Structural Design of a Lunar Habitat

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Structural Design of a Lunar Habitat

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Abstract: A lunar base is an essential part of all the new space exploration programs because the Moon is the most logical first destination in space. Its hazardous environment will pose challenges for all engineering disciplines involved. A structural engineer's approach is outlined in this paper, discussing possible materials and structural concepts for second-generation construction on the Moon. Several different concepts are evaluated and the most reasonable is chosen for a detailed design. During the design process, different solutions—for example, for the connections—were found. Although lunar construction is difficult, the proposed design offers a relatively simple structural frame for erection. A habitat on the Moon can be built with a reasonable factor of safety and existing technology. Even so, we recognize the very significant difficulties that await our return to the Moon.

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Introduction

Mankind set foot on the Moon over three decades ago. Ever since then, National Aeronautics and Space Agency (NASA) and other space agencies have planned to build an outpost on the Moon for evolving reasons. Was it to initially show the technical advances of the United States during the Cold War? Today's reasons for a base on the Moon are more practical: Astronomy, mining, or tourism are possible arguments for the human presence on Earth's only natural satellite.

On January 14th, 2004, President George W. Bush announced a new course in America's space program. After completing the International Space Station by 2010, the Space Shuttle will be retired. The next generation of space vehicles will be the Crew Exploration Vehicle, ready for flight by 2014. This new vehicle will enable a return to the Moon, and future explorations beyond, as early as 2015. The extended human presence on the Moon will enable astronauts to develop new technologies and harness the Moon's abundant resources to allow manned exploration of more challenging environments. A human presence on the Moon could also reduce the cost of further exploration, since lunar-based spacecraft could escape the Moon's lower gravity using less energy at less cost than Earth-based vehicles. The experience and knowledge gained on the Moon will serve as a foundation for human missions beyond the Moon, beginning with Mars.

Other nations have plans to visit the Moon as well. The Chinese lunar program, named Chang'e after a legendary Chinese goddess who flew to the Moon, aims to eventually place an unmanned vehicle on the Moon by 2010. Plans also call for a vehicle to land by 2020 that would collect soil samples and conduct other tests, possibly in preparation for a manned lunar base.

The European Space Agency's Aurora Program also aims to set out a strategy for Europe's solar system exploration over the next 30 years that eventually includes manned expeditions to the Moon and Mars. A human mission to the Moon, proposed for 2024, would demonstrate key life-support and habitation technologies, as well as aspects of crew performance and adaptation to a long-distance space flight.

One part of these ambitious visions will be the construction of a lunar base. This work summarizes the lunar environmental conditions, a classification of structural concepts being considered for lunar habitats, the preliminary and structural design of a possible lunar base, the construction process, and challenges for future research. More details can be found in the first writer's Master's thesis (Ruess 2004).

Reasons to Go to the Moon

Why do we need to go to the Moon? Many researchers believe robotic exploration is the best way to conduct most space science. Others disagree. Only humans can properly investigate other worlds, they say, to answer the most pressing questions about the origin and fate of humans and the possibility that life exists elsewhere (Chang 2004).

For many space visionaries and practical scientists alike, human spaceflight is about to open up profitable commercial opportunities and, perhaps more importantly, continue the immutable human desire to explore. All of these issues are discussed extensively in the literature. The list below is representative; however, there are many more references available than given here.

Here are some of the top reasons for going back to the Moon.

Accessibility

The Moon is in orbit around Earth at an average distance of 233,000 miles. This relatively small distance means that we can reach the Moon with modified existing rocket systems. A trip to

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the Moon takes only about three days using existing propulsion technology and teleoperating is possible; the radio delay time being within seconds (Schrunk 2002).

Inspiration

Beyond the basic needs for food, shelter, and clothing, we humans are a restless lot. The desire to explore and understand is part of our character. The quest for knowledge is one of the motivators in the desire to venture across land, sea, air, or cosmic frontiers. A settlement on the Moon would greatly stimulate the interest of our young in science and engineering (Eckhart 1999).

International Cooperation

Just as the International Space Station packed explorers from previously antagonistic nations into tight quarters, an effort to return to the Moon could bring nations together in an era of increasing international tension.

There are several reasons why a lunar base project should be an international effort. First, any efforts by nations to do it alone would be unnecessarily redundant and limited in scope. Second, it is the intention of the ratified outer space treaties that space development should be a peaceful effort for the benefit of all people. Third, cooperation among nations on lunar base planning, construction, operations, and growth has the potential to create and reinforce peaceful relations among nations.

China, with its own lunar ambitions, is a good example of a country the United States might want to work with more closely (Benaroya 1998).

Geology

The Apollo era answered many questions about the Moon. However, much was left undone or needs to be revived.

The Moon is the attic of Earth, a place where rocks blasted long ago from our planet are sitting around waiting to be studied. The history etched in these rocks has not decayed much because there is no atmosphere and little geological activity on the Moon.

A lunar base could be designed that would benefit not just planetary scientists who want to study lunar rocks, but a wide range of sciences, such as biology, physics, paleontology, planetary science, historical geology, and even exobiology. This knowledge will lead to new insights in the fields of psychology and sociology (Duke and Benaroya 1993; Johnson et al. 1995).

Study Asteroid Threat

The Moon's nearly pristine state means billions of years of asteroid impacts are preserved, as obvious scars on the surface. These craters hold a record of how frequently and intensely the inner solar system, including Earth, was hit by asteroids through time.

Studying many of these craters up close would allow scientists to figure out if mass extinctions on Earth, including the death of dinosaurs, that allowed the rise of mammals, were the result of single large asteroid impacts, flurries of smaller assaults, or neither. An answer would impact many scientific fields.

A human presence on the Moon would also be the beginning of a long-range program to ensure the survival of our species (Benaroya 2002).

Astronomy

Astronomers would love to set up observatories on the Moon. Optical telescopes could be placed almost anywhere on the lunar surface and, since there is no atmosphere to scatter light, they would get clear Hubble-type views of the cosmos. Astronomers could build scopes that are far larger than Hubble is, as well. At the same time, they could be shielded from radiation and other hazards that plague telescopes in the Earth's orbit.

Radio telescopes could be placed on the far side of the Moon. There they would be shielded from all the radio noise of Earth (Chua et al. 1990).

Energy Production

Sunlight that reaches the lunar surface is constant, predictable, and inexhaustible, and can be converted into electric power by solar panels. Several sites around the South Pole of the Moon always have Earth in view for continuous communications, and receive over 300 days of sunlight per year. The temperature difference between the sunlight and dark areas of the Moon can also be used for the operation of heat engines and for thermal management systems. The produced power could be beamed to Earth or to satellites for distribution around the world, 24 h a day/7 days a week, greatly decreasing Earth's dependence on fossil fuels. A lunar power station will not be built in a day, but a return to the Moon ought to include plans to eventually route power back home (Spudis 2003; O'Dale 1994).

Resources

The Moon has a wealth of raw materials. Lunar regolith contains iron, aluminum, silicon, titanium, oxygen, and traces of hydrogen, carbon, helium3, and nitrogen. Gaining experience and mastering the necessary technology to extract these might then allow a lunar colony to become self-sufficient or even export resources to Earth.

The Moon may also have water, frozen in dark polar craters. If so, it could be converted to rocket fuel, turning the Moon into a base for all other solar system exploration (Happel 1993; Spudis 2003).

Technology

Space exploration induces technology and health care spin-offs that benefit economies and societies. The construction of the first lunar base will provide business opportunities and jobs for people on Earth in many diverse fields, such as aerospace, robotics, and environmental sciences.

A lunar base would also serve as a test bed for the "space faring" technologies, such as in situ resource utilization, electromagnetic propulsion, life-support systems, and power beaming, required to place humans on Mars and beyond.

Commercialization

There is no agreement among scientists over the role that private enterprise ought to play in human spaceflight. Yet already, companies help build the machines that carry astronauts into space. In fact, investor-financed commercial enterprises already surpass the expenditures of governments on space objects.

The lunar surface could serve as scenery for movies, advertisements, and video games. Space tourism and certain mining and manufacturing will succeed in space if only entrepreneurs are turned loose (and perhaps assisted with federal money or incentives). ^{3}He (helium3 is a very rare helium isotope) mining could solve energy problems for generations once nuclear fusion technology becomes practical. And the demand for trips into space is there, so entrepreneurs have started to provide the supply (Benaroya 1998; O'Dale 1994).

Steppingstone to Mars

Lifting heavy spacecraft and fuel out of the Earth's gravity is expensive. Spacecraft assembled and provisioned on the Moon could escape its lower gravity using far less energy and thus far less cost. With the experience and knowledge gained on the Moon, we will then be ready to take the next steps of space exploration: Human missions to Mars and beyond (Dubbink 2001).

Lunar Environment

Environmental Conditions

Gravity

On the Moon, gravity is $1/6\ g$. That means a structure will have, in gross terms, six times the weight bearing capacity on the Moon as on Earth; the structural dead loads will be reduced by 5/6 compared to the ones on Earth. Mass-based rather than weight-based criteria are recommended to maximize the utility of concepts developed for lunar structural design (Benaroya et al. 2002).

Internal Air Pressurization

The lunar structure is in fact a life-supporting closed environment. Generally, the optimum habitat internal pressure is Earth's atmospheric pressure, but the pressure differential between the extravehicular activity (EVA) suits and the habitat should be minimized for safety reasons. Much like scuba diving, the dangerous aspect of changing pressures is the formation and expansion of gas bubbles in the blood and lungs. Historical internal pressures used for NASA programs have ranged from 34.5 kPa (5 psi; $21{,}300\ \text{kg/m}^2$ on the Moon) to 101.4 kPa (14.7 psi; $62{,}600\ \text{kg/m}^2$) to provide a livable environment for the astronauts.

The habitat module pressure and the pressure used in space suits for EVA influence one another. EVA productivity increases with the use of lower pressures because the gloves become more flexible (Elrod 1995). At the same time, low pressures increase the fire hazard, and lower voice and cough mechanism effectiveness for astronauts. It is assumed that the actual habitat pressure will be around 69 kPa (10 psi; $42{,}600\ \text{kg/m}^2$). The enclosure structure must contain this pressure, and must be designed to be failsafe against catastrophic and other decompression.

Radiation/Shielding

A prime consideration in the design is that the structure must be able to shield against the types of hazards found on the lunar surface: Continuous solar/cosmic radiation, meteoroid impacts, extreme variations in temperature, and radiation.

There are two kinds of incoming radiation on the lunar surface: Electromagnetic radiation and ionizing radiation. These particles interact with the Moon in different ways, resulting in penetration depths that vary from micrometers to meters. Any kind of lunar surface habitat will have to be protected from three different kinds of ionizing radiation in space: Solar wind, solar cosmic rays, and galactic cosmic radiation.

Meteoroids are naturally occurring small solid bodies traveling through space at very high speeds.

Most likely, a layer of compacted regolith will be placed atop the structure for protection against all of those hazards. It provides shielding against most micrometeoroid impacts because the relatively dense and heavy regolith absorbs the kinetic energy. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 5 rem, which is the allowable level for radiation workers. In addition, it greatly reduces the effects of the extreme temperature cycles. The mass of regolith is about $1.7\ \text{g/cm}^3$. With an assumed regolith cover of 3 m, the resulting dead load on the structure will be $5{,}100\ \text{kg/m}^2$.

Other shielding concepts include passive bulk shielding with material other than regolith, electromagnetic shielding, electrostatic shielding, and chemical radioprotection.

Vacuum

A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be stable if exposed under such conditions. Outgassing materials and structures, e.g., hydraulic systems, have to be avoided. A lunar structure will not be subjected to any kind of wind loads.

Dust

The lunar surface has a layer of fine particles that is easily disturbed and placed into suspension. These particles cling to all surfaces, are highly abrasive, and pose serious challenges in the utility of construction equipment and the operation and maintenance of airlocks (Benaroya and Ettouney 1992a,b).

Moonquakes

There is little or no seismic activity on the Moon. Therefore, lunar structural design will not include earthquakelike loads.

Temperature

Temperatures on the lunar surface rapidly change from approximately 100 to $-150°\text{C}$ in the transition between day and night, which occurs in roughly two-week cycles.

Structural Requirements

Building a structure on the Moon results in many different and additional requirements that have to be fulfilled by the structure.

Structural Adequacy

The structure must sustain all dead and live loads with an acceptable degree of safety. A minimum of structural material is desired. The use of lightweight high stiffness to weight ratio materials is necessary.

Material Properties

Properties for lunar construction materials should include high strength, ductility, durability, stiffness, and tear and puncture resistance, together with low thermal expansion. The stability of these mechanical properties and low leakage are important.

Maintenance

Upkeep, inspection, maintenance, and repairs have to be kept at a minimum.

Functionality
A low ratio of internal volume to usable floor area will ensure that the habitat efficiently and economically houses and supports the operations for which it is designed.

Compatibility
The structure must be designed for compatibility with the internal environment, heat management, and rejection, as well as other support systems.

Transportation
Small stowage volume and light mass minimize transportation costs and volume.

Ease of Construction
The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures should be designed for ease of construction so that the EVA of the astronaut construction team is minimized. Construction components must be practical (easy connections of structural components) and, in a sense, modular in order to minimize local fabrication and needed construction equipment. Single components should be designed to be handled by one or at most two astronauts. Easy handling and moving of the regolith used for shielding cover can be achieved by bagging it. Robotic and automated construction methods are desirable, but cannot be assumed to exist in the near future.

Excavation
Grading and excavation are difficult and expensive because of the lack of traction and the locking nature of the regolith. Design solutions that keep excavation at a minimum need to be found. The use of footing pads might be a solution to eliminate excavation.

Foundations
Large and complicated foundations will not be feasible in the beginning. This is because regolith/soil mechanics are not fully understood yet, and the transport and use of heavy construction equipment is very expensive. Footing pads might once again be the solution for early applications.

Use of Local Materials
This is to be considered extremely important in the long-term view of extraterrestrial habitation. However, feasibility will have to wait until a minimal presence has been established on the Moon.

Materials

Metals

Steel
Steel can be cast either directly to shape, or into ingots that are reheated and hot worked into a wrought shape by forging, extrusion, rolling, or other processes. Wrought steels are the most common engineering material used, and come in a variety of forms with different finishes and properties.

According to the chemical composition, standard steels can be classified into three major groups: carbon steels, alloy steels, and stainless steels. Carbon steel is what is most commonly used for construction all over the world as a relatively cheap and effective material. Because of that, engineers probably have the most experience with this material, and many applications can be modified to suit lunar construction. However, for lunar applications, the specific weight of the material is very high and therefore makes transport to the Moon very expensive and maybe ineffective.

Aluminum
Aluminum is a very versatile metal and can be cast in any form known. It can be rolled, stamped, drawn, spun, roll-formed, hammered, and forged. The metal can be extruded into a variety of shapes, and can be turned, milled, and bored in the machining process. Aluminum can be riveted, welded, brazed, or resin bonded.

At extremely high temperatures (200–250°C) aluminum alloys tend to lose some of their strength. However, at subzero temperatures, their strength increases while retaining their ductility, making aluminum an extremely useful low-temperature alloy.

Titanium
Titanium is 40% lighter than steel and 60% heavier than aluminum. Its combination of high strength and low weight makes titanium a very useful structural metal. It is used in a variety of applications, including products where weight is of importance, such as aircraft.

Titanium is rather difficult to fabricate because of its susceptibility to oxygen, nitrogen, and hydrogen impurities that cause the titanium to become more brittle. Elevated temperature processing must be used under special conditions in order to avoid diffusion of these gasses into the titanium. Commercially produced titanium products are made in the following mill wrought forms; plate, tubing, sheet, wire, extrusions, and forgings. Titanium can also be cast, which must be done in a vacuum furnace because of its reactive nature. All of the problems in fabrication make titanium products quite expensive. However, its lower specific weight might enable it to compete with steel, if transport costs are taken into account.

Magnesium
Magnesium is among the lightest of all the metals, and the sixth most abundant on Earth. Magnesium is ductile and the most machinable of all the metals. Due to its lightweight, superior machinability, and ease of casting, magnesium is used for many purposes, such as auto parts, power tools, sporting goods, aerospace equipment, fixtures, and material handling equipment. Automotive applications include gearboxes, valve covers, wheels, clutch housings, and brake pedal brackets. Wrought alloys are available in rod, bar, sheet, plate, forgings, and extrusions.

Fabrics

Fabrics for membranes, for example, are manufactured using fibers; weaving them into a canvas and finally coating them for protection. Among the fibers used in textile construction are polyester, glass, polytetrafluoroethylene (PTFE), nylon and Kevlar fibers. Again, Kevlar is the most suited for lunar applications since it has the highest strength combined with low self-weight. The final fabric properties, especially tear resistance, depend on the way the chain and shoot directions were interwoven. For coating, mainly polyvinylchloride and PTFE are used. Polyethylene membranes will most likely not be used because they develop poisonous gases in case of a fire accident. Layered membrane

Table 1. Conventional Terms of Relative Density (Eckhart 1999)

Relative density	Description
0–15	Very loose
15–35	Loose
35–65	Medium
65–85	Dense
85–100	Very dense

construction seems promising, addressing not only structural but safety and insulation problems, as well (Kennedy and Adams 2000).

New Materials: Composites and Carbon Nanotubes (Braun 2003; Burgoyne 1999)

Composites

Fiber reinforced plastics belong to the group of fiber composite materials. They consist of reinforcing fiber lying in a matrix material. Such a combination results in a new material that typically has different properties than single components. The properties of this new material can be altered to result in a highly effective and lightweight alternative to common structural materials.

Carbon Nanotubes

Carbon nanotubes are a very young research area. These systems consist of graphitic layers seamlessly wrapped to cylinders. With only a few nanometers in diameter, yet (presently) up to a millimeter long, the length to width aspect ratio is extremely high. A truly molecular nature is unprecedented for macroscopic devices of this size. Accordingly, the number of both specialized and large-scale applications is growing constantly.

Extremely high strengths in the direction of the tubes with low self-weight are the result and might revolutionize all areas of engineering, enabling structures that have been thought impossible before.

Indigenous Materials (Happel 1992, 1993; Happel et al. 1992)

Loose and Compacted Regolith

Lunar soil or regolith is by far the most common material available on the Moon. The top layer (about 15 cm) of regolith is loosely compacted fine soil particles. Below this surface, the density increases rapidly with depths below 1 m achieving relative densities greater than 95%. The relative density describes how the particles of a soil are assembled. The loosest possible state has a relative density of 0%; the densest possible arrangement, one of 100%. In conventional terms, the relative density of a soil deposit can typically be described as given in Table 1.

Regolith will probably be used for shielding habitats from radiation, meteoroid impact, launch blast debris. Regolith can be compacted into very steep slopes. However, it is a brittle material when compacted to high slope angles. It can fail suddenly from slight dynamic loads and slump to its angle of response (about 40°C). This is the maximum angle for a stable slope of uncompacted soil. The structural uses of unprocessed regolith remain very limited.

Table 2. Typical Properties for Lunar Glass (Happel 1993)

Property	Unit	Flawed glass bars	Unflawed glass bars	Glass fibers
Maximum bending strength	N/mm^2	125	360	630
Average bending strength	N/mm^2	100	205	630
Young's modulus	kN/mm^2	450	450	450

Sintered Regolith

Loose regolith can be collected, placed into forms, compressed, and heated via microwaves or solar energy to sinter or fuse the material. The resulting products, such as bricks, blocks, and other shapes, could be used in construction in a manner similar to terrestrial masonry. With suitable interlocking and reinforcement, bricks could even be used for pressurized environments. Introducing prestressing, it might be possible to produce beams and slabs. However, prestressing is a very sensitive operation and will be difficult to apply to sintered regolith.

Sintered regolith simulant generally has low and highly variable mechanical strength. The material is highly heterogeneous and the properties are difficult to exactly characterize. Reported values for modulus of rupture vary from 9–18 MPa. Compressive strengths are about the same. There is little terrestrial experience available that can be extended to the lunar environment. Based on what is currently known about sintered regolith, its sophisticated structural design is not feasible. Sintered blocks may be good candidates for nonstructural uses, such as radiation shielding, berms, and launch debris barriers.

Lunar Glasses and Glass-Glass Composites

Lunar glass products hold great promise as lunar construction materials. Lunar glass could be used in bulk to form windows and maybe even structural members. Very high strength glass fibers can be manufactured and used as reinforcement material in concrete or woven into cables. Glass could also be made into glass-glass composites combining high strength, high melting point glass fibers with low strength, and a low melting point glass matrix.

The raw material for glass production is readily available on the lunar surface, in some areas up to 40% of the regolith is glass. Even the regolith itself, if melted and cooled rapidly, forms glass. Manufacturing of high strength glass fibers is a simpler operation with fewer steps and therefore requires a lower initial investment in infrastructure than metal manufacturing. Lunar dust is expected to cause fine scratches on the surface of glass. This negative effect is somewhat offset by the anhydrous lunar conditions. Table 2 gives properties for lunar glass.

Glass is a brittle material. Bulk glass should not be used in applications that involve loading in tension because of the sudden failure due to crack propagation, even at low load levels. This limitation can be overcome by using glass composites or glass fiber strands, because the crack length is generally limited to the diameter of a single fiber. Thermal prestressing during the manufacturing process, as applied to terrestrial safety glazing, is a promising solution to this problem.

Cables made from lunar glass seem particularly promising because of the high strengths of the glass fiber.

The mechanical properties of glass-glass composites have not yet been determined. The material remains experimental. It is not clear at this time whether lunar glass-glass composites are feasible.

Table 3. Typical Properties for Cast Regolith (Happel 1993)

Property	Unit	Value
Tensional strength	N/mm^2	34.5
Compressive strength	N/mm^2	538
Young's modulus	kN/mm^2	100
Density	g/cm^3	3
Temperature coefficient	$10^{-6}/K$	7.5–8.5

Table 4. Typical Properties for Lunar Concrete (Happel 1993)

Property	Unit	Value
Compressive strength	N/mm^2	39–75.7
Young's modulus	kN/mm^2	21.4
Ultimate strain	%	
Density	g/cm^3	2.6
Temperature coefficient	$10^{-6}/K$	5.4

Cast Regolith (Cast Basalt)

Cast regolith is very similar to terrestrial cast basalt. The terms have been used interchangeably in the literature to refer to the same material. Cast regolith can be readily manufactured on the Moon by melting regolith and cooling it slowly so that the material crystallizes instead of turning into glass. Virtually no material preparation is needed. The casting operation is simple requiring only a furnace, ladle, and molds.

Vacuum melting and casting should enhance the quality of the end product. More importantly, there is terrestrial experience producing the material; but it has not been used for construction purposes yet.

Cast basalt has extremely high compressive and moderate tensile strength. It can easily be cast into structural elements for ready use in prefabricated construction. Feasible shapes include most of the basic structural elements, such as beams, columns, slabs, shells, arch segments, blocks, and cylinders.

Note that the ultimate compressive and tensile strengths are each about ten times greater than those of concrete (see Table 3).

Cast basalt also has the disadvantage that it is a brittle material. Tensile loads that are a significant fraction of the ultimate tensile strength need to be avoided. The fracture and fatigue properties need further research.

It should be feasible to use cast regolith in many structural applications without any tensile reinforcement because of its moderately high tensile strength. However, a minimum amount of tension reinforcement may be required to provide a safe structure. The reinforcement could be made with local materials.

Cast regolith is most suited for use in structures that are dominated by compression. However, using prestressed applications will offer a wide variety of shapes and structures. Prestressing tendons can be made from lunar materials.

Since it is extremely hard, cast regolith has high abrasion resistance. This is an advantage for use in the dusty lunar environment. It may be the ideal material for paving lunar rocket launch sites and constructing debris shields surrounding landing pads. The hardness of cast basalt combined with its brittle nature makes it a difficult material to cut, drill, or machine. Such operations should be avoided on the Moon.

Production of cast regolith is energy intensive because of its high melting point.

The estimated energy consumption is 360 kW h/MT.

Lunar Concrete

The basic materials needed for the manufacturing of lunar concrete are the same as for concrete on Earth: Aggregate, water, and cement. Properly screened and sized lunar regolith makes high-quality concrete aggregate. Small quantities of actual lunar regolith have been used as aggregate in the preparation of concrete in the laboratory. The resulting properties for lunar concrete are given in Table 4.

Cement can be manufactured by beneficiating high calcium content lunar rock. Water is not available. Once lunar oxygen facilities are established, water could be produced by combining lunar oxygen with hydrogen extracted from lunar soil. Hydrogen is also a by-product of ^3He mining operations. If the formwork needed to cast concrete on the Moon could also be made from lunar materials, then concrete could become a versatile lunar construction material. Furthermore, lunar concrete cannot be cast in a vacuum. It has to be cast and cured in a pressurized environment, because the vacuum draws off the water needed for the chemical reaction that hardens the concrete. Thereby, it greatly weakens the final product. Premixing of the dry ingredients, placing the dry powder in forms, and using steam injection to harden and cure the concrete has been proposed to overcome the problem of casting concrete in a vacuum. An alternative is to construct a large pressurized concrete production facility to fabricate precast concrete modules.

Concrete is brittle and weak in tension. For most structural uses, concrete is extensively reinforced with a high strength ductile material, such as steel. Lunar glass could also be used as reinforcement. Fiberglass concrete reinforcement material is gaining popularity on Earth.

Concrete can be cast into an infinite variety of shapes making it a very versatile material. Civil engineers have extensive experience with concrete construction on Earth. Its uses, performance, and properties are well understood and characterized.

However, the manufacturing and use of lunar cement and concrete is a complex multistep operation. Production of cement is also an energy intensive process. Cement requires 2,200 kW h/MT. Establishing the infrastructure necessary to accomplish concrete production on the surface of the Moon would be an expensive, difficult, and time-consuming operation. Lunar concrete production will only occur late in the establishment of a lunar colony.

Lunar Metals

Aluminum, titanium, magnesium, and iron are among the seven most common elements present in lunar regolith (see Fig. 1).

These metals may be obtained as by-products of a lunar oxygen manufacturing operation. This would make them readily available as feedstock in the manufacturing of structural shapes. Iron can be easily separated magnetically from the regolith. Alloys can be made from the major elements—Fe, Si, Mg, Al, Ti, and Ni—and from the minor elements—Cr, Mn, Zr, and V—that are sufficiently abundant to be useful (0.1–2%). Some of the other principal alloying elements are not found in significant quantities on the Moon. Carbon, which is necessary to make steel, is not present in useful amounts and would have to be imported. Once manufactured, the metals and their alloys are outstanding structural materials with very good tensile and compressive strength properties. Steel and aluminum are commonly used in structures on Earth. Their mechanical properties and their uses in terrestrial construction are well understood.

Excluding iron, there are no lunar equivalents of the easy to refine metallic ores found on Earth. Most metals are only present

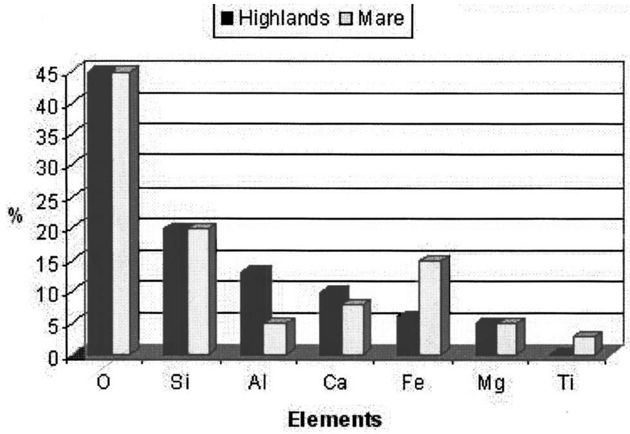


Fig. 1. Elemental composition of lunar regolith (wt %)

in difficult to refine compounds, primarily oxides. The oxides must be concentrated, and then the metals must be separated from the oxides, purified, melted, and alloyed. The additional steps of casting, drawing, and heat treatment are also usually necessary to form metal into useful structural shapes.

These operations would require establishing an extensive industrial infrastructure on the Moon.

The ability to manufacture metals, such as steel and aluminum, even in small amounts would be extremely valuable for lunar industrialization. Metals are a key ingredient for most technologies and have wider uses than construction. Therefore, simplified metal production technology will probably be established early in the development of a lunar colony. Steel is the prime candidate for early production because it can be refined with much less energy consumption than the other metals. Aluminum, for example, requires approximately six times as much energy to produce as steel (Happel 1993).

Material Selection

Selecting an indigenous material for design work that ventures beyond the conceptual is necessarily a somewhat subjective process. This is because there has not been any lunar construction and the lunar environment is very difficult to duplicate on Earth. Therefore, working experience with indigenous materials in a lunar environment is nonexistent. Theory, laboratory results, and terrestrial experience must be extrapolated to the Moon. Such extrapolation is a risky activity at best, fraught with the potential for overlooking a key factor or encountering the totally unexpected.

An evaluation procedure has been proposed (Happel 1993). The perfect indigenous construction material combining all beneficial qualities probably does not exist. However, cast regolith appears to have the best combination of material and manufacturing properties among all the indigenous materials.

Key Structural Concepts

A lunar base will go through evolutionary development, starting with limited capacity and expanding over time.

Lunar development will stage in three main phases. In each of these phases, a different generation of habitats will necessarily evolve (Happel 1993; Benaroya 2002; Cohen 2002).

1. Prefabricated and preoutfitted hard shell modules;
2. Assembly of components fabricated on Earth with some assembly required; and
3. Large-scale building structures comprised substantially of indigenous materials.

Since first-generation concepts are already well understood and third-generation facilities are still far off, highly complex, and can only be based on many assumptions and uncertainties, this work focuses on second-generation mainly prefabricated lunar bases. Second generation lunar habitats can be further divided into four main structural types:

1. Inflatable structures;
2. Cable structures;
3. Rigid structures; and
4. Underground construction.

Inflatables

Inflatable structural concepts for a lunar base are a means to speed up the construction process while lessening the costs (Roberts 1988; Broad 1989). Membrane fabrics efficiently support the internal pressure loads. An unsupported inflatable will collapse from its own weight in the event of a loss of pressure, so the possibility of a puncture has to be addressed in the design process. Simple membrane fabrics, such as those used on Earth, will not be able to meet all material requirements for lunar construction. Abrasion resistance, as well as resistance to all kinds of loads during transport and construction, can only be achieved using layered or composite solutions.

One of the major advantages of inflatable habitats may be the most difficult to qualify: Habitability. It is the sum of the qualities that make an environment a pleasant place to live and a productive place to work. Most inflatables not only provide a large volume, they provide perceptible volume. In a modular base, a person can never perceive (or utilize) a volume larger than that of a single module.

Spherical Inflatable (Roberts 1988)

This inflatable habitat consists of a spherical pneumatic envelope with an interior structural cage to support the floors, walls, and equipment, and to hold up the envelope if pressure is lost (see Fig. 2).

The sphere analyzed in (Roberts 1988), when inflated, will be 16 m in diameter, containing 2,145 m^3 of open volume and 594 m^2 on four floors. Structural analysis is performed assuming an internal pressure of 101.4 kPa. The envelope will consist of a high strength multiply fabric, with an impermeable inner layer and a thermal coating on the outside. With a safety factor of 5, the structural layer made from Kevlar 29 is to be 5 mm thick, amounting to a total mass of 2,200 kg for the structural envelope. The packaged volume will be about 40 m^3. It is planned to cover the habitat with 3 m of regolith in the form of "sandbags" (see Fig. 3).

Placing the regolith is very labor intensive, taking up much of the crew's time during the early missions. An alternative might be to provide some shielding to protect the habitat from galactic cosmic radiation, with a separate "storm shelter" to protect the crew in the event of a serious solar flare. However, operational simplicity, safety, and the possibility to protect from meteoroid impacts favor the concept of regolith shielding.

The interior structure will be a simple frame structure, supporting the floors, equipment, and furnishings. It will also support the regolith shielding in the event of a loss of pressure. A rough estimate puts the mass of the framework at 16,300 kg. This is where one can easily see a problem with this concept. While trying to save mass using an inflatable envelope, because of the interior multifloor layout and the necessity to provide a secondary

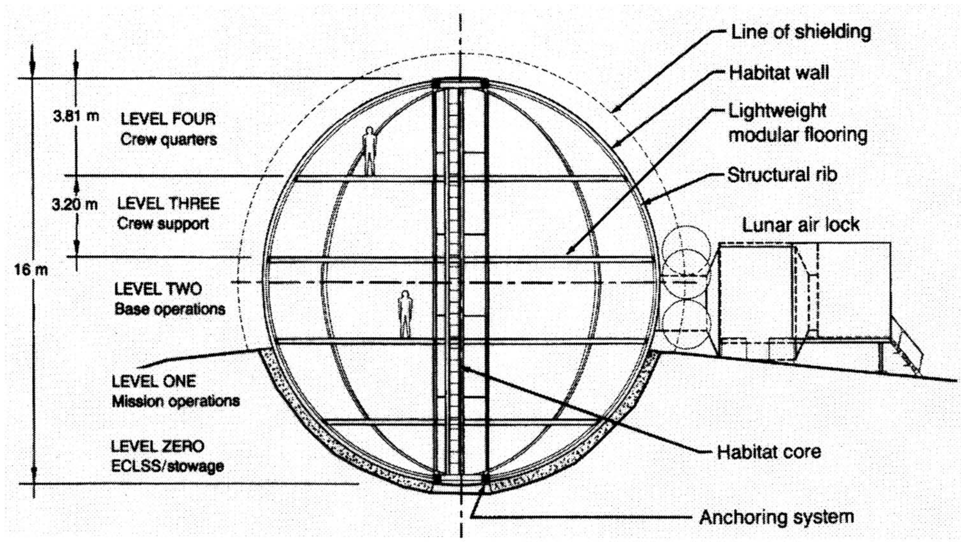


Fig. 2. Cross section of the spherical inflatable lunar habitat (Roberts 1988)

structure for the event of a pressure loss, the mass of the interior structure is about eight times higher than the mass of the main structure. Foundation issues are not addressed but must be considered. Fig. 4 shows an artist's impression of the completed base.

"Tuft Pillow" Inflatable

A pillow- or box-shaped structure is a possible concept for a permanent lunar base. The proposed base consists of quilted inflatable pressurized tensile structures using fiber composites (Vanderbilt et al. 1988). The foundation problem and additional reliability concerns and analysis are considered in Nowak et al. (1990). This concept marks a significant departure from numerous other inflatable concepts in that it shows an alternative to spheroidal inflatables and optimizes volume for habitation. The inflatable structure can be used as a generic test bed structure for a variety of lunar applications (Sadeh and Criswell 1994). Design criteria are also put forward (Criswell et al. 1996).

An inflated tensile membrane is the ideal structural solution for a pressure vessel. Fiber composite membranes are a highly effective material in terms of material properties and transportation costs. An inflatable membrane structure offers at once the advantages of structural efficiency and ease of construction. The proposed structure consists of single-level identical inflatable modules. The basic module of $6.1 \times 6.1 \times 2.44$ m($20 \times 20 \times 8$ ft; length $\times$ width $\times$ nominal height) consists of the following components (see also Fig. 5):

1. A roof and a subfloor membrane which are segments of a sphere of the same radius;
2. Four side wall membranes of a doubly curved prismatic shape which approximates a spherical shape; and
3. An inflatable frame system composed of four tubular tension columns made of a thin membrane with sufficient compressive strength to sustain a deflated configuration and four upper and four lower tubular compression arches also made of a thin membrane placed in a vertical plane extending along the sides of the module.

The orientation of the arches in a vertical plane facilitates the modularity of the system. The frame system must be able to fully support the deflated unpressurized module in an open configuration or the unpressurized module with the regolith cover during construction sequences, operation procedures, and in case of an accident.

When two or more modules are placed together, the design of the common interior walls depends upon the functional design and the pressure differences among adjacent modules. The gravity

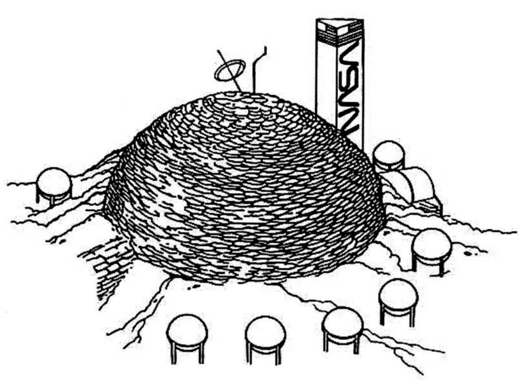


Fig. 3. The habitat "sandbagged" for radiation protection (Roberts 1988)

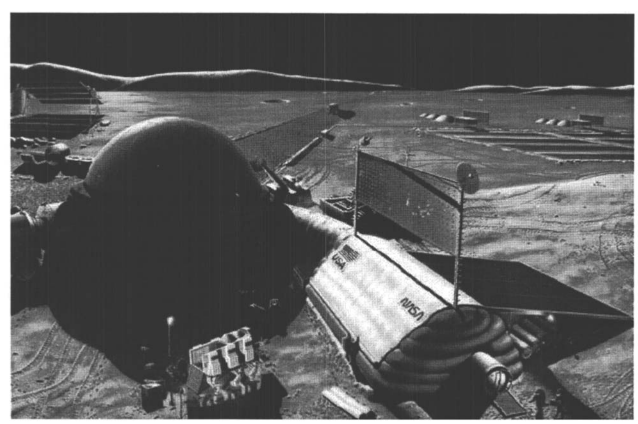


Fig. 4. NASA artist's impression of the spherical inflatable base

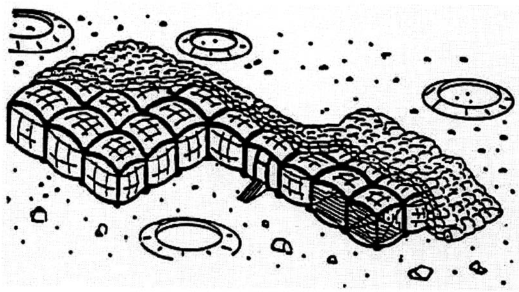


Fig. 5. View of a lunar base layout using tuft-pillow inflatables (Vanderbilt et al. 1988, ASCE)

loads induced by the regolith cover and the weight of the structure and its contents can be transferred through footings attached to the vertical columns. This approach is desirable since it can also be used for the deflated configuration.

After a preliminary design, using Kevlar 49 and an internal pressure of 69 kPa (10 psi), the total mass for a single inflated module meeting all structural requirements amounts only to about 195 kg (429 lb). Additional issues that have to be addressed in a detailed design include module response to dynamic loads, airlock operation, module interaction with outfitting equipment, module fabrication, module testing on Earth, and module construction on the lunar surface. Transportation and construction has to be done very carefully to avoid damage to the membranes. High redundancy exists, for example, if the single modules or areas are connected and can be sealed off with airlocks. Composite membranes cannot be produced from local materials on the Moon.

Cable Structures

Cable structures can be used for all the different stages of lunar colonization. Tension systems, including tension cables, cable reinforced fabrics, cable nets, and cables with stiffened trusses, have been used extensively in Earth environment-based structures (Otto 1973; Buchhold 1985; Leonard 1988). The advantages and disadvantages of these systems, when applied to different building configurations, are also well known. The most obvious reason, however, to use a cable roof system is its ability to carry the intended loads with great efficiency through axial internal tension forces.

Lunar Crater Base (Eichold 2000)

A lunar base cable structure in a crater is a concept that tries to use natural features on the Moon to reduce excavation and the amount of shielding that is needed. The scope of this concept is a larger one. Therefore, it is to be categorized somewhere between second- and third-generation concepts, depending on the actual size of the crater and the materials used. Similar roof structures, as the one proposed in Fig. 6, have been used for stadium roofs and other structures on Earth. A spoked wheel or tensegrity arrangement of the cables, also used for similar structures on Earth, can avoid instability in case of a pressure loss and other load reversals. The compression ring(s) in the rim of the crater has a sectional diameter large enough to permit inspection of the cable anchorage. The cover can be membranes, which will have to be imported, or thin walled metal plates, which can be made from lunar materials. The cables can either be imported or made from lunar material, such as lunar fiberglass. The tension ring(s) on the inside can be equipped with a pair of lenses that track the sunlight

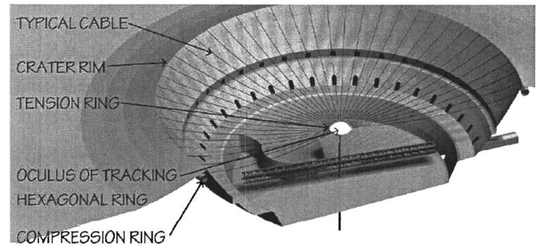


Fig. 6. Possible roof structure for a lunar base (Eichold 2000, with permission from the Space Studies Institute)

across the sky while optimizing the spread of light within the crater. They can be filled with water or some other clear shielding material.

Protection from meteoroid impacts is not addressed. Glass oculus and membrane can be fused together to provide proper sealing. Private, as well as public, rooms can be built in the crater walls for example by rock melting. The crater floor can be used for agriculture, research, and storage, for example. Accessibility may be difficult. However, from a long-term human factor perspective, this concept seems very promising.

Rigid Structures

The most experience is available for rigid structures such as trusses, frames, and arches. A hard structural shell provides certain robustness and high puncture resistance, for example. Rigid structures can be designed to accommodate all load cases at the same time without the need for a secondary structure, such as the inflatable structure, for example. The penalty is a generally higher mass and transportation volume.

Three-Hinged Arch Shell Structure

The structure in Figs. 7 and 8 is an update of an earlier concept (Ettouney et al. 1992). It will be discussed subsequently in detail.

Underground Construction

The geological phenomena known as the lava tube might very well provide an alternative to lunar surface construction. Lava tubes, formed by flow channels of molten lava, are well known on Earth. It is believed that lunar lava tubes will be more frequent and much larger than their terrestrial analogs. It appears that natural caverns of suitable sizes to house an entire lunar base exist on the Moon.

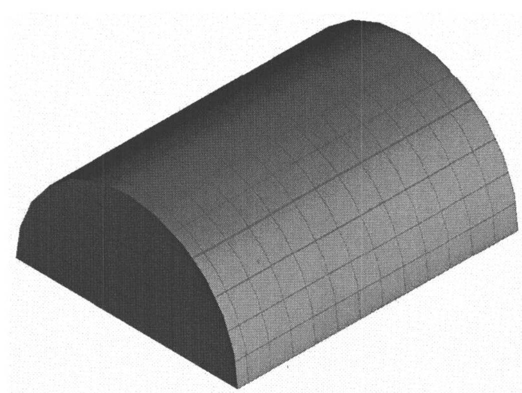


Fig. 7. Rendering of a lunar habitat module

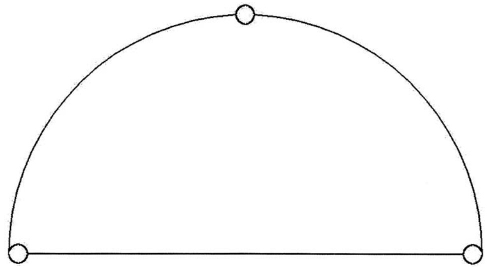


Fig. 8. Three-hinged arch system

Roof thickness in excess of 10 m will provide safe and long-term shelter against radiation and meteoroid collisions. Concerns of material degradation, thermal fatigue, and related exposure problems are moderated or negated. For first applications, prefabricated habitats would use lava tubes as shelters against environmental hazards. Later, it might be possible to modify the lava tubes to function as habitats. Geometry, surface roughness, air tightness, and other problems will have to be addressed. Reliability of the cavern roof is a major concern.

Constructing a habitat inside a lava tube can be achieved using extremely lightweight material, since it does not have to support any shielding material whatsoever. Inflatable solutions seem the most promising. A cross section of a possible arrangement can be seen in Fig. 9. Accessibility, lighting, and other architectural problems of a base inside a lava tube need a satisfying solution for each individual site (Daga and Daga 1988). Human factors and human psychology are issues for further research.

Lunar Base Design Workshop (Zippert 2004)

In the Summer of 2002, an international team of experts, sponsored by ESA, held the first "Lunar Base Design Workshop" in the Netherlands and Austria. Architecture students from 16 countries designed lunar bases with a strong emphasis on architectural problems. At the end of the workshop, the seven teams presented distinctively different and new approaches for lunar habitats.

Fig. 10 shows the result of team Kopernikus, using inflatable cells to expand the habitable volume of the hard-shell main structure.

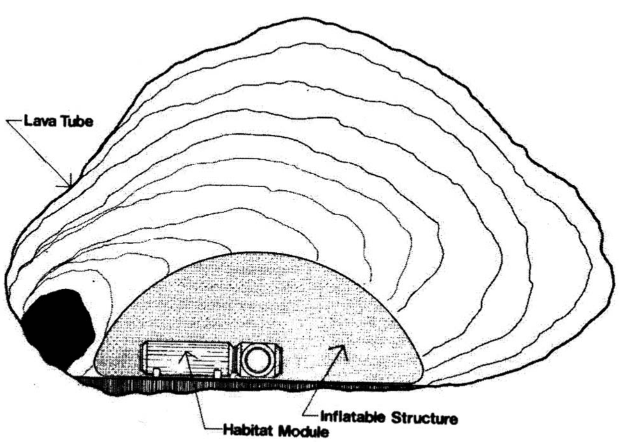


Fig. 9. Cross section of a lava tube with a possible habitat arrangement (Daga et al. 1992)

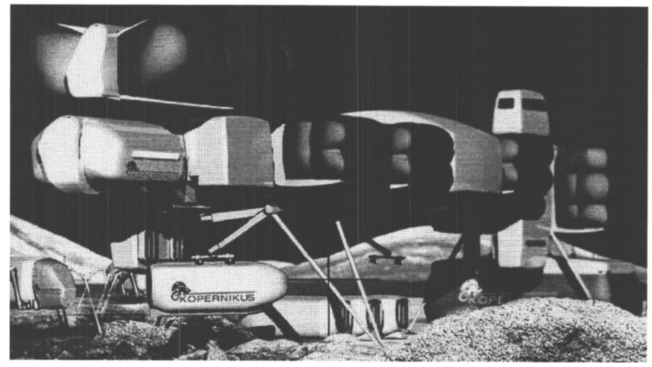


Fig. 10. Model of the Kopernikus Lunar Base (Lunar Base Design Workshop Team Kopernikus; Lunar Base Design Workshop 2002 at ESA-ESTEC HBT–VUT, Vienna, Austria ⟨www.liquifer.at⟩) (LIQUIFER 2002)

The design of team Tycho is also very interesting. A mobile triple-layer sphere provides habitation for workers mining ^{3}He. The sphere can move; pumping the water between the inner two membrane layers. The room between the outer and the middle layer is used for storage and vehicles (see Fig. 11).

These and all the other concepts presented at the workshop are very interesting and promising, most of them taking radical new approaches. However, they lack precise engineering solutions and most of them do not address all lunar problems, which is only natural at this stage of the design.

Concept Evaluation

Evaluation Criteria

Evaluating structural concepts for a lunar base is a very difficult task. There are so many things about construction on the Moon

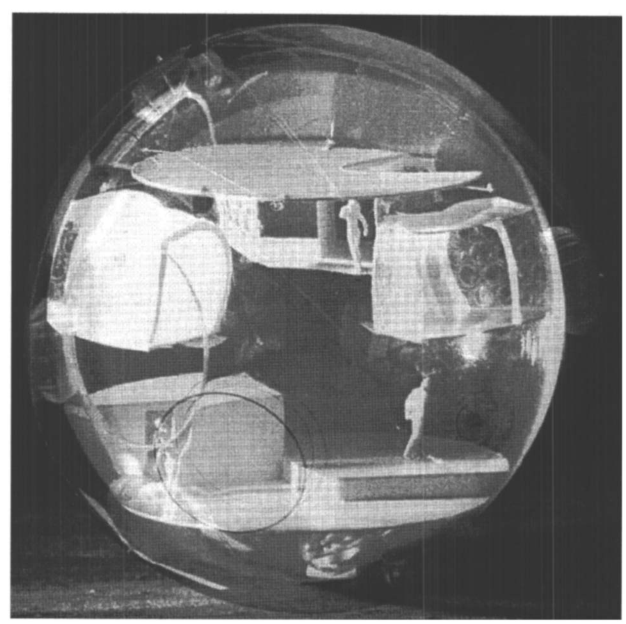


Fig. 11. "Tycho-Sphere" (Lunar Base Design Workshop 2002 Team Tycho; photo, Franz Schachinger; Lunar Base Design Workshop 2002 at ESA-ESTEG, HB2–VUT, Vienna, Austria ⟨www.liguifer.at⟩) (LIQUIFER 2002)

about which we lack knowledge. Most of the criteria given below are also qualitative. Applying them to a structural concept has to be done very carefully. The different criteria are not put into any order on purpose, because objectively weighting them is also quite a problem. However, it is important to make the effort to rationally decide on suitable concepts for lunar design and construction.

The following are among the criteria for evaluating lunar base concepts.

Transportation

The mass and volume that has to be transported will greatly affect the total cost.

Ease of Construction

Does the erection process of the structure need a shirtsleeve environment? Simple modular connections result in less astronaut construction time. What kind of heavy construction equipment is needed? The use of deployable/self-erecting structures can help to minimize EVA activities (Hijazi 1988; Benaroya and Ettouney 1992a,b).

Experience with the General Structural System and Materials

Numerous unknowns and variables accompany lunar construction. Some of the data needed to exactly describe lunar construction will only be available after a certain presence on the Moon is established. Therefore, it is not desirable for early concepts to include structural systems that themselves inherit too many uncertainties. In addition, it will be easier to react to problems arising during construction on the Moon if there is experience with the type of structure from former projects. Extensive prototype testing can help to gain experience. Implicit here is that structural concepts with which we are experienced can be designed in a robust way leading to long lifetimes (Benaroya 1994).

Expandability

Specifically, the second-generation bases will have to be able to adapt to a change in use. The structure must allow adding to or modifying the general layout (Duke and Benaroya 1993).

Excavation

Excavation operations will require heavy machinery that has to be transported to the Moon first. Ground preparation will certainly be needed but deeper excavations should be avoided (Graf 1988).

Foundations

The concrete foundations that are widely used for almost every construction project on Earth will not be available for early lunar bases. New foundation types will have to be developed. Reducing or completely avoiding horizontal and tensile support reactions is essential. The maximum use of the lunar soil strength is mandatory (Chua et al. 1990).

Human Factors

The structure must accommodate lighting, ventilation, insulation, and acceptable acoustics. Crew psychology and therefore effectiveness will greatly depend on the quality of life in the lunar habitat. One important factor is the perceivable volume (Elrod 1995; Eichold 2000).

Recycling

As thoughts turn toward third-generation structures, deconstruction and recycling of old structures will become increasingly important. Structures that are easily assembled can almost automatically be easily disassembled. Metals are easier to recycle than composites, for example.

Maintenance

The longer the desired lifespan of a lunar structure, the more important the maintenance requirements. Maintenance costs can greatly affect overall costs and will therefore have to be minimized. At the same time, maintenance is always necessary for a safe structures, so access to, and the easy replacement of, structural components will be crucial.

Evaluation of Second-Generation Lunar Habitat Concepts

As mentioned earlier, this work focuses on second-generation structures. It is expected that, especially for early second-generation habitats, the following criteria will govern.

- Transportation;
- Ease of construction;
- Experience with the structural system;
- Excavation; and
- Foundations.

In order to evaluate some of the concepts from the preceding section, a points system ranging from 1 to 6 is used. A value of 6 represents the best performance for the given criteria; a value of 1, the worst. Again, an evaluation of lunar habitat structural concepts cannot be 100% objective, but an effort was made here to get close. All of the assigned values are explained below and it was assumed that the five criteria are equally important. Of course, they are not; but their weighting will change with every advance in rocket, materials, and lunar science. So, it was decided not to weigh the categories now. The maximum/minimum values were only used if the conceptual design of the given structure was clear. A more detailed evaluation, including many other lunar base concepts, is available (Ruess 2004).

Transportation

- The spherical inflatable (Figs. 2 and 3) (5 points)

The pressure shell yields a low mass and transportation volume, but the internal arrangement with floors, stairs, and structural ribs results in extra mass and volume that exceeds the one due to the primary structure.

- The Tuft Pillow inflatable (Fig. 5) (6).

Very low mass and stowage volume.

- A lunar crater base (Fig. 6) (5).

A tensile structure. Low mass and volume for the cables. The compression ring will be the heaviest part.

- The three hinged arch (Fig. 7) (3).

A modular structure. Arch segments require more space than cables for example.

- Underground construction (Fig. 9) (6).

Only a very light structure, very likely a membrane type, has to be transported to the Moon.

Ease of Construction

- The spherical inflatable (3).

Care is crucial when working with membranes. Construction very likely will not require heavy equipment. The internal floors will take some time to be built.

Table 5. Results of the Evaluation Process

Concept	Transportation	Construction	Experience	Foundation	Excavation	Sum
Spherical inflatable	5	3	1	3	2	14
Tuft pillow	6	3	1	5	6	21
Lunar crater base	5	2	4	2	6	19
Three-hinged arch	3	4	6	4	6	23
Underground construction	6	2	1	4	4	17

- The "Tuft Pillow" inflatable (3).

No internal floors but the single modules will have to be connected.

- A lunar crater base (2).

Ease of construction very much depends on the span of this structure. The cables will have to be prestressed, which is rather difficult on the lunar surface.

- The three-hinged arch (4).

The arch shell is prefabricated in parts and can be erected with easy-to-assemble hinged connections.

- Underground construction (2).

An access tunnel to a lava tube/cavern has to be built. After that is done, the pressure shell can be constructed in a protected environment and unlike all the other concepts, no regolith placing will be required. However, there are many difficulties with subterranean construction.

Experience with the Structural System

- The spherical inflatable (1).

There is very little experience with inflatable membrane fabric structures.

- The Tuft Pillow inflatable (1).

See spherical inflatable.

- A lunar crater base (4).

This concept is similar to modem stadium roofs. Many specialists with experience are available for such a structure.

- The three-hinged arch (6).

Arch structures are well understood.

- Underground construction (1).

Cavern stability is unknown. No experience available.

Foundations

- The spherical inflatable (3).

Foundations were not considered in the preliminary design. It is assumed that minor foundation efforts will be sufficient.

- The Tuft Pillow inflatable (5).

Footing pads may be enough. Maybe no foundations are needed at all.

- A lunar crater base (2).

Again, foundations were not considered in the design. However, intermediate to large efforts will be needed to support the mainly vertical loads.

- The three-hinged arch (4).

Only vertical support reactions are introduced and small foundations will be sufficient.

- Underground construction (4).

The structure is already there. Of course, no foundations are needed. However, some remediation of the cavern will be needed to provide a safe structure. The pressure shell also will not need a foundation.

Excavation Requirements

- The spherical inflatable (2).

According to the design in (Roberts 1988)., one-half of the structure is below the ground. That means that one-half of a sphere needs to be excavated. With luck, natural features may be used to reduce excavation.

- The Tuft Pillow inflatable (6).

Leveling of the ground is all that is needed.

- A lunar crater base (6).

This concept is based on the use of natural craters. Tunneling into the crater walls is desirable, but not strictly necessary.

- The three-hinged arch (6).

Ground leveling is enough.

- Underground construction (4).

Access to the cavern/tube has to be established. To do that, excavation/tunneling may be necessary.

A summary of the evaluation results is shown in Table 5.

Based on this table of judgments, one could certainly argue that concept "X" deserves a point more or one less in category "Y". However, the sums are within a small range of only 9 points. This represents the fact that all of the proposed concepts were accommodated to fit the lunar requirements to the best possible degree. All concepts have their strengths and weaknesses. Inflatables generally satisfy the transportation criterion better, arch and other rigid structures satisfy the experience criterion better, for example.

In order to illustrate the design process and give a recommendation for a possible lunar habitat structure, one concept has to be selected.

The arch structure is chosen for a number of reasons. First, it satisfies all criteria well. Second, it has the highest sum among all concepts.

Generally, a rigid structure will be airtight. However, the hinged connections will have to be looked at in detail. A detailed design including mass calculations is done subsequently.

Design Process

Habitat Dimensions

Determining the dimensions of a lunar base habitat is a very complex task.

Numerous factors, such as crew size, mission duration, and function of the base as an industrial or scientific outpost influence the necessary habitat size. Hence, a global approach considering the necessary habitable volume per person will be pursued. Habitable volume is interpreted as free volume, excluding volume occupied by equipment or stowage.

As demonstrated by the Gemini missions, relatively short duration missions of up to two weeks can be endured by a person

Table 6. Total Needed Floor Area with Respect to Crew Size

Crew size	6	8	10	12
Habitable area [m^2]	206	275	343	412
+20% for equipment and stowage [m^2]	41	55	69	82
Total area (rounded up) [m^2]	250	320	415	500

restrained to a chair most of the time. The habitable volume per crew member in Gemini was 0.57 m^3. Currently, the NASA Man-Systems Integration Standards (NASASTD3000) recommend a minimum habitable volume, at which performance can be maintained for mission durations of four months or longer, of about 20 m^3. Despite this recommendation, a design volume (living and working areas) of 120 m^3 per person for a lunar habitat has been recommended, based on research of long-term habitation and confined spaces (Kennedy 1992). This value is about equivalent to the volume per crew member onboard the International Space Station.

The next question is to find an optimum floor height. Proposed floor heights for lunar habitats range from 2.44 m (Vanderbilt et al. 1988) to 4.0 m (Chow and Lin 1989; Kennedy 1992). People moving in low gravity will certainly require more vertical space than on Earth. They will lift off the floor higher while walking and especially trying to run. Therefore, a floor height of 4.0 m seems most suitable and will therefore be used henceforth. A very interesting thought on how to reduce the needed floor height is the use of slightly magnetic boots. Of course, this is only possible with structural concepts using metal floors.

However, floor height is not equal to clear height. Support systems, such as lighting and ventilation, will use 0.5 m up to 1.0 m of this space. This leaves, in most cases, about 3.5 m for the actual habitable volume.

With these numbers fixed, one ends up with

$$120 \text{ m}^3/3.5 \text{ m} = 34.4 \text{ m}^2 \tag{1}$$

floor area per person. The total floor area depends not only on crew size but also on the amount of equipment and stowage space that is needed. A summary for different sizes is given in Table 6.

Now, having determined the total floor area, one can begin to size the structure. Depending on the chosen structural system, one has to find the most efficient span of the main structure and, depending on the structural system chosen, the spacing between primary structural elements. The necessary clear floor height can for some concepts, e.g., arches, govern the span. The layout of the habitat is also very important at this point.

Loading Conditions

With respect to the construction sequence the main loading conditions are (Sadeh and Criswell 1995):

- The structure is deployed and fully pressurized, but no regolith cover is in place.
- The structure is fully pressurized with the entire regolith layer in place, which is the usual operational condition of the constructed structure.
- The structure is fully depressurized (by accident or planning) with the regolith cover in place.

All members must be designed for adequacy under all possible loading conditions. At the same time, the various members are not always controlled by a single loading. Assuming the same global safety factor for all loading conditions and construction stages, the second condition is generally less critical than the other two because the regolith loading is much smaller than the internal pressure (Factor 4-12). Other loading conditions are construction and operational loads. For example, attention should be paid to account for temporary nonuniform loading and accumulation of regolith induced by the placement of the regolith. In general, the structure is to be designed for the most critical situation (different safety factors can be applied to account for the likeliness of each scenario).

The extreme temperature changes on the Moon may lead to fatigue problems but again, regolith shielding will help to reduce temperature differentials on the structure. Another solution proposed might be to site the structure at one of the lunar poles (Spudis 2003). There are areas of near-permanent sunlight at the poles. Because the Moon's axis of rotation is nearly perpendicular to the plane of the ecliptic, the sun always appears on or near the horizon at the poles. If one is in a hole, one never sees the Sun; if one is on a peak, one always sees it. Several areas have been identified near both the north and south poles of the Moon that offer near-constant sun illumination. Moreover, such areas are in darkness for short periods, interrupting longer periods of illumination.

Thus, an outpost or establishment in these areas will have the advantage of being in sunlight for the generation of electrical power (via solar cells). It was also mentioned that a polar site would provide a benign thermal environment (because the sun is always at grazing incidence); such a location never experiencing the temperature extremes found on the lunar equator. However, this scenario is not advantageous for a lunar structure. One side of it being in sunlight, the other in shadow results in a significant temperature difference. From a structural engineering point of view, this scenario is even more disadvantageous than a constant temperature drastically changing every two weeks.

Temperature will play an important role during construction. The structure will be fully exposed to the sun on the upper side while the side facing away from the sun will be at a temperature 250°C below the one of the exposed side. The designer has to make sure that all connections still fit and construction is not hindered by this.

Extreme loading conditions might be impact loads; an accidental impact from a vehicle, for example. Depending on the layer thickness, regolith shielding will be able to absorb much or all of the rain of micrometeoroids. However, the rare larger particle might get through and the designed structure must be able to contain a possible explosive decompressive force.

The question is: Is it possible or reasonable to design against such impacts? Space vehicles have been shielded from meteoroid impact hazards by the use of thin sacrificial plates placed at some distance in front of the surface to be protected. Incoming meteoroids strike and perforate the shielding plate, are disrupted, and result in a cloud of debris that expands behind the plate. The protected surface then is subjected to greatly reduced impulse intensity. Such an approach has saved much weight when comparing single-plate and dual-plate armor providing equivalent protection. Once a shielding plate is hit, it has to be replaced, of course.

In the case of a layer of regolith on top, this will be a difficult task, and it is assumed that plate armor cannot be used below the regolith shielding. Putting armor plates on top of the regolith might reduce their dimensions, as well as the required regolith layer thickness. Effectiveness is unknown for this scenario, however. This whole issue is a broad field for further research.

Until better alternatives to regolith shielding are found, we have to assume that in case a particle gets through and depressurizes the habitat, the structure must not collapse. That means we have to design the structure to be failsafe against depressurization (Duke and Benaroya 1993; Benaroya 2002).

Codes

A lunar building code does not exist. For most purposes, national design codes can be applied to help the structural engineer. Care is advised with respect to the different ground acceleration (g) because all existing design codes only address the gravitational conditions on Earth. The gravitational conditions are sometimes hidden in design aids and formulas.

For the purpose of this work, several building codes were used as guidelines for the structural design. The design of the main structure was done according to the American steel design code (AISC Manual of Steel Construction, 9th Edition) and details, such as the hinged connections, are based on the German steel design code (DIN 18800, Part 1,8.3).

At a later stage in lunar colonization, it will be helpful to establish a series of rules for construction on the Moon. A discussion on lunar design codes has already started (Ettouney et al. 1992; Ettouney and Benaroya 1992).

Safety and Reliability

Human safety and the minimization of risk to "acceptable" levels are always at the top of the list of considerations for any engineering project. The Moon offers new challenges to the engineering designer. Minimization of risk implies in particular structural redundancy and, when all else fails, easy escape for the inhabitants (Benaroya 1994; Kennedy 2002).

The problem is to decide how much safety is needed for construction on the Moon. Economic considerations will be a major factor when deciding on final safety factors for a project. From a pure engineering point of view, lunar safety factors will have to be higher than terrestrial ones because the hazard risk and the number of unknowns is much higher on the Moon than on the Earth.

On Earth, the failure probability of structures is implicit in the various design codes for different materials, loads, and structural types. Until more knowledge about construction on the Moon is available, the use of global safety factors for lunar construction is advised.

Geotechnics and Foundations

Lunar regolith will be the soil a lunar structure is built upon. Its properties will be especially important for foundation engineering (Chua et al. 1990).

The bulk density of regolith ranges from 0.9 to 1.1 $\mathrm{g/cm^3}$ near the surface and reaches a maximum of 1.9 $\mathrm{g/cm^3}$ below 20 cm. The average is at 1.7 $\mathrm{g/cm^3}$.

- The porosity of the regolith surface is about 45.
- Cohesion of undisturbed regolith is c=0.1 to 1.0 $\mathrm{kN/m^2}$.
- The friction angle is from about 30 to 50°.
- The regoliths' modulus of subgrade reaction is typically 1,000 $\mathrm{kN/m^2/m}$.
- The compressibility ranges from C_c=0.3 (loose regolith) to 0.05 (dense regolith).
- Interparticle adhesion in the regolith is high. It clumps together like damp beach sand.

The bearing capacity can be calculated (Chua et al. 1990; Johnson et al. 1995) using Eq. (2):

$$q_0 = cN_c\zeta_c + 0.5\rho N_\gamma \zeta_\gamma \qquad (2)$$

where c=cohesion coefficient; N_i=soil coefficients; ζ_1=shape coefficients; ρ=regolith density; and g=ground acceleration.

The regolith's shear strength is given in Eq. (3) (Johnson et al. 1995)

$$\tau = c + \sigma \tan \varphi \qquad (3)$$

where τ=regolith shear strength; σ=normal stress; and φ= regolith friction angle.

This work idealizes the lunar soil using the modulus of subgrade reaction. All structural analysis calculations are thus done with the soil simulated by springs of stiffness C_c=1,000 $\mathrm{kN/m^2/m}$. It is a simplified method and a more detailed study of the regolith mechanics might be needed in the future.

Structural Design

Main Structure

General Assumptions

A modified version of the arch structure (proposed in Ettouney et al. 1992) is chosen based on the previous evaluation process. First, the shape and rise of the arch were determined.

A single floor layout is preferred to avoid additional structural mass for internal flooring and reduce the size of the main structural members at the same time. Therefore, a rise of 5 m was chosen for the arch. Fig. 12 shows how the space within the arch will be divided into the different functional areas.

On Earth, where gravitational loads usually govern our design, parabolic arch shapes are most efficient. An arch can be designed to be only in compression with little or no bending moment introduced into the structure. Bending moment should be avoided wherever possible. It is a very inefficient way to transfer the loads to the foundations. Simple tension or compression is much more efficient and is henceforth one of the design goals.

On the Moon, however, the governing load is not gravitational. A comparison of parabolic and circular arches under internal pressure loads can be seen in Fig. 13. It shows clearly that the circular arch is the more suitable structure because no bending moments are introduced in the arch. An in-plane two-dimensional analysis was found to be sufficient, no major three-dimensional effects are expected since the structure runs continuously in the third direction only. Internal forces, member stresses, and deflections are calculated using the RSTAB finite-element software (Dlubal 2004a).

The bending moment in the tie is a result of soil structure interaction. It depends on the ratio of foundation to soil stiffness. The final bending moment in the tie can only be determined iteratively because every change in tie stiffness results in a change in bending moment that in turn may require a different tie cross section. Thus, the final bending moment distribution will only be available after the structural design is finished. Figs. 13 and 14 only show one possible general shape of the bending moment distribution.

Another question is the use of hinges. Hinges are easier to construct than rigid connections. They also enable the designer to easily divide the structure into different segments, reducing the transportation dimensions. The maximum allowable number of hinges is three. With four or more hinges, the structure turns into a mechanism and is not statically stable anymore. The differences

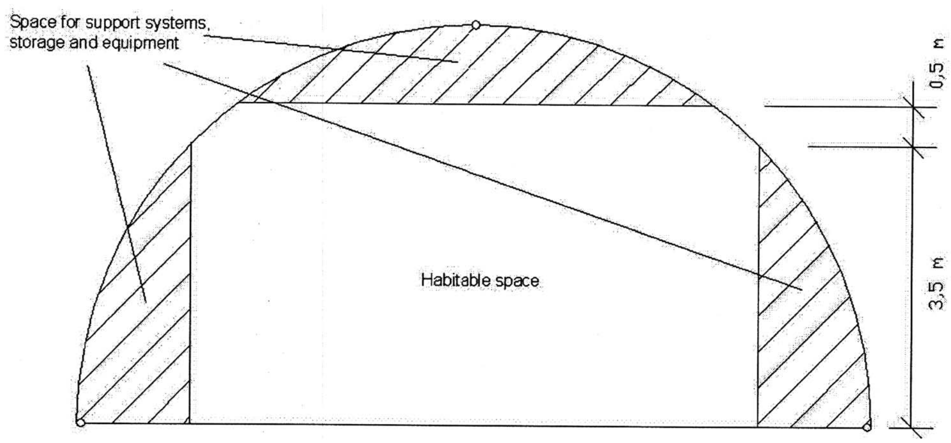


Fig. 12. Space use within the arch

in bending moment with all loads applied are shown for a one-hinge, a two-hinged, and a three-hinged arch in Fig. 14. The two- and three-hinged arrangements are better than a one-hinge arrangement because they do not introduce bending moments in the arch. The three-hinged layout is chosen because of constructability. The three-hinged arch is a statically determinate structure. Therefore, temperature loading during construction will not introduce stresses in the members, only deflections. This is another advantage of the three-hinged concept.

Structural Analysis

Loads

Note on Weight Mass Calculations:

$$W[\mathrm{N}] = \mathrm{m}[\mathrm{kg}]\mathrm{g}[\mathrm{m/s^2}] \tag{4}$$

where $g_{\mathrm{Earth}}=9.81\ \mathrm{m/s^2}$; and $g_{\mathrm{Moon}}=1.62\ \mathrm{m/s^2}$.

The mass of a body never changes. However, its weight depends on the gravitational acceleration. On the Moon, the designer has to be careful when applying gravitational loads. They are usually given as weight based in kiloNewton or kiloNewton meters. For lunar analysis, they have to be calculated using the lunar gravitational acceleration. The resulting loads will be only about 1/6 of similar ones on Earth.

For the static analysis of the structure, five main load cases were identified in addition to the structure's self weight (illustrated in Figs. 15 and 16):

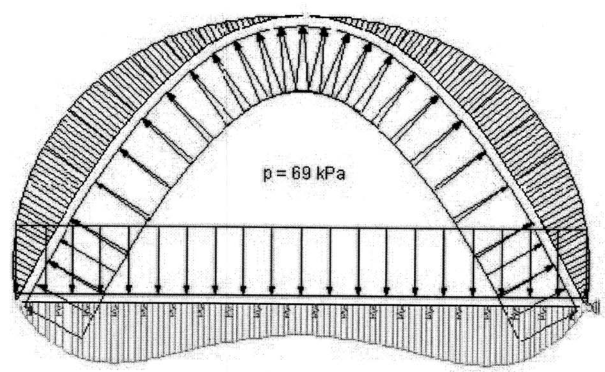
1. Internal pressure $p=69$ kPa;
2. Regolith covering the whole structure $q=8.3$ kPa;
3. Regolith covering one-half of the structure $q=8.3$ kPa;
4. Floor service loads $q=1$ kPa; and
5. Installation loads attached to the roof $q=0.25$ kPa.

The loads for the regolith cover assume that the regolith is bagged and can therefore be placed uniformly on the structure. If, instead of bagging, loose soil is simply heaped upon the top of the structure, the resulting load will be trapezoidal, not uniform. Modification of the performed analysis to suit this changed scenario is straightforward.

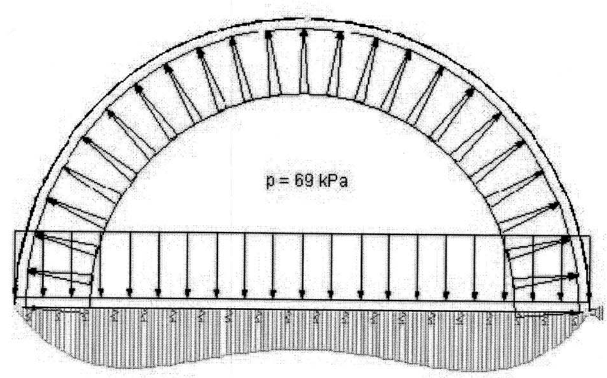
Load Combinations

Most of the loads described above may act at the same time. There are also a number of different scenarios starting with construction stages, the structure being initially pressurized with the regolith not yet on top of it, next the regular operational mode with all loads acting, and finally a planned or accidental decompression. The maximum impact on the structure has to be found using load combinations. For each scenario, only the loads that increase the stresses in the structure are to be included. Self-weight is always present. Four combinations were used to find the maximum stresses in the members.

1. Internal pressure plus floor loads;
2. Regolith cover plus installation loads;



(a)



(b)

Fig. 13. Comparison of bending moments for the parabolic and circular arches: (a) parabolic arch; (b) circular arch

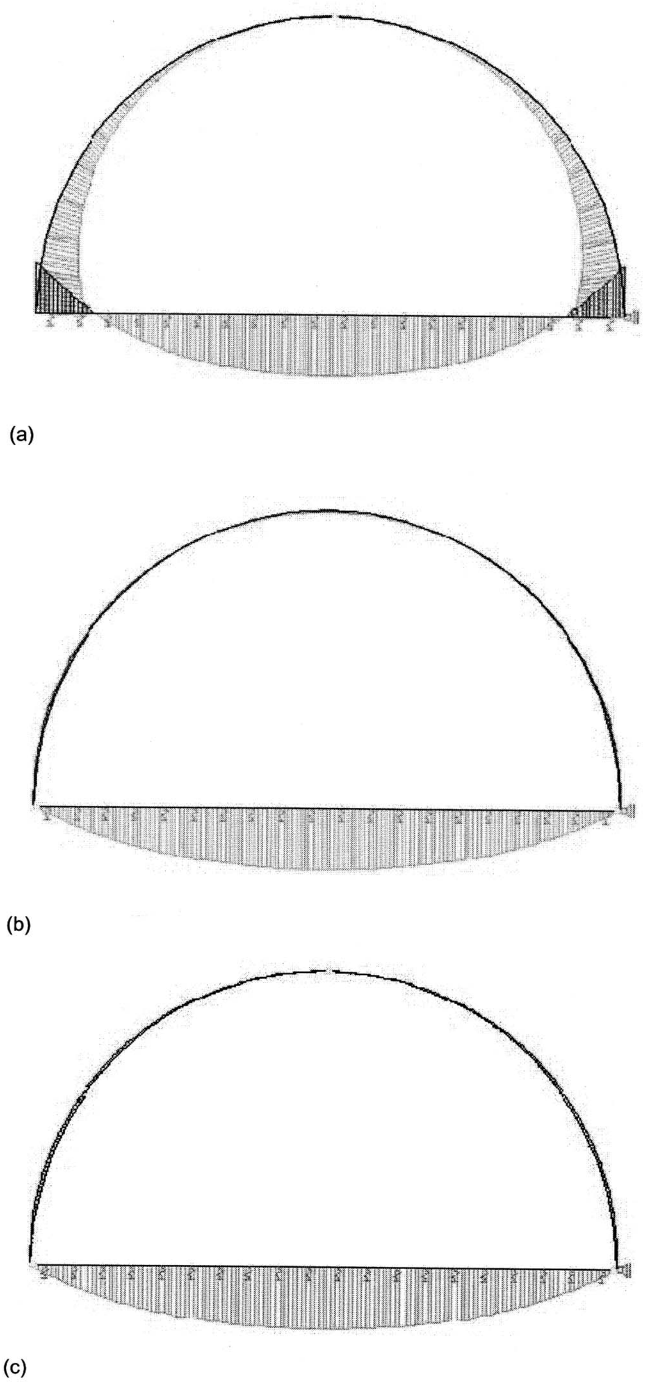


Fig. 14. Bending moments for a one- two- and three-hinged arch: (a) one-hinged arch; (b) two-hinged arch; and (c) three-hinged arch

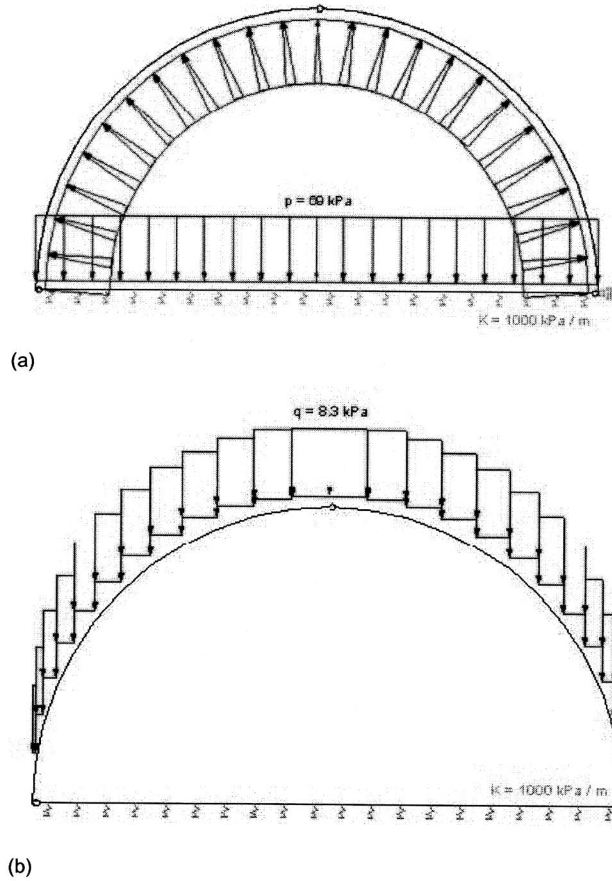


Fig. 15. Static Load Cases 1 and 2: (a) Load Case 1 internal pressure; (b) Load Case 2 regolith cover

3. All loads; and
4. One-half of the regolith cover (during construction).

The RSTAB software was used to determine the governing internal forces, deflections, and cross-section utilization. The two-dimensional analysis includes several simplifications. For example, only 0.25 m of the cross section was modeled. Consequently, the design loads were calculated per 0.25 m.

Main Structure: Three-Hinged Arch

To minimize structural mass, it is crucial to optimize the cross section. An infinite number of cross-section types are possible. Four different types were examined in this study (see Fig. 17). Determining the stresses in the structural members for the different load combinations can be done by applying the linear superposition rule. Load combination one was found to give the highest stresses for the tie, and load combination three gives the maximum stresses for the arch segments. The regular operation mode will be with all loads acting, so the deflections have to be calculated for load combination three.

The construction material was assumed to be high strength aluminum, the members being prefabricated on Earth and transported to the Moon. Composite materials that could further save mass are not used mainly because of the lack of experience and calculation techniques for those materials. So, all calculations are based on a high strength aluminum alloy with a yield strength of 500 N/mm^2. The depth of the legs on cross-sections 2 to 4 was limited to a maximum of 15 cm for the arch segments in order to limit transportation volume.

The design of the end walls will be discussed in a subsequent subsection. However, one of the results is already needed at this point. Internal air pressure on the end walls introduces tensile forces into the arch structure perpendicular to the already calculated forces. These need to be taken into account when designing the arch and tie members. The values needed are 130 kN/m for the arch segments, and 170 kN/m for the tie, respectively. The sandwich type is the most efficient cross section and is used for both arch and tie.

The arch member design is relatively easy. It is a structure governed by the interaction of bending moment and tension force. The design of the tie/foundation member is more complicated. It

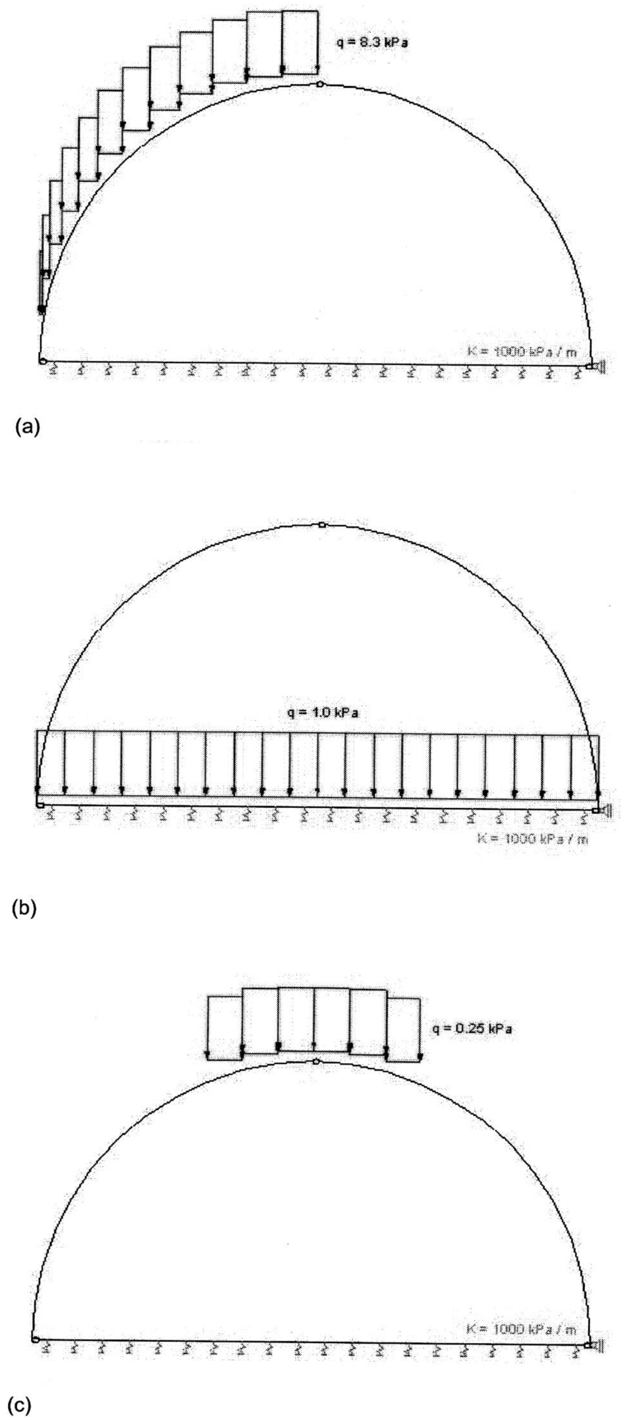


Fig. 16. Static Load Cases 3 and 5: (a) Load Case 3—partial regolith cover; (b) Load Case 4 floor loads; (c) Load Case 5 installation loads

is governed by bending moment. The bending moment depends on the ratio of foundation versus soil stiffness. A stiffness increase in the foundation yields a higher bending moment, since stiffness attracts forces. So designing the foundation plate is an iterative process. To find out the influence of a difference in the factor of safety on the design, it is done and compared for two different global safety factors: safety factor one=4.0, and safety factor two=5.0. The range for the factor of safety on Earth is, e.g., in the German design code (DIN), approximately between 1.7 and 3.5. All of the problems and uncertainties on the Moon will certainly require higher safety factors, so factors of safety of 4.0 or higher seem reasonable.

Finite element method calculation results for the final iteration can be looked up in Ruess (2004). The ASD (American Steel Design) Module, a part of the RSTAB software, was used to optimize the members (Dlubal 2004a). It includes cross-section classification to avoid local buckling, stress analysis for axial, bending, and shear stress and analysis of the allowable stresses. This is a program based on terrestrial design codes, so a few modifications were necessary. Modification of the material yield stresses allowed for implementation of the desired global safety factor. For example, implementing a safety factor of 5.0 for the arch requires the following calculation for the input value for the yield strength of aluminum in the program [Eq. (5)]:

$$\left(\frac{5}{3}\right)\left(\frac{50\ \text{kN/cm}^2}{5} - \frac{130\ \text{kN/m}}{60\ \text{cm}^2\text{/m}}\right) = 13\ \text{kN/cm}^2 \qquad (5)$$

where 5/3=programs material safety factor; 50 kN/cm^2=actual aluminum yield strength; 5=chosen design safety factor; 130 kN/m=tension force introduced by the end wall loads; 60 cm^2/m=assumed cross-section area in the direction of the wall tension forces; and 13 kN/cm^2=ASD input value for the aluminum yield strength.

Two main conclusions result from the structural analysis. First, the arch segments can have a uniform cross section. It is possible, but not necessary, to adjust the arch cross section to the distribution of internal forces since these are almost uniform. Second, in order to get an efficient cross section for the tie, it has to be adjusted to the distribution of internal forces. The bending moment has the shape of a parabola, so it was decided to give the tie a similar shape. The section height is affine to the square root of M. That means that the depth of the tie cross section varies, with the smallest depth at the ends and the largest in the middle. Fig. 18 shows the principal shape of the tie/floor/foundation.

Deflections under all loads, with the structural members designed using a safety factor of five, can be viewed in Fig. 19.

The allowable limit for typical terrestrial buildings is usually taken to be $L/200$, L being the span of the structure. The limit would be 10 m/200=50 mm. If the members are designed using a global safety factor of 4.0, the cross sections become lighter and this results in slightly higher deflections, Max u=68 mm. However, it is questionable if the deflection criterion should govern the design, especially when the expected deflections only slightly exceed it.

Reducing deflections can be done in many different ways.

- Strengthen the members. This approach results in extra mass that is not needed from a strength point of view. Since low mass is crucial for an economic design, this is not a desirable approach.
- Strengthen the soil. Sintering the regolith before erecting the structure will result in a higher modulus of subgrade reaction, and therefore lower deflections of the tie. It does not affect the arch deflections. Calculations show that the modulus of subgrade reaction would have to be increased about tenfold to get in the range of desired deflections. This is very likely not possible to be achieved by sintering the regolith. More research data is needed for this topic.
- Cambering. All of the loads can be assumed permanent. Therefore, cambering of the members is a solution. The members can simply be manufactured in a shape opposite to the calculated deflections. Manufacturing has to be done very carefully

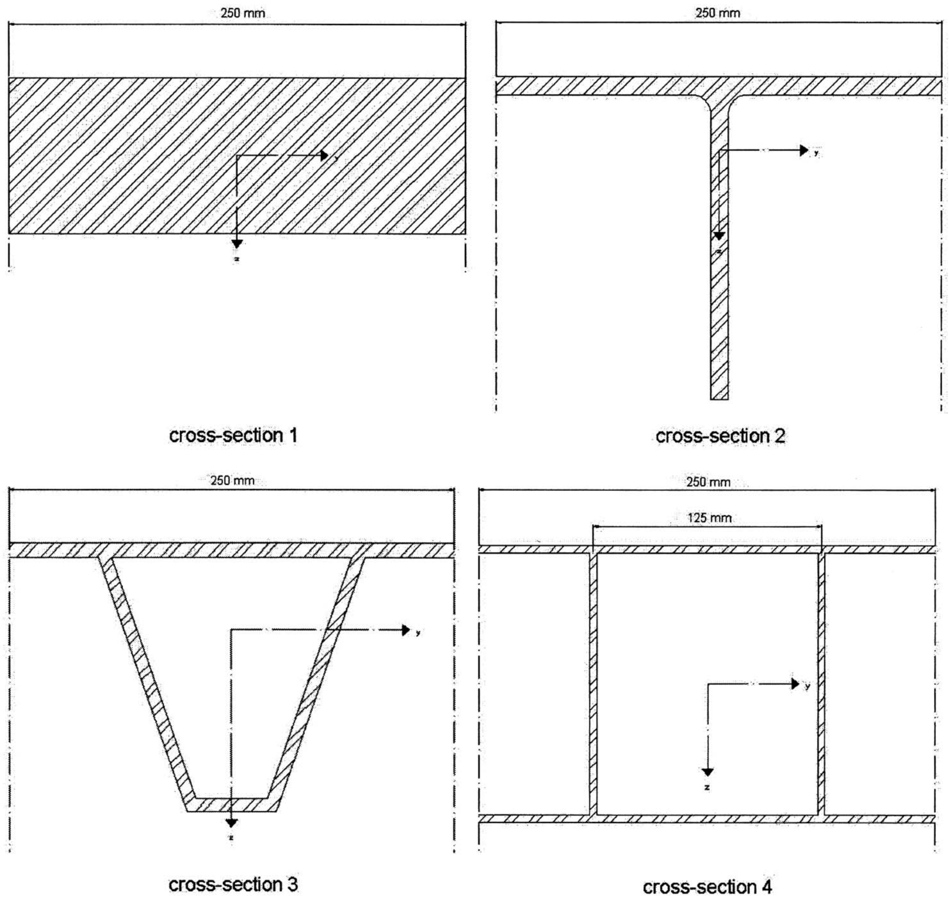


Fig. 17. Cross-Section 1 is a simple plate and in Cross-Section 2, the plate is stiffened with a leg perpendicular to it. Cross-Section 3 is very similar to a corrugated plate and Cross-Section 4 is essentially a sandwich construction.

and exactly to enable construction onsite. A comparison of habitat masses for different safety factors will be given after the end walls have been designed.

End Walls

The end walls are also designed to be of the sandwich-type cross-section. This cross section type is simply the most efficient.

The most efficient shape would be a quarter sphere. Bending moments for this layout are reduced to a minimum. However, for various reasons, such as low transportation volume, easy implementation of air locks, and expandability of the complex, a simple plate layout is chosen.

The design for these plate structures has to take into account bending moments in both directions. The finite-element software RFEM was used to calculate these internal forces (Dlubal 2004b). Linear hinged supports are chosen along the perimeter of the plate to represent the connection of the end wall to the arch. The connection design has to be done carefully to ensure that this assumption is correct.

The only load acting on the end walls is the internal air pressure. Loading and support conditions can be seen in Fig. 20.

The structural design is done according to Eq. (6)

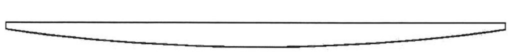


Fig. 18. Front view of the general tie shape

$$m_x/w_x + m_y/w_y \leq \sigma_r/\mathrm{SF} \tag{6}$$

where m_x=90 kN/m; m_y=150 kN/m; σ_r=50 kN/cm^2; and SF=safety factor.

Assuming the same cross section in both directions, a safety factor of 4.0 results in a minimum section modulus of 1920 cm^3/m, and a safety factor of 5.0 requires a minimum section modulus of 2400 cm^3/m. Possible cross sections are shown in Figs. 21 and 22. This results in the following masses for the end walls:

- 2600 kg for a safety factor of 4.0; and

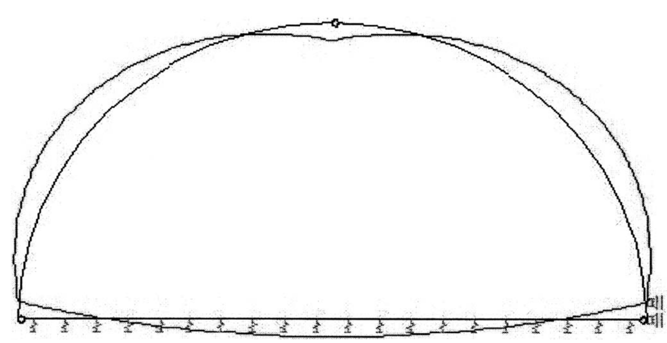


Fig. 19. Total deflections with the structural members designed for using safety factor of 5.0. The deflections are magnified by a factor of 10 for better illustration.

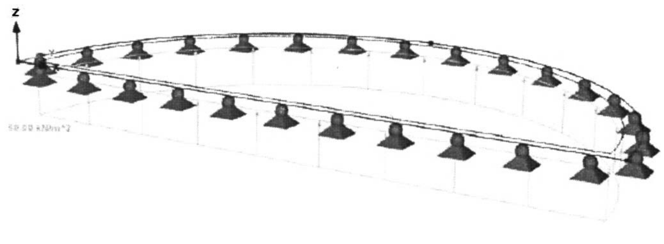


Fig. 20. Loading and support conditions for the end walls

- 3400 kg for a safety factor of 5.0.

Total habitat masses are summarized for different crew sizes and safety factors in Table 7. The values are for a simple layout with the structure running only in the longitudinal direction, so just two end walls were included.

For the safety factors compared, the masses are directly proportional to the applied factor of safety. Fig. 23 shows the mass ratios for the three different structural components: The foundation component is the main contributor to mass. This is a result of the design approach that focused on statically optimizing the arch structure and providing a ready-to-use floor system.

Dynamics

A dynamic analysis is done for the design using a safety factor of five. In order to simulate vibrating machinery, the dynamic response of the structure for a cam mechanism with an amplitude of approximately 4.6 cm and a frequency of 172 Hz was calculated. No significant deflections or additional internal forces were found.

Construction Sequence

The habitat dimensions in the longitudinal direction depend mainly on the crew size. The transportable length for members is limited by the transportation system, so dividing the members into different segments for transportation is necessary. A reasonable segment length is 2.5 m. Ten segments put together would then provide enough space for a crew of six astronauts. Connecting the segments has to ensure that all the loads can be transferred and that the pressure is sealed. It is believed that welding the full section is the best solution to this problem. Welding in space has been performed on the Russian Soyuz T 12 mission, for example.

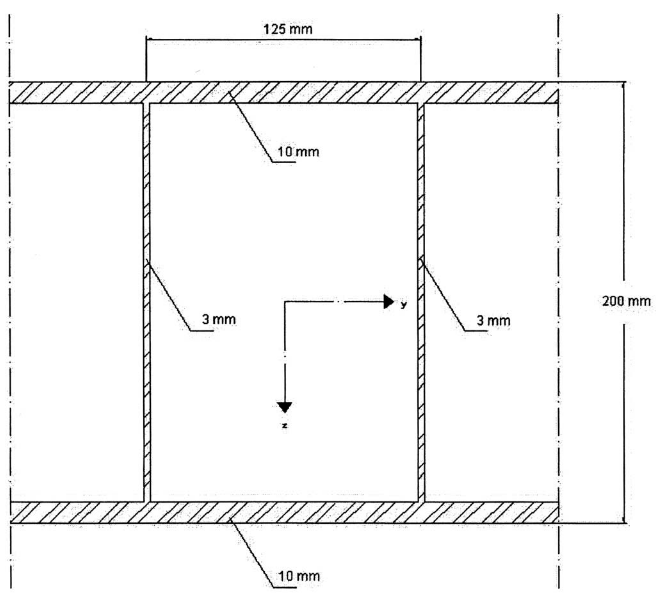


Fig. 21. Possible wall cross-section for a safety factor of 4.0

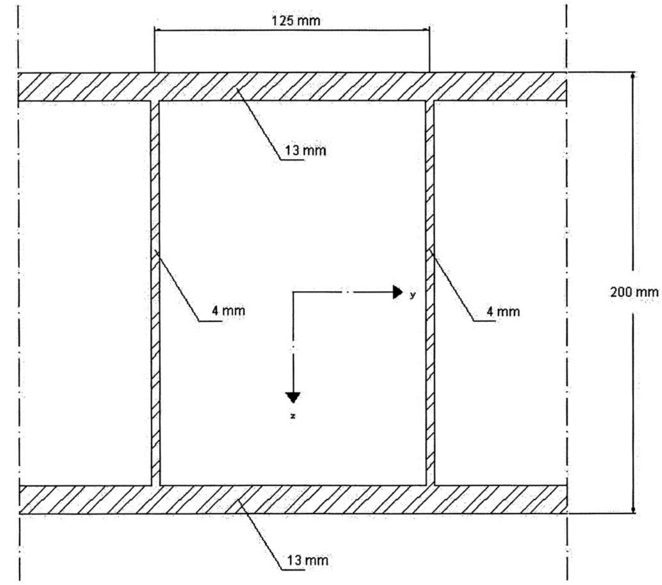


Fig. 22. Possible wall cross-section for a safety factor of 5.0

Erection of the structure can be done step by step. It will be a linear process. First, the floor is constructed. The 2.5 m long panels are laid out on the site and joined using tongue and groove joints. Cables may help to pull all panels together. Welding all panels provides sealing and guarantees that all forces can be transferred.

The arch panels are erected one after the other, by placing one arch segment on a temporary construction scaffolding and bolting it to the floor at the bottom. The second arch segment is placed in the same way.

Finally, the two arch segments are bolted together. The temporary scaffolding is lowered and transferred to the next section, where the placement of the next arch segments can begin. The panels then have to be welded together. All welding is best done at night to minimize inherent deflections due to temperature-induced deformation. If construction is performed during the lunar day, unprotected members are exposed to the sun and temperatures on the member surface climb up to 150°C. However, the member's other side will be in shadow and therefore at a temperature of −100°C. This causes the member to deflect. These deflections are in the range of 0.5 m. However, they do not play a role in the arch construction. A three-hinged arch can always be joined together, for example by lowering the scaffolding until the pieces fit. Fig. 24 shows the structure after the one arch is put in place.

When the desired structure length is achieved, the end walls are slid in at the arch ends. The connections between arch and

Table 7. Lunar Habitat Masses

Crew size	Total structural mass, SF=4	Total structural mass, SF=5
6	38.6*t*	48.3*t*
8	49.7*t*	62.2*t*
10	60.8*t*	76.0*t*
12	72.0*t*	89.9*t*

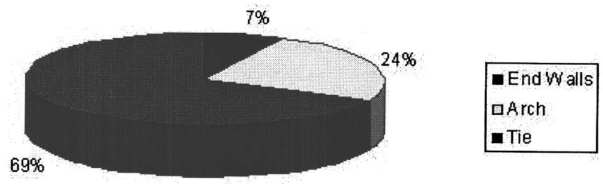


Fig. 23. Mass ratios for the three structural components

walls have to be established next. The structure is then sealed with membrane fabric strips glued to the structure along the structural connections where necessary. After completing all necessary seals, the habitat can be initially pressurized and finally the regolith cover is put into place.

The floor segments have a mass of 2,945 kg, so they weigh approximately 5 kN; where the arch segments have a mass of 605 kg, and weigh about 1 kN each.

Certainly, there will be equipment needed to move the parts from their landing site to the construction site and into place there, but no heavy equipment is needed to move 5 kN. A light crane is a good solution to put the segments in place onsite.

A solid rendering of a habitat module for a crew of three is illustrated in Fig. 25. The lines on the surface are to enhance curvature and three-dimensional appearance.

Habitat Layout

The question of lunar base layouts is a very complex one and deeply routed in architectural and operations considerations. However, providing different modules for research, habitation, manufacturing, storage, etc., seems like a reasonable approach. These modules can be arranged in a multitude of scenarios. The five basic configurations are (Reynolds 1988):

1. Linear: The linear configuration is the simplest of all configurations. It is the repetition of modules with one primary circulation path. The internal distances from one end to the other are maximized. The spatial characteristics are primarily public-type spaces that are noisy and conductive to space sharing with the circulation path. One of the main problems with the linear system is safety.
2. Courtyard: When a linear configuration closes on itself, its basic characteristics change: The area coverage becomes greater and the enclosure minimizes. The courtyard is a unique identifiable space. There still exists one primary circulation path; however, it now forms a closed loop. An additional attribute is the courtyard area itself.

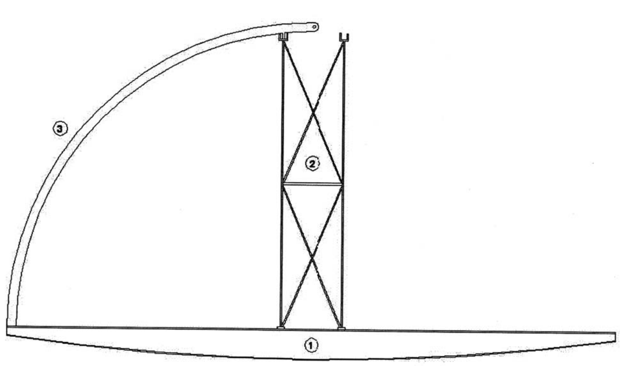


Fig. 24. Erection of the main structure: 1–floor; 2–scaffolding; and 3–arch segment

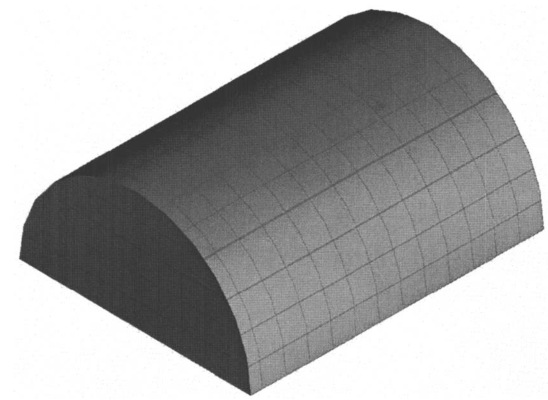


Fig. 25. Rendering of a lunar habitat module

3. Radial: The radial configuration is a centralized space with linear extensions in more than two directions. The central area provides a major functional space with secondary areas radiating. These secondary spaces can be private quiet areas or main circulation routes to additional functional zones. One advantage is the easy access to the central zone.
4. Branching: A linear growth system that expands with secondary paths from the main linear one characterizes a branching configuration.
5. Cluster: Cluster configurations have no dominant circulation patterns. Generally, a large area is created.

The proposed habitat modules favor linear expansion over branching. Therefore, linear and radial layouts are more suited than courtyard, branching, or cluster layouts. A radial arrangement is most promising with respect to emergency egress, accessibility of facilities and the lunar surface, as well as for including an easily accessible safe haven to protect from solar flares (Reynolds 1988). The central functional zone can be designed in different ways. Renderings of a radial lunar habitat configuration with different possible central zone layouts are shown in Fig. 26.

Details

It is assumed that all parts described above the arch segments, the floor members, and the end walls can be transported to the Moon in one piece. However, it is also possible to further divide them into smaller parts if necessary, e.g., dividing the end walls or the floor segments into two parts. The connections for this scenario are not designed here, but it is generally possible and should not impose great problems. A general solution is welding them back together on the Moon. Therefore, the only connections actually designed here are the hinged connections in the arch structure as well as the connection of the end wall to the arch, which is also idealized to be a hinged connection.

Connections

- The arch connections: Variant 1. The best way to create a hinge is a bolted connection. Bolted connections are also easy and fast to construct, even for astronauts in EVA suits. The cross-section's "webs" can be easily strengthened locally and then used to make the connection. It is also possible to allow for tolerances, e.g., by making the holes larger than the bolts' diameter. This way manufacturing inaccuracies and member deformations during construction; for example, due to nonlinear temperature loads, can be included in the design. However, it is not necessary to include large tolerances in this design.

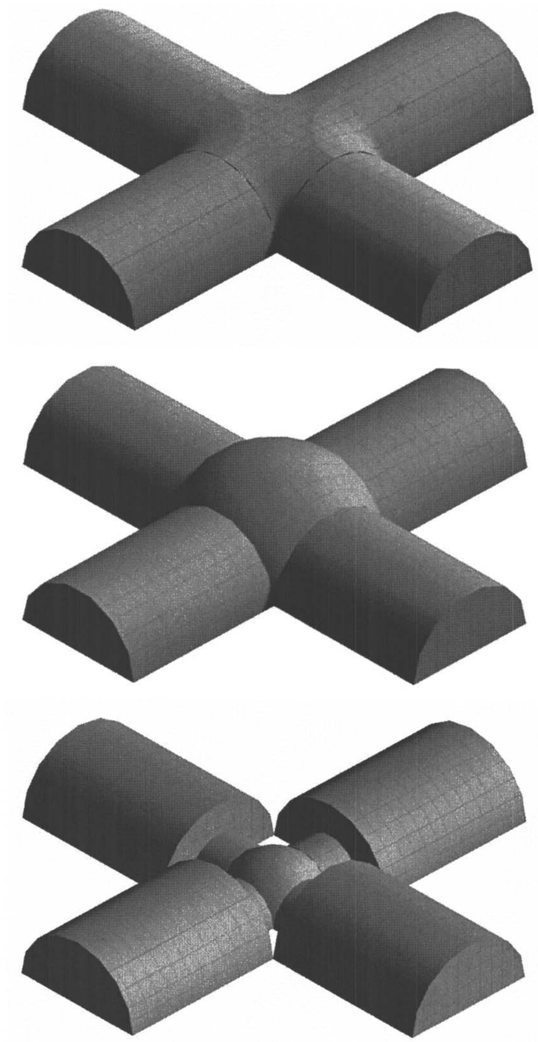


Fig. 26. Different solutions for a radial arrangement

The connection design process and connection dimensions have been performed, and Figs. 27 and 28 show detailed drawings of the hinged connections.

- The arch connections: Variant 2. Although the sealing procedure for variant one is relatively easy, it is inconvenient and labor intensive. If it were possible to design the hinges to be airtight, the structure would be cheaper and likely faster to erect. The result of these thoughts can be seen in Figs. 29 and 30, and were conceived by the second writer this paper.
  The tension bar area is determined in Eq. (7):

$$A = \mathrm{SF}^{*}N/fy = 4.3\ \mathrm{cm}^2 \tag{7}$$

where A=required tension bar area; SF=safety factor=5.0, N=design tension force=43 kN; and fy=material yield strength =50 kN/cm^2.

The strengthened plate is designed like a simple beam (see Fig. 31). This approach is more conservative than designing it like a plate. The plate has to satisfy the following two conditions [Eqs. 8 and 9],

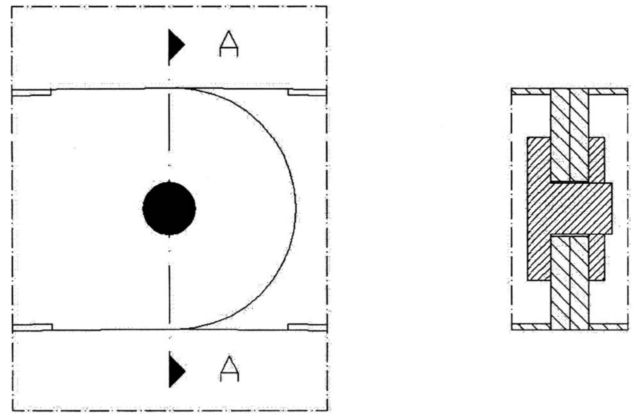


Fig. 27. Connection of the arch segments

$$\frac{M}{W} = \frac{f_y}{\mathrm{SF}} \tag{8}$$

where M=design moment; W=elastic section modulus=$bh^2/6$; fy=material yield strength=50 kN/cm^2; and SF=safety factor =5.0.

$$\frac{V}{A} = \frac{f_y}{\sqrt{3}\cdot \mathrm{SF}} \tag{9}$$

where V=design shear, A=area in shear; f_y=material yield strength=50 kN/cm^2; and SF=safety factor =5.0.

Bending governs the design and yields a plate thickness of t=11.4 mm. A thickness of t=12 mm will be used.

End Wall Connections

The shape of the arch construction right before the end walls are put into place will determine the end wall shape. This is to ensure that the wall fits in place. The wall panel rests on the floor, but there will be a gap between the wall and the arch segments because of construction tolerances. Aluminum plates extend from the wall, and have to be welded to the floor and arch, respectively. These plates can only be welded at the end, so using fillet welds with the same material strength as the aluminum for the members, the weld size is governing the plate thickness, too. Welding has

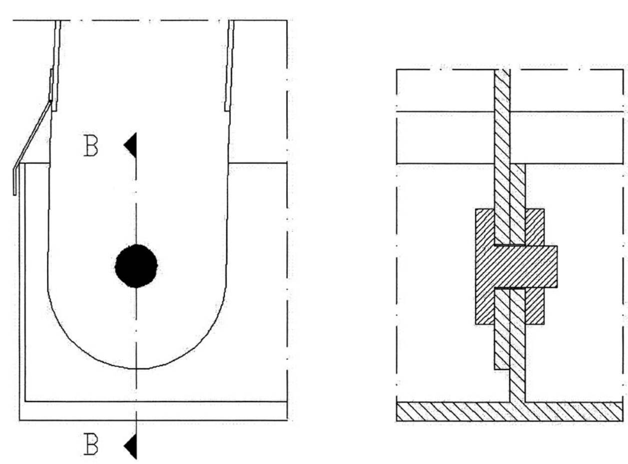


Fig. 28. Connection of the arch segments to the floor

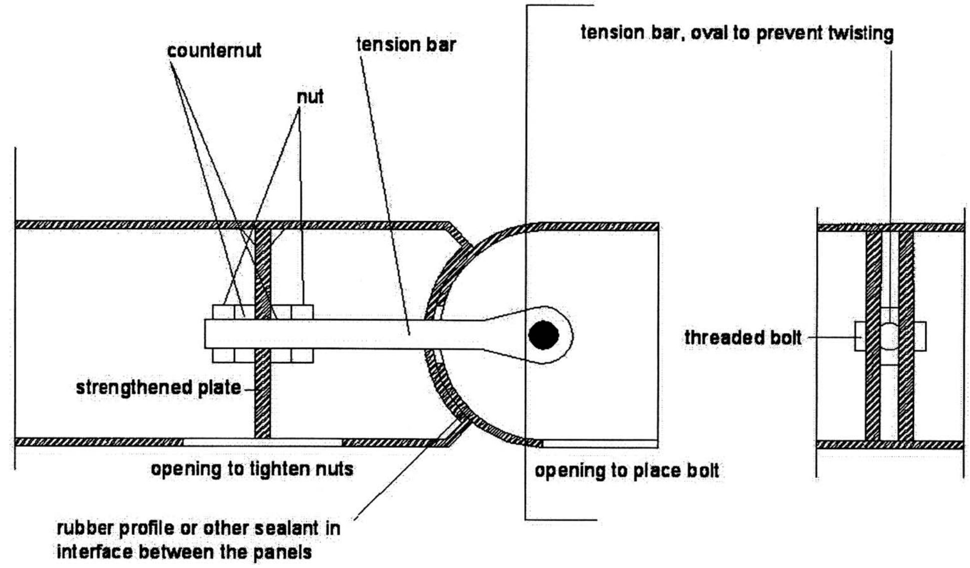


Fig. 29. Alternative connection of the arch segments (concept by Schaenzlin, University Stuttgart)

the advantage of also sealing the connection, but additional membrane fabric strips can be applied if desired. The weld sizes are calculated in Eqs. (10) and (11):

$$\frac{130\ \text{kN/m}}{a} \leqslant \frac{50\ \text{kN/cm}^2}{5.0} \Rightarrow a \geqslant 0.13\ \text{cm} \qquad (10)$$

where 130 kN/m=wall support reaction on the arch (tension); a=fillet weld size (throat); 50 kN/cm^2=weld material yield strength; and 5.0=applied global safety factory.

$$\frac{170\ \text{kN/m}}{a} \leqslant \frac{50\ \text{kN/cm}^2}{5.0} \Rightarrow a \geqslant 0.17\ \text{cm} \qquad (11)$$

where the wall support reaction is now 170 kN/m.

According to DIN 18800, the weld size is also limited to

$$a \leqslant 0.7 t_{\min} \qquad (12)$$

where $t_{\min}$=smallest plate thickness. For both the arch and floor, this requirement is met. To make construction simpler, full fillet welds will be used. This results in a=1.4 mm for the wall connections using two welds. The floor weld will very likely be governed by onsite manufacturing accuracy, and can be thicker if necessary.

Additional bracing is not necessary, but for a conservative design it could be a good idea to make sure the wall support reactions (tension) are transferred to the full cross section of both arch and floor—by including an inclined plate in between the webs where the weld is made. Detailed drawings of the connections without additional bracing are shown in Figs. 32 and 33.

Pressure Sealing

The nature of the structural system makes it necessary to seal the openings in the structure with a separate application. The area around the three hinges has to be sealed air tight with a system

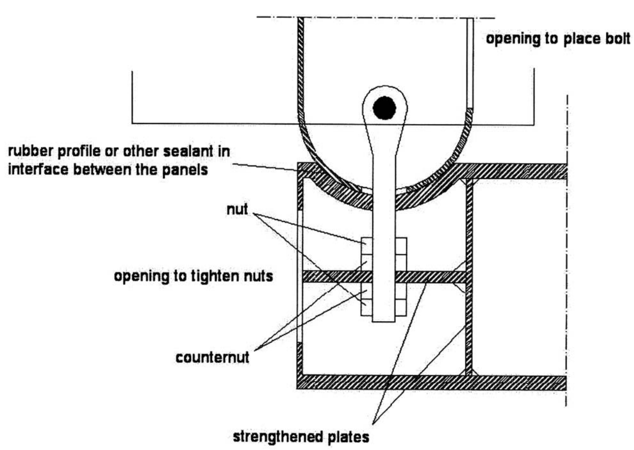


Fig. 30. Alternative connection of arch segments to the floor (concept by Schänzlin)

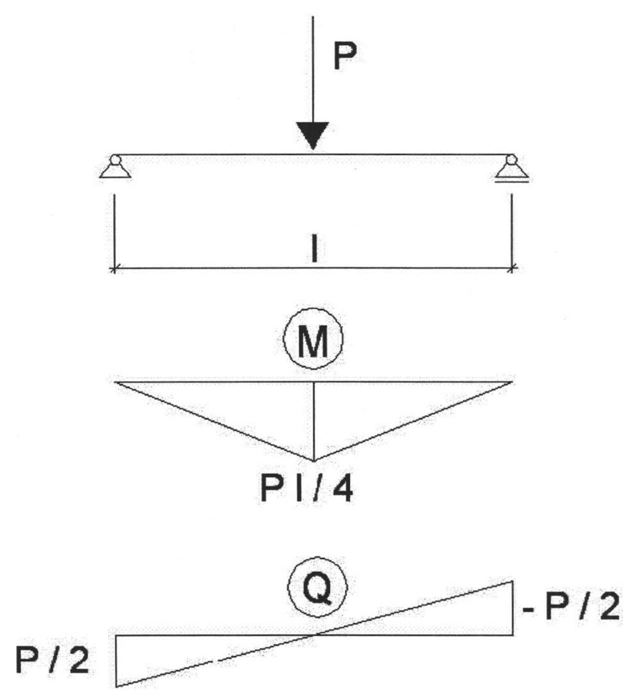


Fig. 31. Statics for a simple beam under a concentrated load

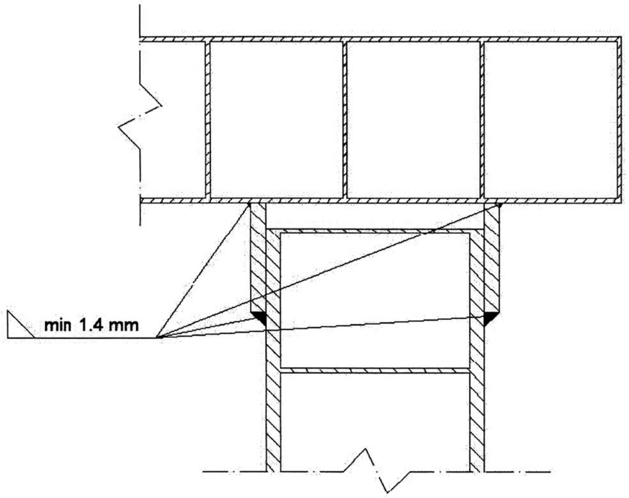


Fig. 32. Connection of wall and arch

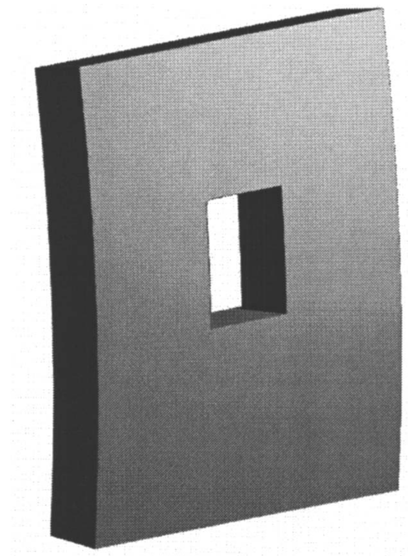


Fig. 34. Opening in the structure to accommodate windows

that is capable of supporting the pressure loads and flexible enough to allow for the movement of the structure until the regolith cover is finished. The use of membrane fabric strips, glued to the aluminum structure, is a very promising and feasible scenario.

The properties of membrane fabrics have been summarized, and the technology to glue them to a metal surface is available from the aerospace engineering community. Huntsman Structural Adhesives, for example, offers suitable composite epoxy glues (Huntsman 2004).

Openings

Sunlight ingress or access for the support systems will require openings in the structure. They can be at every point of the structure as long as the immediate boundary is strengthened appropriately. Fig. 34 shows a window opening in the structure. The vertical boundaries of the window are the web plates of the arch cross section, strengthened if necessary. The horizontal boundaries are additional aluminum plates.

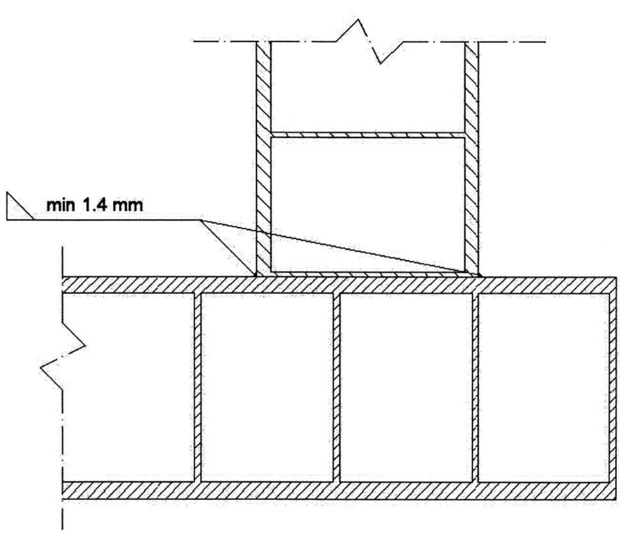


Fig. 33. Connection of wall and floor

It will be a bigger problem to produce a 3 m deep opening in the regolith cover. Aluminum tubes, for example, could keep the regolith from falling into the opening.

Every manned U.S. space program has included windows in the vehicles. Windows are extremely important to a manned space flight. However, benefits, such as high crew morale, come at a high engineering cost. For all the programs from Mercury to Apollo to the Space Shuttle and the International Space Station, the use of glass for most of the windows is prominent (Estes and Edelstein 2004).

Glass provides many optical benefits over other transparent material, such as plastics, for use in space. For example, glass is comparatively impervious to attack from atomic oxygen. Most plastics would haze over in a matter of days from atomic oxygen attack if exposed to the space environment. Ultraviolet exposure usually causes embrittlement of plastics. Glass does not experience such degradation.

Glass has many undesirable features as a structural material. It experiences static fatigue, has brittle failure modes, and its strength is easily reduced by very small damage. The lunar/habitat environment provides every possible disadvantage to glass. This includes a humid environment, constant loading of the glass in tension, long expected design life, and impact environments on both the internal surfaces and external surfaces.

Careful design considers these disadvantageous conditions and ensures the safety and structural integrity of the glass over the desired life span. The International Space Station window design, for example, includes sacrificial panes. On the exterior side of the window, a pane is implemented that is present for the sole purpose of protecting the pressure panes from impact. It is a completely unloaded pane designed to act as a shield. A similar sacrificial pane is implemented on the interior of the International Space Station windows. This pane protects the pressure pane from damage and provides a heater that prevents the window from fogging (condensation) (Estes and Edelstein 2004).

Problems and Outlook

Lunar construction is possible and reasonable. However, the design process for a lunar habitat structure showed several problematic areas.

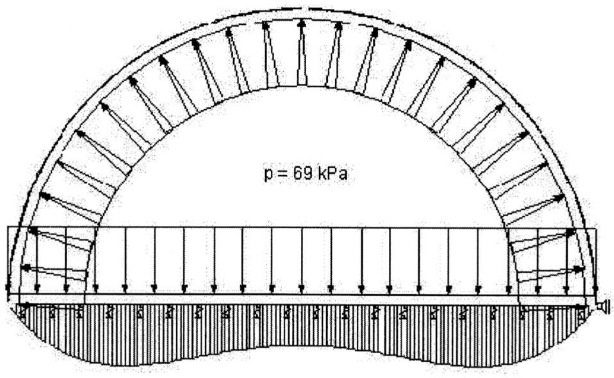


Fig. 35. Altered general floor bending moment distribution

1. Providing a floor system that is ready to use resulted in high bending moments and therefore high mass for the examined approach. The high interdependency of floor stiffness and bending moments is a result of the soil model that was used. If it is possible to reduce the floor stiffness below a certain level and still make the cross section capable of resisting the internal forces, the floor could be designed to be significantly lighter. This is because of a change in the general shape of the floor bending moment once the ratio of floor stiffness to soil stiffness is below a certain level. Maximum bending moments are greatly reduced (compare Figs. 35 and 14).

   With the employed aluminum alloy and safety factors, this scenario is not working. However, advances in ultrahigh strength materials—e.g., carbon nanotubes, and continued lunar research and exploration that enable the use of lower safety factors—might benefit the floor design in the future. If, for example, a safety factor of only 2.0 could be used with the same aluminum material, the mass of the floor members would be reduced to about 25% of the floor member mass used for a safety factor of 4.0.
2. Extreme temperature may be a problem during the erection of the structure. The chosen sandwich-type cross section is very efficient for the operational loads but not for the temperature differentials between top and bottom plates while exposed to the Sun. But although the members deform, erection is no problem because of the three-hinged static system. An additional insulation layer is proposed for statically indeterminate structures to protect the structure from the Sun-induced temperature variations. There is much room for further research on the temperature gradient problems on the lunar surface.
3. With every advance in science related to lunar construction, different concepts will have to be re-evaluated. Evaluation criteria have to be weighted eventually.
4. A lunar transportation system does not exist. So all dimensions are based on assumptions on what is "transportable." When the transportation vehicle for this purpose is developed, and dimension restrictions are available, structural members might be subject to dimension changes.
5. In addition, one has to be aware of the wide range of assumptions and unknowns that cannot be checked now. Many of these assumptions will be verified in the near future during the space agencies' lunar programs. Most important will be data on regolith properties, meteoroid activity, and radiation.

The most important point to make is that there are significant difficulties with our return to the Moon with permanent outposts. Our study was primarily focused on a possible structural design, recognizing that the design must be coupled with many other technical and nontechnical aspects of creating a civilization on the Moon.

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