

# AN ASSEMBLED AND INTERLOCKING LUNAR BASE AND ITS STRUCTURAL ANALYSIS

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## Abstract

Establishing a base on the lunar surface has become a new goal for space powers and even all humankind to explore the moon. However, the extreme environment and the lack of resources pose many challenges to the construction project. In this paper, an assembled and interlocking mixed structure was designed. The sintered lunar regolith can be used to build the load-bearing arch structure and the foundation structure, which are assembled by interlocking modules to facilitate construction on the lunar surface. An independent inflatable structure is needed inside the arch structure to ensure the air pressure environment suitable for human survival. The structure is covered with a 3m-thick lunar regolith layer to withstand large temperature fluctuations, intense radiation, and occasional micrometeorite impact. The main mechanical advantage of this structure is that each component is used to bear the load that it is best able to resist. The load-bearing arch structure and the foundation structure can be assembled and constructed with only 6 types of modules. Besides, the modules are self-supporting so that they can be assembled without support during construction. Subsequently, the finite element method was used to analyze the stress state after construction. The results showed that this lunar base structure is feasible, but the optimization design needs to be carried out at the module joint because it will produce stress concentration. This study provides a scheme for the construction of human lunar bases.

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**Keywords:** finite element method, interlocking arch structure, lunar base, structural analysis.

## 1. Introduction

The Moon is the nearest extraterrestrial body to the Earth, and also the advance station of human exploration of space. Many countries are actively exploring the Moon and are committed to building lunar bases. The existence of a lunar base will facilitate human's in-depth exploration on the Moon, including resource exploitation and scientific research. The lunar base will include habitat, landing pads, roads, energy stations and other infrastructure. Due to the high cost of transporting construction materials from the Earth, in-situ resource utilization (ISRU) will be the sustainable development direction of lunar surface construction projects in the future.

Given its abundance and availability, lunar regolith is considered a potential resource for in-site production of building materials on the Moon. Many methods of treating lunar regolith have been proposed, such as melting, sintering, and binding with additives. Sintering is one of the most promising technologies because it does not require any additives. Many studies have been conducted on the feasibility of various sintering technologies, including furnace sintering [1], laser sintering [2, 3], microwave sintering [4-6], and solar sintering [7].

Although the lunar regolith can be used in situ for construction, the cost of processing it into building materials is also very high. Therefore, the reasonable design and optimization of the building structure is also very important to save building materials and reduce the resource consumption of the building project.

## 2. Structural design

Different types of lunar bases, including inflatable [8], rigid [9, 10], and mixed structures [11-14], have been proposed over the years. Inflatable structures must be carried from the Earth and have good gas tightness and excellent ability to withstand internal pressure. Rigid structures could be built in situ using lunar regolith, eliminating the need to carry building materials from the Earth. The mixed structure is a combination of these two structural forms and has the advantages of both.

The construction scheme proposed in this study is based on the assumption that sintered lunar regolith is used as building material, so the physical and mechanical properties of sintered lunar regolith should be fully considered, and the structural form that conforms to its mechanical characteristics should be designed.

1. The tensile strength of the sintered lunar regolith was much lower than the compressive strength. Hence, buildings constructed from sintered lunar regolith should be designed as structural forms mainly used to withstand compressive stress, such as arches and domes.

2. Lunar regolith sintering requires the use of molds, which need to be carried from Earth. Therefore, construction components should be modular, and the types of modules should be minimized. The modules need to be interlocked to ensure the high reliability of the structure.

Interlocking assembly structures have been proposed for lunar bases, including habitats [13, 14], lunar landing pads [15, 16], and more. An assembled and interlocking mixed structure was designed according to the above suggestions, as shown in Fig. 1. The sintered lunar regolith was used to build the load-bearing arch structure and the foundation structure, which were assembled by interlocking modules to facilitate construction on the lunar surface. The interlocking foundation structure had an excellent bearing capacity. The load-bearing arch was covered with a compacted lunar regolith layer with a thickness of 3.0 m to withstand high-frequency meteorite impacts, large temperature differences, and heavy radiation. An independent inflatable structure was needed inside the arch structure to ensure an air pressure environment suitable for human survival. The main mechanical advantage of this structure was that each component was used to address the challenge that it was best able to resist. This division of the different mechanical tasks reduced the complexity of the internal force systems, which consequently made the structural behavior safer.

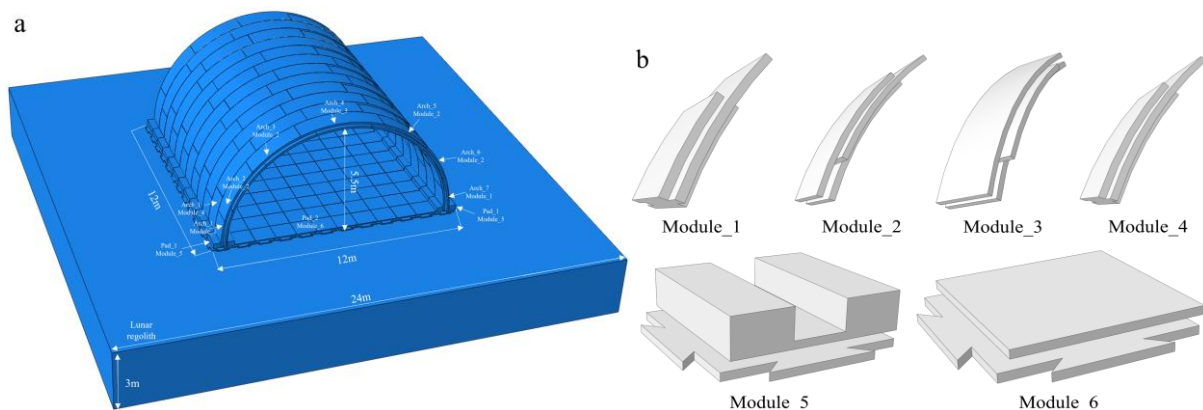


Fig. 1. (a) Structural scheme of arch structure and foundation structure of the lunar base, (b) interlocking assembly modules.

## 3. Finite element model

The finite element software ABAQUS was used for modeling and static analysis of the lunar base under the self-weight and overburden pressure induced by the lunar regolith layer. The inflatable structure was not considered in the model because it is independent of the arch-regolith system. The finite element

model is shown in Fig. 2. The mechanical properties of the samples sintered at 1040 °C were adopted as the material properties of the arch structure and foundation structure, and the Drucker-Prager Cap plasticity model was employed to represent the lunar regolith that exhibits frictional properties. Table 1 summarizes the bulk density and shear strength used in this material model. Table 2 lists the lunar soil model properties that were consistent for all layers.

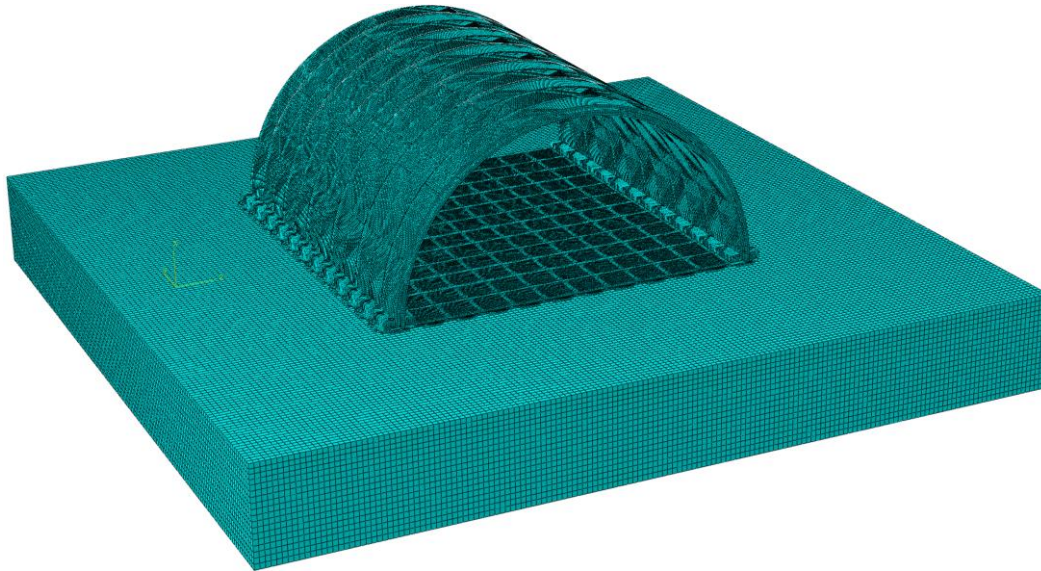


Fig. 2. Finite element model of the proposed lunar base structure and regolith basement.

Table 1. Bulk density and shear strength parameters of lunar regolith model layers.

Depth Range (cm)	Bulk Density $\rho$ (g/cm <sup>3</sup> )	Cohesion d (kPa)	Internal friction angle $\beta$ (degrees)
0-30	1.58	1.01	49.2
30-60	1.74	2.78	51.9
>60	1.80	2.78	51.9

Table 2. Lunar regolith model properties.

Elastic	Young's modulus E (MPa)	182
	Poisson ratio $\nu$ (-)	0.28
Cap plasticity	Cap Eccentricity Parameter R (-)	0.4
	Initial Cap Yield Surface Position $\epsilon_0$ (-)	0
	Transition Surface Radius Parameter $\alpha$ (-)	0.05
	Flow Stress Ratio K (-)	1

For static analysis, the self-weight of the lunar base and the overburden pressure induced by the lunar regolith layer were considered. As Table 1 shows, the density of lunar regolith is 1.80 g/cm<sup>3</sup> when the depth is greater than 60 cm. The overburden pressure induced by the lunar regolith layer over the arch structure can be calculated as:

$$P = \rho \times g_l \times h = 1800 \text{ kg} / \text{m}^3 \times 1.63 \text{ m} / \text{s}^2 \times 3 \text{ m} = 8818 \text{ kPa} \quad (1)$$

where  $g_l$  is the gravity on the moon, and  $\rho$  and  $h$  are the density and thickness of the lunar regolith layer, respectively.

#### 4. Results and discussion

The vertical deformation and principal stress contours are illustrated in Fig. 3 and 4, respectively. Considering that the proposed lunar habitation is a prefabricated structure, the principal tensile stress governs structural safety. As shown in Fig. 4, the arch modules located on both ends receive higher maximum principal stresses compared to the arch modules located in the middle position. The maximum principal tensile stress of Arch\_1 was 59.45 MPa, and the maximum principal tensile stress of Arch\_5 was only 11.27 MPa. Thus, the arch modules located on both ends should be thicker or use materials with higher tensile strength. The middle arch modules can be designed to be thinner. Moreover, the stress was mainly concentrated in the interlocking parts of the arch modules, which means that the interlocking parts should be specially designed to reduce the stress concentration.

The maximum principal tensile stress received by the foundation modules was much higher than that of the arch modules, which indicated that the foundation structure should be made of materials with higher tensile strength. In addition, the stress was mainly concentrated in the interlocking parts of the foundation modules, and the maximum principal tensile stress for Pad\_1 was as high as 400.4 MPa. Thus, the interlocking parts should be specially designed to reduce the stress concentration or use a larger foundation structure.

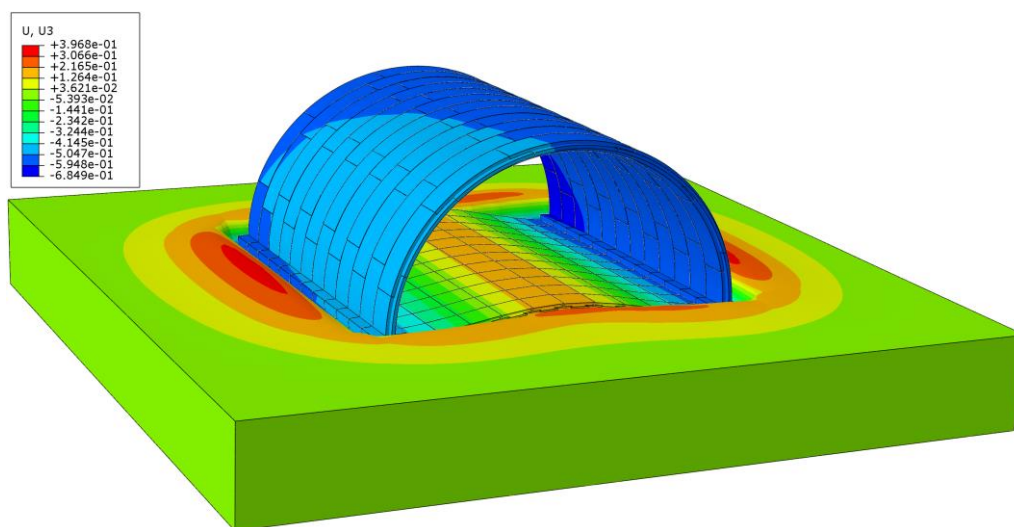


Fig. 3. Vertical deformation fields for the lunar base.

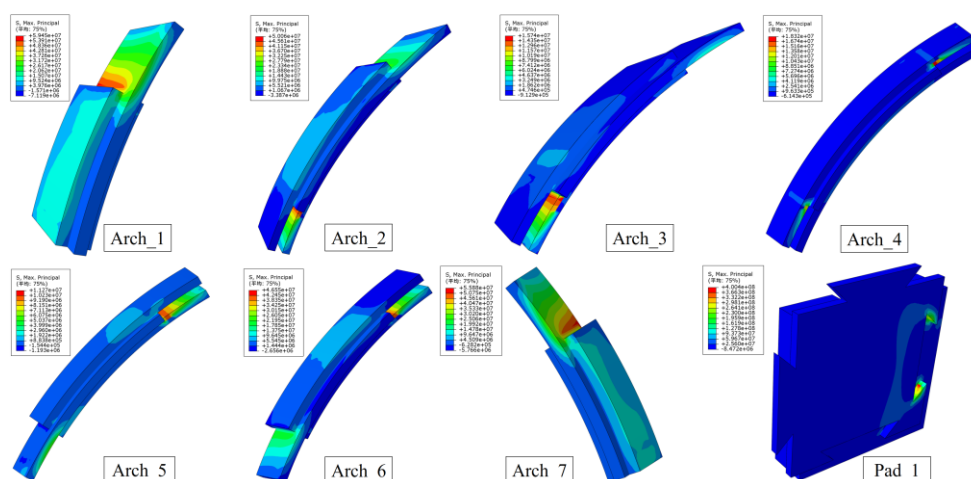


Fig. 4. Maximum principal stress of the arch modules and foundation modules.

## 5. Conclusion

In summary, this study proposes an assembled and interlocking mixed lunar base structure, which can be assembled by 6 types of modules. The finite element method was used to model this structure, and the interaction between modules was considered. The stress state of the structure under the self-weight and overburden pressure induced by the lunar regolith layer was analyzed, and the following conclusions were obtained:

- (1) The module is prone to produce large stress concentration at the joint, which should be avoided by optimizing the design of the joint;
- (2) The stress of the arch modules located on both ends is higher and should be designed for thicker structure;
- (3) The tensile stress of the bottom plate structure is very high, so thicker structure design or other ways should be adopted to improve its performance of bearing tensile stress.

The maximum principal tensile stress received by the foundation modules was much higher than that of the arch modules, which indicated that the foundation structure should be made of materials with higher tensile strength. In addition, the stress was mainly concentrated in the interlocking parts of the foundation modules, and the maximum principal tensile stress for Pad\_1 was as high as 400.4 MPa. Thus, the interlocking parts should be specially designed to reduce the stress concentration or use a larger foundation structure.

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