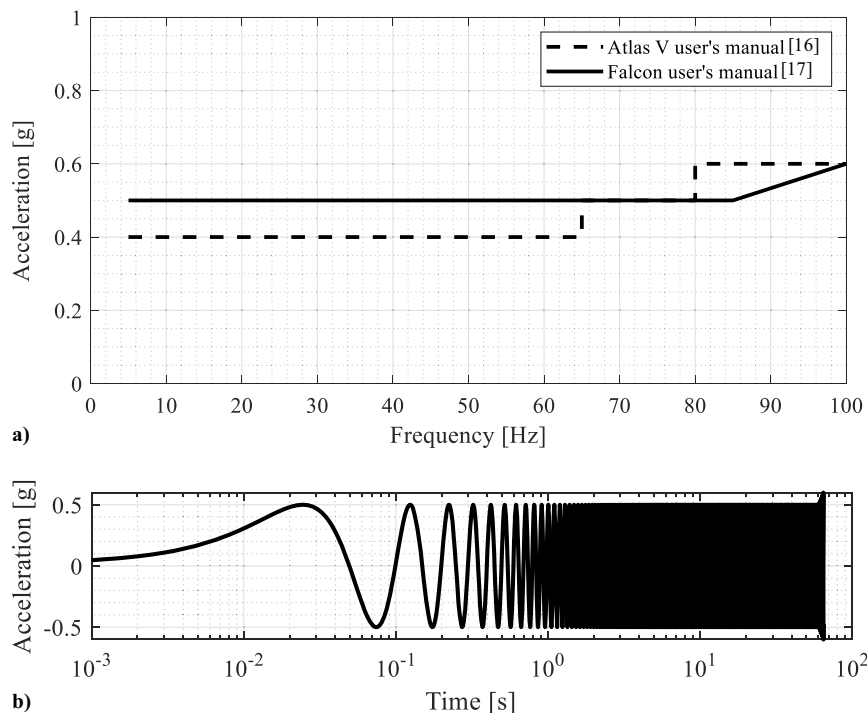


Fig. 5 Sine sweep vibration test signal: a) users' guide specification seed from space vehicle manufacturer; b) time history generated from specification.

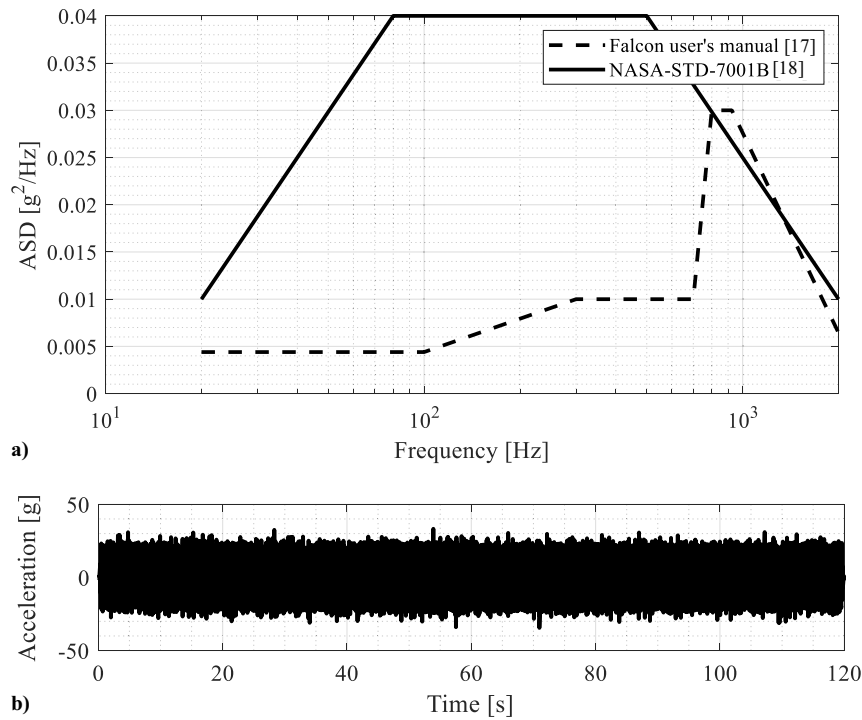


Fig. 6 Random vibration test signal: a) mass-attenuated workmanship vibration spectrum from NASA-STD-7001B; b) white noise time history generated from specification.

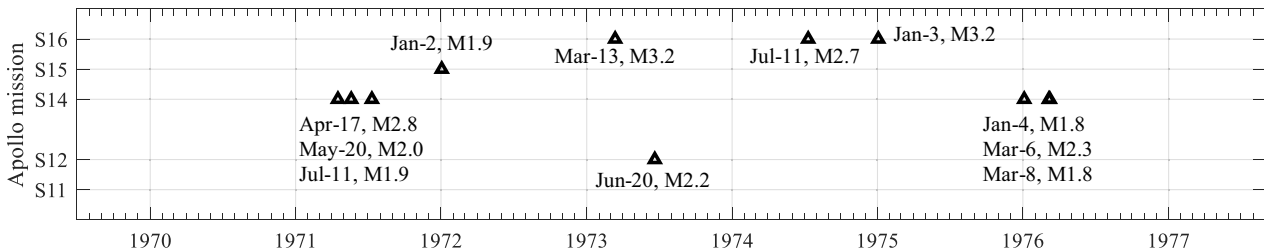


Fig. 7 HFT events used for analysis; 11 out of 28 APSE-recorded events are used.

It is crucial to highlight that all these events occurred at distances as far as 500 km from the measuring station, with the majority of them being recorded at distances of at least 1000 km from the epicenter [21]. Seismic waves traveling through the lunar crust experience attenuation with distance, meaning that ground acceleration measurements decrease as the distance from the seismic station increases. Unfortunately, there is insufficient seismometer data to confidently establish these relationships. However, some researchers have explored this issue by observing satellite images. They have discovered that in close proximity to the seismic event source, ground acceleration can reach up to $1.6g_L$ [9], and for a moment magnitude event of $M_w = 4$, this acceleration can increase to as much as $4g_L$ [22]. Both sources concur that beyond 50 km from the source, the acceleration levels begin to flatten out, approaching zero. Drawing conclusions about seismic motions using the directly measured data would be an oversimplification. To accurately predict seismic hazard, it is necessary to investigate variations in motion amplitude with distance and the occurrence patterns of these events. This comprehensive analysis aligns with the principles of earthquake engineering, particularly probabilistic seismic hazard analysis (PSHA).

V. Framework for Lunar Seismic Vulnerability Assessment

In the modern field of earthquake engineering, countries continue to grapple with a fundamental debate among engineers regarding the tradeoff between designing for higher seismic demands and reducing economic and life losses. This delicate balance can only be struck

when there is a clear understanding of what to anticipate at a specific site. Engineers play a crucial role in leveraging the expertise of seismologists and geologists to make informed decisions about the cost and capacity of a structure. On the other hand, seismologists face the challenging task of developing geophysical models for seismic sources and transmission media while working with limited available data from the Earth's interior. Ultimately, it falls upon the engineer to make informed decisions in a project, as they possess a wider range of tools for assessing the risks involved. Historical data can offer insights into seismic activity, but the method used to delineate seismic hazard into specific areas often depends on data availability, especially when the precise occurrence of seismic events is unknown.

Engineering seismic risk analysis, widely used and accepted as detailed in [23], has undergone significant evolution over the last 10 decades, with contributions from various authors culminating in what is now known as PSHA. To this day, PSHA relies on two main inputs: ground motion prediction equations (GMPEs) and site-specific magnitude-recurrence data. The accuracy and reliability of the method are heavily contingent upon the quality of these inputs. Following its global recognition, ongoing efforts have focused on gathering sufficient data for the site of interest to establish robust magnitude-recurrence estimations and achieving an accurate representation of the GMPE for the site through geophysical models of the specific seismic setting. The method to this day is represented with the following equation:

$$P(Y > y) \cong \sum_{i=1}^n v_i \iint P[Y > y | M, R] f_{M,R}(m, r) dm dr \quad (2)$$

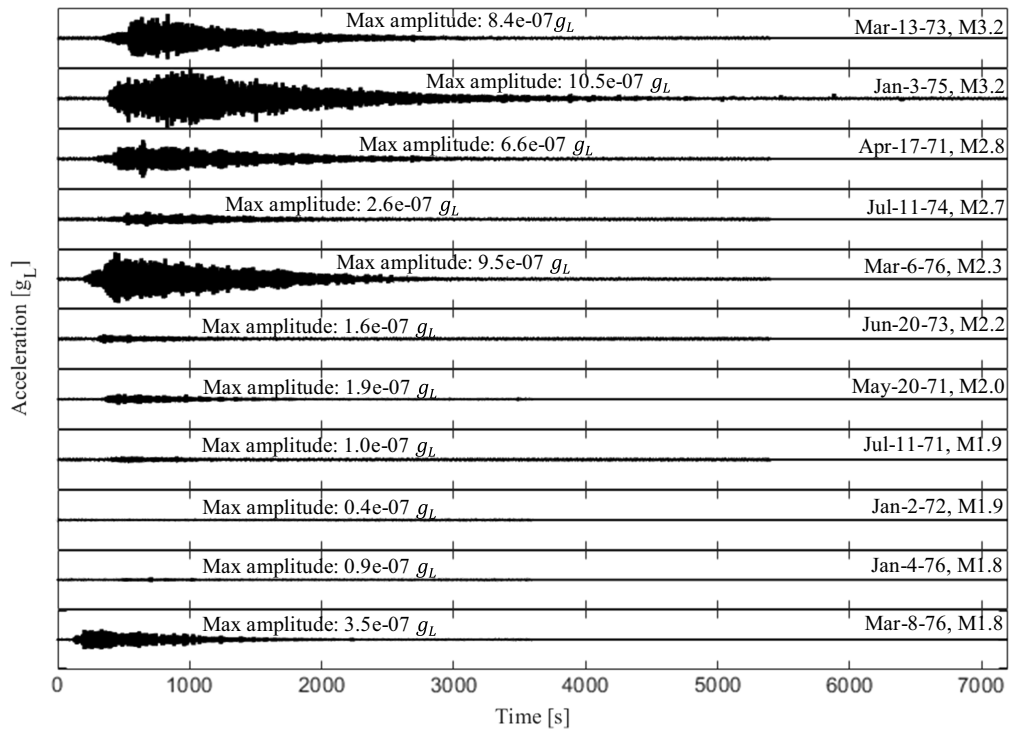


Fig. 8 Shallow seismic events used in the analysis.

where Y and y are earthquake ground motions, M and m are magnitudes, R and r are distance from the source, v_i is the occurrence rate of earthquakes for source i , and the summation is over all n sources [24]. Capital letters represent random variables.

To construct an accurate seismic model, it is essential to acquire sufficient quantities of data in close proximity to the targeted site. For instance, consider the state of California in the United States, which spans an area of approximately 5000 km², similar in scale to the lunar south pole. The state's seismic instrumentation has evolved significantly over the years. In the 1930s, there were around 50 instruments in place, and by the 1970s, that number had grown to 500. Today, the state boasts more than 1000 instruments. In the case of GMPEs for California, the wealth of data collected over several decades has enabled substantial advancements. In the 1980s, they had only a rudimentary model of the internal seismic mechanism, primarily based on 16 known fault sources. By the 2000s, this number had increased to 200, and in the most recent model, they have incorporated 350 faults and the interactions between them. This progression highlights the importance of accumulating data to develop accurate seismic risk models and underscores that understanding the internal mechanisms requires significant time and research efforts.

The authors in [25] conducted a PSHA evaluation for a specific site near the Apollo 17 landing site. Their work involved applying the methodology and accounting for epistemic uncertainty in their models. Their findings emphasized the necessity of enhancing the seismic characterization of the site with additional data. The preliminary results

of their work yielded a design spectrum, suggesting that any structure situated in the studied lunar location should be designed with a maximum ground acceleration of $2g_L$ for a 10% probability in 50 years, depending on the structure fundamental frequency. However, when it comes to other lunar regions, like the lunar south pole or other sites of interest, the lack of information makes the method unreliable.

On the moon, the APSE recorded a total of 28 shallow moonquakes over an 8-year period. The frequency of occurrence, organized according to event magnitude, is a typical way of representing seismic motions on a site. Figure 9 provides a plot showing the cumulative annual frequency, which is the total number of seismic motions that occurred with a magnitude greater than the previous lower magnitude over the 8-year span. On Earth, a comprehensive interpolation process is typically employed, leveraging a multitude of data points from seismometers located in close proximity to one another [26]. However, on the moon, such an approach is not feasible due to the dearth of information. Seismometers were positioned as far as 1000 km apart, rendering it impossible to draw conclusive results for a specific site. Instead, a logarithmic extrapolation can serve to give us a first estimate on the occurrence of greater, more intense events. As more data become available, the arbitrarily selected upper and lower bounds (shown here as an illustration) would be replaced with bounds based on the standard deviation of the cloud of points to set the confidence limits of the hazard.

Similarly, the construction of GMPEs on Earth relies on data collected from seismometers recording a variety of peak ground

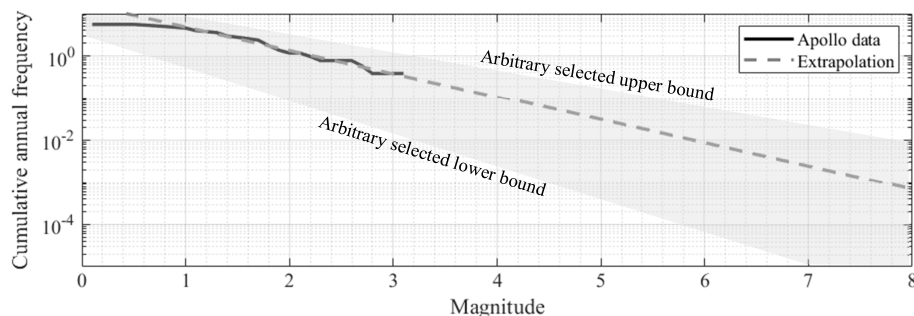


Fig. 9 Magnitude–frequency relationship established based on the limited APSE data.

accelerations, which can be correlated with their distance from the seismic source to formulate predictive curves. Unfortunately, this approach is also hindered by the limited data available thus far.

Knowing the state of the PSHA on the moon, a framework to assess the vulnerability of a Class I inflatable lunar habitat is presented. It is developed for structural engineers with the goal of establishing the impact that a strong motion could mean for the contents of a habitat.

The framework depicted in Fig. 10 commences with the definition of the disturbances, taking into account both the launch environment and lunar seismic environment as discussed in previous sections. It is important to note that launch environment motions are a standardized laboratory representation of the flight environment, based on a wealth of data and experience from past flights. In contrast, lunar seismic motions are nondeterministic, lacking standardization, and are hampered by a dearth of data and real-world application experience. This knowledge gap is precisely why the application of PSHA is necessary to estimate the motions that a lunar habitat might encounter.

Directly applying PSHA with the available data is not feasible due to the limited information, which is insufficient to adequately support the methodology and produce precise results. At best, only preliminary results could be obtained. Instead, the framework suggests resolving the issue in a conservative manner, particularly until sufficient data becomes available to enhance our engineering understanding. The initial step of the inverse PSHA block involves establishing a design ground acceleration scaling factor that adjusts the amplitudes of the available lunar ground motion data up or down to find the scale factor that best resembles the governing design requirements for lateral load. In practice, lateral load design considerations originate from the lateral vibrations experienced during launch. Subsequently, the framework excludes the usage of the attenuation on the GMPEs since the structure is assumed to be in proximity to the seismic source. It relies only on the near-source peak ground acceleration from the uncertain GMPEs based on state-of-the-art studies. These uncertain GMPEs are then correlated with the magnitude and frequency of occurrence. As a result, the probability of occurrence of that ground acceleration can be associated with various mission durations. This

approach, referred to as the “inverse PSHA,” is a central component of this work.

Simultaneously, once the design ground acceleration is established, a structural analysis becomes necessary to assess the response of the primary structure. This analysis, in turn, informs the response of the components or NSE, allowing for the determination of their expected performance. The simplest method to transfer the seismic disturbance to the internal components is the floor response method. Here the floor acceleration of the primary structure is first determined, and then used as an input to the base of the dynamic model of the NSE [27–29]. Other more sophisticated methods can account for dynamic interactions, but are not needed here to assess overall performance [27].

Several values of the design ground acceleration must be considered to explore all levels of the structure’s response due to changes in its magnitude. Through this process, one can find the scale parameter that approximately produces the same response of the structure and its NSE elements, resembling the response of the launch dynamic environment. In earthquake engineering this iterative process is called incremental dynamic analysis (IDA) [30]. In establishing the proposed framework, the IDA intensity measure (IM) used is a scale factor on the ground acceleration that monotonically increases using enough increments needed to trigger the established acceptance criteria. With this set of responses, the acceptance criteria function of the protection necessary for given NSE must be applied to determine whether the structure, under the specified probability of exceedance for the mission duration, meets the expected performance standards for the NSE. For illustrative purposes, the material’s yield is used to represent damage to NSE.

In the next section, we present a detailed description of the results obtained by applying the framework to the illustrative example. It is important to emphasize that any dynamic model based on first principles that satisfy equilibrium and material behavior can be used to assess the vulnerability of a structure to the lunar seismic environment. This work does not primarily focus on the complexity of the dynamic model itself and, as a result, the accuracy of the results. The

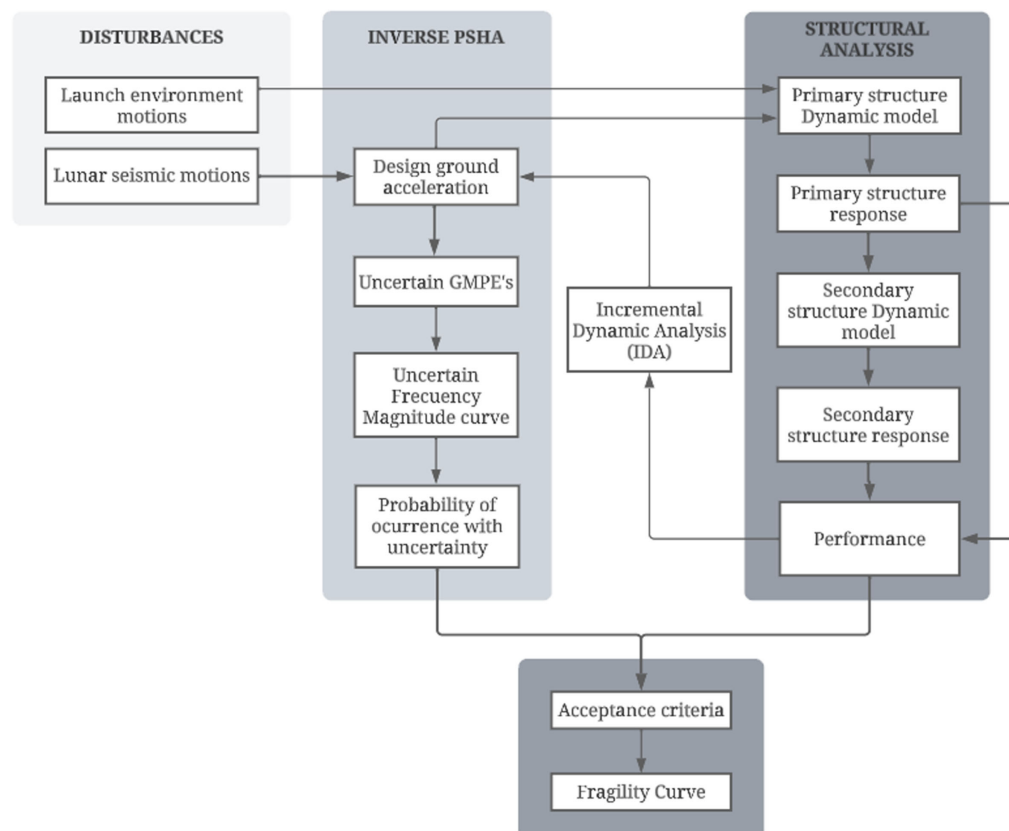


Fig. 10 Framework for lunar seismic vulnerability assessment.

process involves several steps, which can be further refined as the project progresses, leading to increased complexity and reduced uncertainty in the results.

VI. Numerical Simulation

Implementing the framework into the illustrative example, as defined in the previous section, and considering all aspects of the analysis reveal that seismic motion produces distinct responses in terms of amplitude, frequency content, and duration for the Class I lunar habitat. Additionally, seismic activity introduces a risk into the habitat's integrity associated with the mission duration due to the levels of uncertainty inherent in the engineering process. Following the framework's steps, the disturbances are determined based on the definitions provided in earlier sections. An inverse PSHA is conducted, followed by a structural analysis using these ground accelerations. Finally, a chosen acceptance criterion is established for the NSE to qualify the responses using its fragility curve.

First, the response of the primary structure is evaluated using the recording from the lunar seismic environment, with a scaled value of $1.0g_L$ arbitrarily selected as the maximum expected peak ground acceleration for the habitat. It is worth noting that other authors suggest that, near the source, this parameter could reach values far greater than $1.0g_L$ [9,22]. The deployed structure, shown in Fig. 11,

exhibited a maximum displacement of 2.4 cm, while the undeployed structure, within the payload fairing, experienced an estimated maximum displacement of 0.6 cm. Furthermore, the displacement response time histories revealed that this response due to the lunar seismic environment lasted for over an hour, whereas the launch environment's effect persisted only for a couple of minutes.

Recognizing these variations in response, it becomes evident that there must be a scale factor for the lunar seismic environment that can produce similar results with the launch environment, as the latter is already incorporated into the design guidelines and requirements. After the IDA, a scale factor of $3.0g_L$ is identified as the ground acceleration that closely approximated the deformation responses of the structures. With the responses obtained for the primary structure under consideration of both scale parameters, $1.0g_L$ and $3.0g_L$, the accelerations at the supports of the NSE from the second floor, as illustrative purposes, are transferred as ground accelerations for the latter. Subsequently, the responses of the ECLSS under both scaling parameters are presented in Fig. 12. In the case of $1.0g_L$, the deformed shape indicated a maximum displacement of 0.6 cm for the deployed state and 1 cm for the ECLSS inside the undeployed habitat. Transitioning to the $3.0g_L$ case, the response remained similar, with displacements of approximately 0.6 cm for both scenarios.

Furthermore, when assessing the energy across different frequency ranges, it is observed that the launch environment predominantly

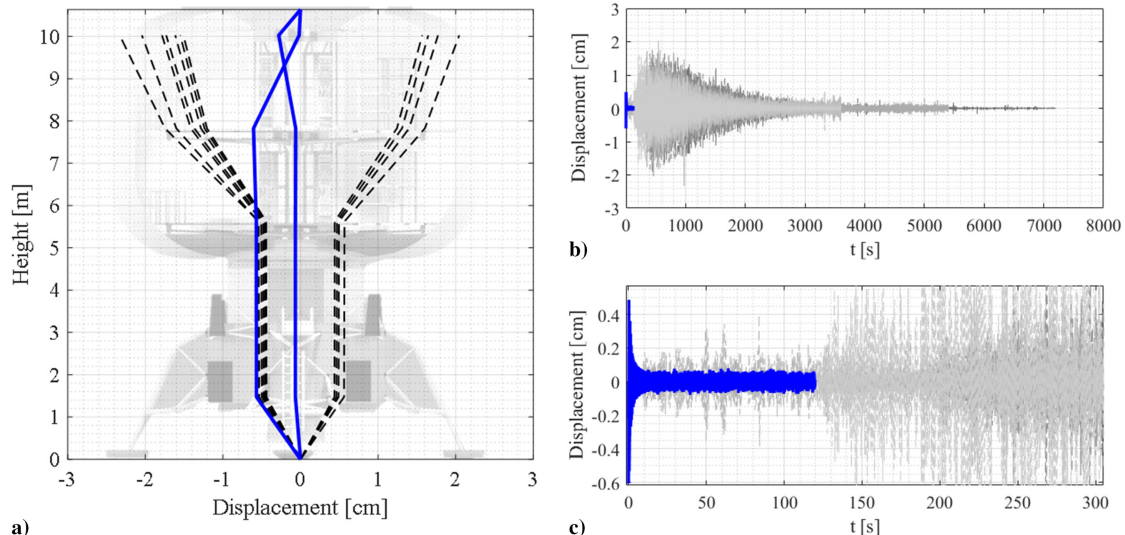


Fig. 11 Deployed Class I Inflatable Lunar Habitat response: a) deformed shape; b) time history of maximum displacement; c) zoom-in. Solid lines: launch environment; dashed lines: lunar seismic environment.

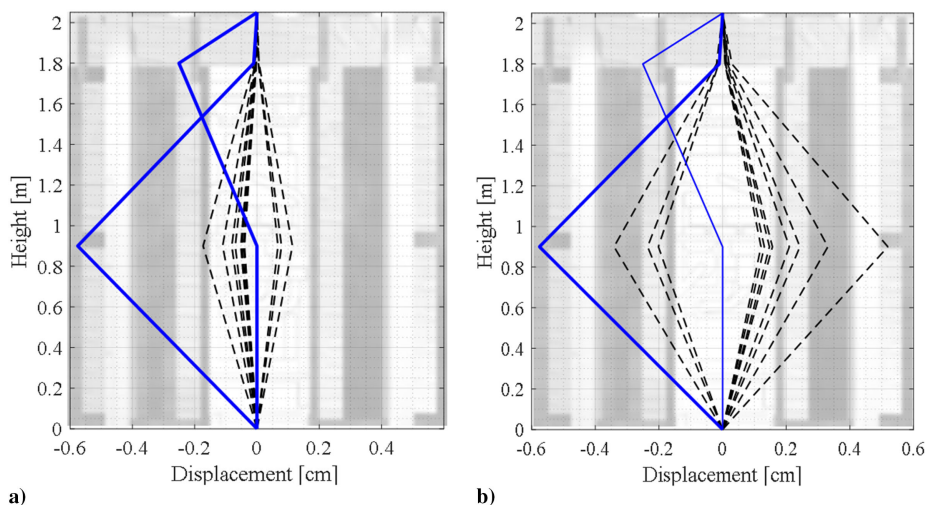


Fig. 12 ECLSS's deformed shapes for the scaled lunar environment to a) $1.0g_L$ and b) $0.1g_L$. Solid lines: launch environment; dashed lines: lunar seismic environment.

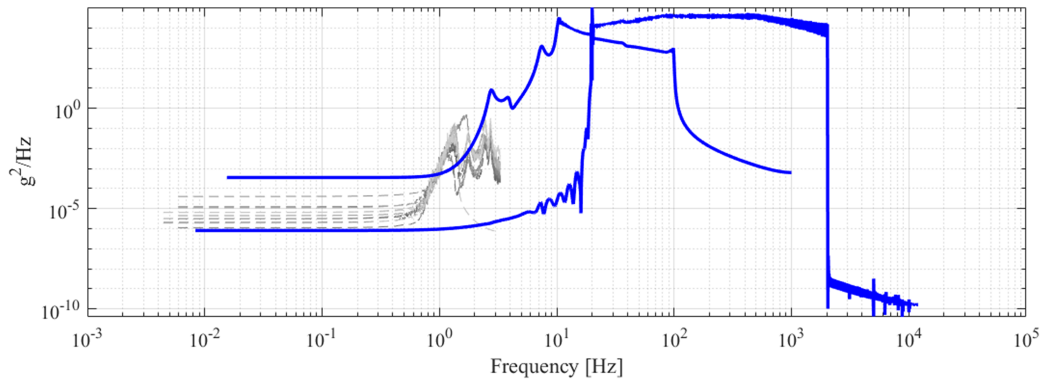


Fig. 13 Power spectral density curves of the ECLSS response. Solid lines represent the launch environment responses, while dashed lines correspond to the 11 lunar seismic environment responses.

encompasses frequencies above 10 Hz, extending up to 2000 Hz, for the minimum workmanship criteria. In contrast, the lunar seismic environment primarily operates within frequencies near 1 Hz, where various habitat configurations can exhibit resonance at their fundamental frequencies Fig. 13. Analyzing the energy within this specific frequency range, it becomes evident that the launch environment contains approximately 10–100 times more energy compared to the lunar seismic environment. However, the structure is more susceptible to the frequency range covered by the seismic motions, including the effects of response duration.

Other results can be observed for the other NSE, specifically the storage rack and desk. These elements are assumed to not be present in the launch configuration. Therefore, their evaluation focused solely on the lunar seismic environment. When considering these elements with their nominal dimensions, the results showed low transmitted accelerations (Fig. 14). This study can be complemented in future work with an acceptance criteria based on comfort and the requirements for sensitive equipment on their support structures.

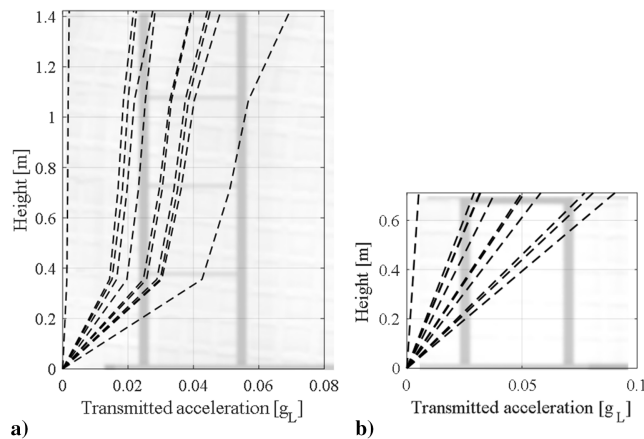


Fig. 14 Transmitted accelerations: a) storage rack; b) work desk.

The acceptance criteria for the ECLSS, for instance, involve a set of limits that correlate the magnitude of the motion with different damage states. To illustrate the implementation of these criteria, the defined limit states for the ECLSS rack constructed of aluminum members are based on the cumulative integral of the absolute displacement response, also named cumulative absolute absement (CAA).

Ultimately, the framework yields a comprehensive analysis of the system's response, considering the acceptance criteria and their probability of exceedance over the mission duration. Figure 9 illustrates the probability of exceedance in the form of the cumulative annual frequency. As more data become available, one can then associate the structure's response with a return period.

In Fig. 15, the probability of structural damage within the ECLSS is described based on the defined acceptance criteria, in response to the maximum ground acceleration imposed by the set of 11 seismic motions. The figure demonstrates that, when considering the launch environment, the ECLSS has a 95% probability of remaining in a low damage state, indicating that it does not sustain permanent damage, which aligns with expectations for the launch environment. However, increasing the ground acceleration by moving to the right on the horizontal axis in Fig. 15, the probability of experiencing more severe damage states increases. These lateral acceleration values may be realized in the lunar seismic environment. In the case of $1.0g_L$, the structure has a high likelihood of being in the failure state. It is essential to emphasize that these results are significantly influenced by the dynamic model defined in the previous section, as well as the chosen acceptance criteria, all of which were determined based on judgment and very limited data available.

VII. Conclusions

The used dynamic conditions during launch and within the lunar surface habitat exhibit significant variations in terms of both amplitude and frequency content of dynamic forces. Employing the proposed framework allows for a comprehensive assessment of the

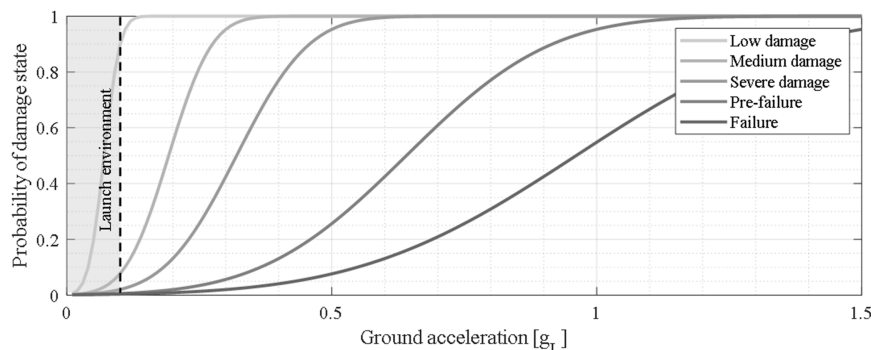


Fig. 15 ECLSS's fragility curves using arbitrary selected acceptance criteria.

potential impact of shallow seismic motions on the habitat's contents concerning different mission durations.

The lunar seismic environment primarily operates at low frequencies compared to the launch dynamic environment, less than 10 Hz, which can resonate with certain lunar surface habitat designs, similar to the illustrative example utilized in this work. Additionally, the more than 1 h duration of lunar seismic events could have further implications for material integrity. Further studies in this regard are warranted.

It is evident that even a relatively low ground acceleration can yield results comparable to those generated by the launch environment. Therefore, there is a need for future surface missions to consider the characteristics of the lunar seismic environment until more is known. Once empowered with more data leading to an understanding of this environment, the proposed framework can be a valuable tool for engineers to analyze both the structures and their contents in this unique setting. ECLSS functionality is clearly critical to maintain during and after any seismic motions. Such systems can be vulnerable to these vibrations, as demonstrated by the potential dynamic forces generated in this environment.

The results using the process could mean, in qualitative terms, that the lunar seismic environment produces a higher requirement for lateral loads and should be considered in the design of the habitat and, in quantitative terms, that the uncertainty range of the results is too high due to a lack of information on the site. This means that ignoring the risk of the lunar seismic environment and only considering the launch environment could result in undesirable outcomes for the habitat, occupants, and contents.

A primary consideration made in the design of space structures is to function effectively for mission objectives while optimizing material usage. This design philosophy conflicts with terrestrial seismic design principles, which aim to accommodate the maximum expected motion. This approach is fundamentally problematic in a seismic context, where the optimization of a nondeterministic force inherently involves a probabilistic dimension. This work highlights the need to refine probabilistic methods in lunar seismic assessment to better understand their implications for overall structural design. Future work should aim to address these issues.

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