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ANALYSIS OF MONOLITHIC DOME SHELL FOR LUNAR LIVING MODULES

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Problem statement. Today, many countries around the world are developing projects aimed at exploration of outer space and colonization of other planets and space bodies, including the Earth's satellite − the Moon. To ensure the process of large-scale research and development of the lunar surface, it is necessary to create high-performance structures that can protect humans from the adverse conditions of space and can be built from local raw materials using cost and time effective construction technologies. The world's leading researchers are working on the problems of the creation of objects on the surface of the Moon. Peculiarities of geographical, geological, gravitational, temperature and other parameters of the lunar environment and their influence on the features of structures and equipment for human settlement on the moon are considered in [1]. Recommendations for the conceptual designs for lunar buildings and the development of building codes for the design of structures on the moon are given in [2; 3]. In the paper [4] the authors outlined a structural design approach, reviewed possible materials and evaluated several structural concepts for lunar living modules construction on the Moon.

To minimize the cost of transporting the necessary materials to the moon, it is proposed to use local raw materials (moon dust, regolith) for production of structural materials (sintered regolith bricks and blocks, lunar glasses and fiber-glass composites, lunar waterless concrete, etc.) [5−7]. 3D-printing as a construction technology is considered a promising strategy for construction on the Moon. In [8] the authors presented the conceptual architectural and structural solution of the living module on the basis of a pneumatic shell with a protective layer of the reinforced regolith put using 3D-printing. The mechanical properties of additively manufactured lunar regolith samples were investigated in [9]. Despite a significant amount of scientific projects in the field of construction on the Moon surface, the data on the analysis of the geometric parameters depending on the number of crew members and the stress state of the lunar modules under the action of loads typical for the lunar environment, are still limited and require further study.

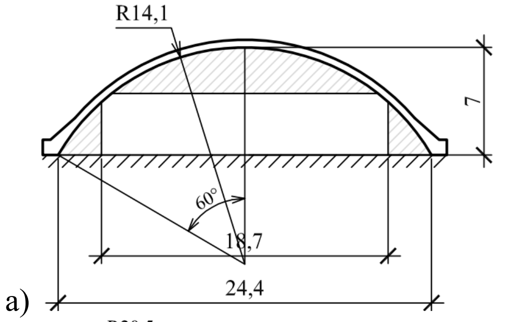
Therefore, the ***purpose*** of this work is to perform the structural analysis of lunar living module with load-bearing structure in the form of a monolithic dome shell.

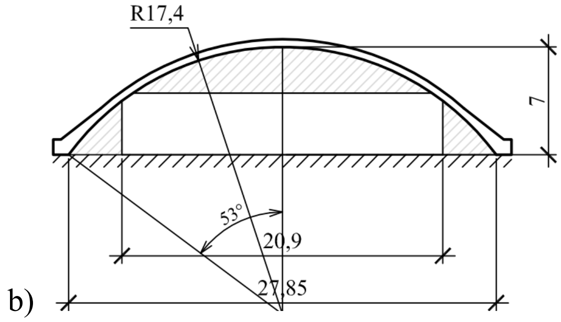
Main material. A monolithic dome-shaped shell located on the surface of the Moon was considered as a load-bearing structure for the lunar living module. The erection of a monolithic dome is provided using pneumatic formwork. Concreting is carried out using a 3D-printer after lifting the formwork surface and the reinforcement cage into working position.

The dimensions of the living module were taken based on the number of crew members according to the data [4]. Variants of residential modules for 8, 10 and 12 people were considered with the parameters shown on Figure 1. The effective height of the module in all cases was taken of 4 m and the total height was taken of 7 m.

Lunacrete is used as "concrete" for monolithic dome structure. Lunacrete is an artificial material which is produced directly on the Moon using the regolith heated at 2 000 °C as cementitious material, processed Moon rocks as aggregates and sulphur as a binding agent instead of water since it is not present on the Moon surface. Physical and mechanical properties of lunacrete were adopted using available literature [6] and summarizes in Table 1.

Fiber glass rods is used for reinforcement the monolithic dome structure Reinforcing bars for lunacrete is supposed to be formed from glass derived from lunar regolith using the technology of melting and cooling it [7]. Physical and mechanical properties of fiber glass rods made by processing the lunar regolith according to data available are shown in Table 2.





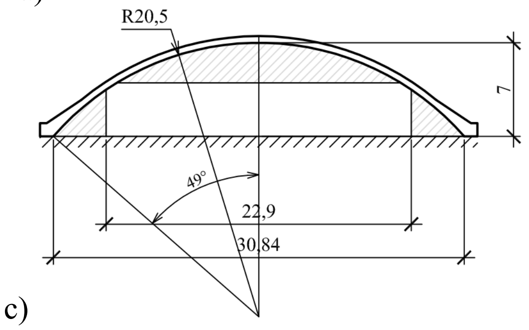


Fig. 1. Schemes and dimensions of the living modules:
a) 8 crew members;
b) 10 crew members;
c) 12 crew members

Table 1

Properties of lunacrete

Strength in compression, MPa	Strength in tension, MPa	Modulus of elasticity, MPa	Poisson's ratio	Density, kg/m^3
24.0–33.8	2.0–3.7	21 400	0.18	2 200

Table 2

Properties of fiber glass rods

Strength in tension, MPa	Modulus of elasticity, MPa
690	40 800

The main loads acting on the shell of the living module are the weight of the covering regolith layer and the pressure of the internal "atmosphere". To determine the weight of the regolith, the thickness of the layer was taken equal to 2.5 m in terms of providing protection from radiation, as well as falling small size meteorites. The density of the regolith is taken as 1 700 kg/m^3. Taking into account the gravity acceleration, which is typical for the conditions of the Moon and amounts to 1.62 m/s^2, the weight of the regolith layer will be 7.1 kN/m^2. To ensure normal living conditions, it is required to maintain pressure inside the residential module, which is varying from 34.5 kPa to 101.4 kPa according to different sources. For the calculation purpose the internal pressure was taken as 69 kPa (kN/m^2), similar to the data presented in [4].

Preliminary design of dome structure of lunar living module was carried out as for a statically indeterminate spatial system according to membrane theory of shells. According to the the results obtained, the elements of the dome structures resist primary on the tension stresses. Thus the design procedure is the same as for reinforced concrete structure in axial tension [11] with special requirement to the tightness of the module (cracks formation are not allowed). The necessary parameters of dome shell were calculated. The obtained thickness of dome shell for 8 crew members module is 160 mm, for 10 crew members – 200 mm, for 12 crew members – 240 mm. These values were used in finite element modeling of lunar living modules.

The finite element modeling was performed using LIRA−SAPR commercial software. Universal triangle shell finite elements were used to create 3D models. In order to simplify the model, the lunacrete was considered as an elastic isotropic material. The deformative characteristics of finite elements (modulus of elasticity and Poisson's ratio) were assigned in accordance with Table 1. Hinged support was applied to the end-nodes of the dome.

A static analysis of the shell was performed. As a result data on the magnitude and intensity of internal stresses were obtained and used to analyze the internal forces in the dome elements, as well as the required thickness and reinforcement of the dome shells of the living modules.

Comparative diagrams of the meridional and hook forces in the dome shells obtained as well as of the necessary area of fiber glass reinforcement and thickness of dome shell according to finite element modeling (FEM) and to membrane theory are presented on Figures 2−4.

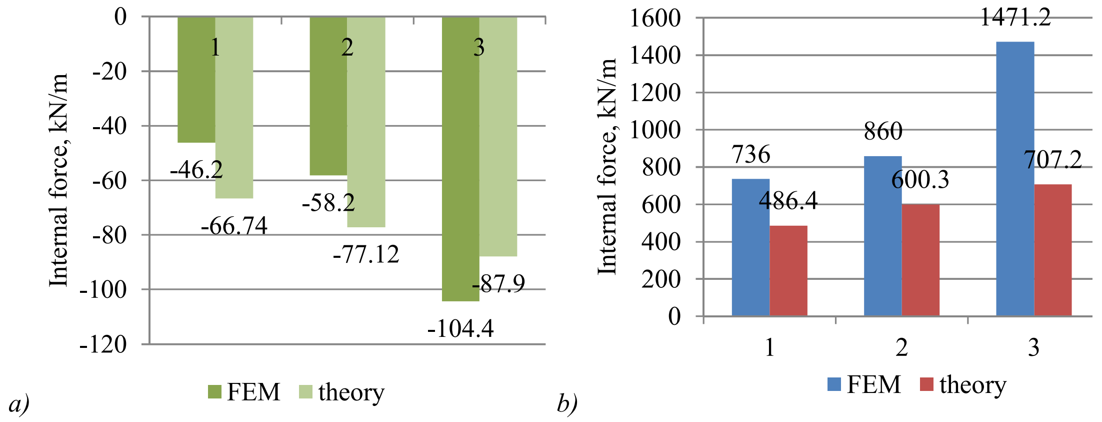


Fig. 2. Comparative diagram of the meridional forces in the dome shells obtained according to FEM and to membrane theory: a) regolith cover weight; b) internal pressure; 1 − 8 crew members; 2 − 10 crew members; 3 − 20 crew members

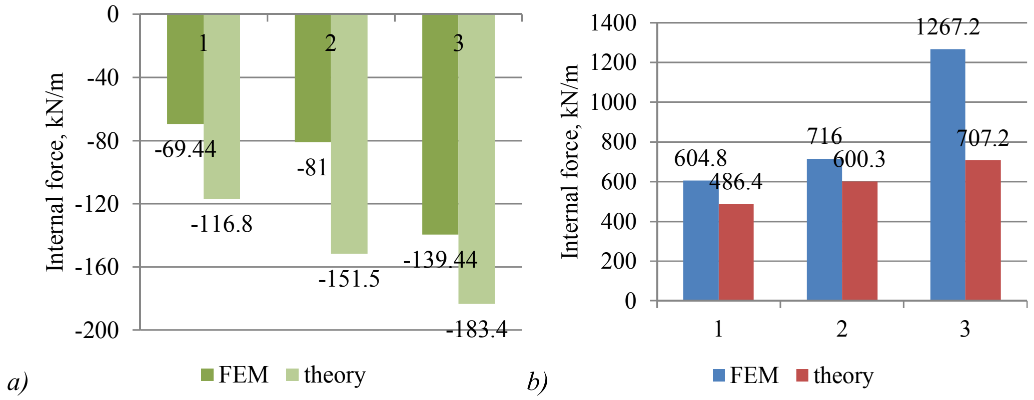


Fig. 3. Comparative diagram of the hook forces in the dome shells obtained according to FEM and to membrane theory: a) regolith cover weight; b) internal pressure; 1 − 8 crew members; 2 −10 crew members; 3 −20 crew members

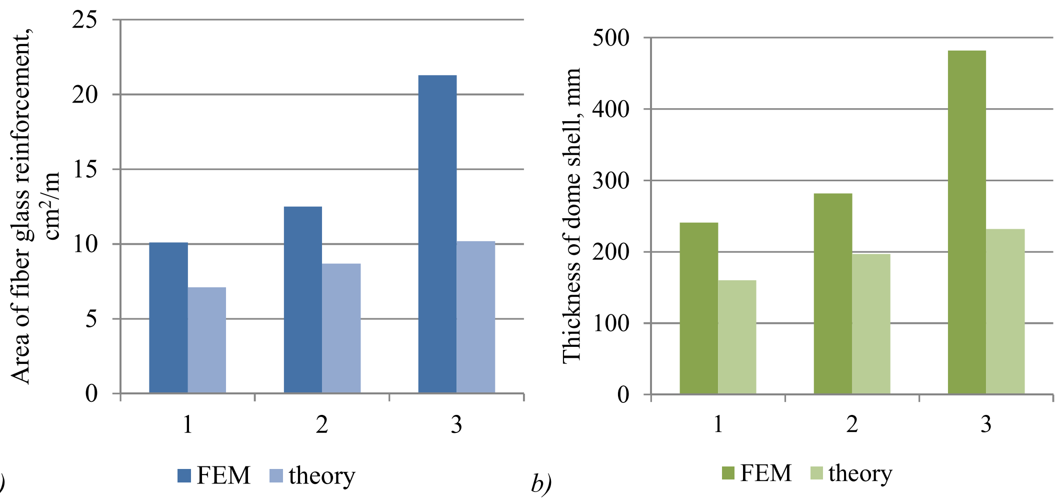


Fig. 4. Comparative diagrams of the fiber glass reinforcement area (a) and thickness of dome shell (b) according to FEM and to membrane theory:
1 − 8 crew members; 2 − 10 crew members; 3 − 20 crew members

Conclusions. Geometric parameters of monolithic dome shells for lunar living modules for 8, 10 and 12 crew members for the construction of shells using 3D-printing technology are proposed. The physical and mechanical characteristics of lunar concrete and fiber glass rods reinforcement on the basis of lunar raw materials for strength calculation and finite element modeling are systematized.

According to the well-known methods for reinforced concrete structures design, a preliminary calculation of dome shells on the loads from internal pressure and weight of the protective regolith layer has been performed. Based on the data obtained, the finite element modeling of shells was carried out using LIRA commercial software.

The internal forces obtained according to finite element modeling (FEM) differ from those according to membrane theory. The values of the meridional internal forces from the weight of the regolith layer according to the membrane theory exceed in 1.3−1.45 times the FEM results, hook forces – in 1.32−1.87 times. As for the internal pressure, the FEM results exceed the data on the membrane theory by 1.4-2 times for meridional forces and 1.2−1.8 for hook forces.

The structural parameters of the domes according to the results of FEM are as following: for 8 crew members module − the shell thickness is 240 mm with the fiber glass reinforcement area of 10.1 cm^2; for 10 crew members module − the shell thickness is 280 mm with a reinforcement area of 12.5 cm^2. For 12 crew members module it is necessary to consider ribbed or T-shaped section to provide rational structure.

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