IN-SITU MARTIAN CONSTRUCTION – MDRS CREW22 MASONRY CONSTRUCTION SIMULATION

Georgi Petrov
Laguarda.Low Architects
Boston, MA
gpetrov@alum.mit.edu
James Harris
Austin Community College
Austin, TX
james@james.harris.name

ABSTRACT

As part of the Mars Society's continuing operational research this project aimed to demonstrate that masonry construction is a viable building method that will help establish a permanent human presence on Mars. It has been proposed that bricks can be manufactured from Martian regolith. Using pitched-brick vaults and self-supporting domes a wide range of spaces can be constructed using no scaffolding, thus greatly simplifying construction.

To explore this possibility Crew 22 aimed to manually construct a barrel vault with a one meter inner radius, using local stone and sand under simulation constraints. Portland cement and hydrated lime were the only imported materials. Construction lasted for 64.5 man-hours in Sim, and six man-hours out of Sim for comparison. Working in the Mars suits was difficult, but not overwhelming. The biggest constraints were decreased visibility and communication had a bigger effect than the weight of the backpack and suit. The use of irregular stone also proved to be a major obstacle. Time and mortar can be reduced by using masonry units of the same shape and size.

OVERVIEW OF MASONRY CONSTRUCTION

If the decision to establish a permanent presence on Mars is made and the construction of a large, permanent habitat begins, then the construction methods must be carefully considered. Relying on habitats brought entirely form Earth is an unsustainable strategy. A more realistic approach would be to maximize the use of Martian materials and to implement simple, well understood, and tested building techniques.

Masonry has been proposed as one possible construction method that might be employed by early settlers on Mars, because it is the only readily available resource on the Martian surface, it is simple to produce, and is extremely durable. The most abundant material on the surface of Mars is regolith and rocks. In fact the whole planet, except for the polar caps, is covered with nothing but regolith and rocks. Bruce Mackenzie, has proposed that it the first settlers can manufacture bricks using the regolith [Mackenzie 1987]. Using pitched-brick vaults and self-supporting domes one can construct a wide range of spaces using no centering, thus greatly simplifying construction [Richards 1985], [Robinson 1993], [Petrov 2004].

Masonry's low tensile strength however poses a challenge that must be overcome. In order to balance the interior pressure, the only option is to cover the masonry structures with as much as 10 m of regolith. However, turning the settlers into cave dwellers is highly undesirable. Therefore, in order to give the settlers the ability to view outside the habitat and to facilitate access to the surface, it is necessary to use masonry in combination with another system that can resist the pressure through tension [Kennedy 2002].

The history of masonry arches and vaults can be traced back to about 3000 b.c. in Lower Egypt and Mesopotamia. One of the oldest brick vaults covers the storehouses at the Ramesseum, the tomb complex of Ramses II who reigned to about 1224 b.c. There are three distinct methods for constructing vaults that were developed in antiquity. The most common is the radial vault, where the space between the side walls is filled with loose bricks that serve as temporary support for the vault. Then, bricks are laid in successive courses, with mud and small stones placed at the outer edges to cant the bricks in until the vault closes at the crown. After the mud dries the centering is removed. The most rare method involves leaning two long, slightly curved bricks against one another over the center of the space. Though they are the simplest to construct, ribbed vaults are the least strong [van Beek 1987].

Pitched-brick vaults, also known as leaning arches, is the most useful technique for work on Mars, because it requires no centering. The first bricks on each side are laid at an angle against a side wall; the second set of bricks is placed on top of the first, also leaning against the wall and so on until the arc of the vault closes at the top. Successive arcs are leaned on the first one until the end of the vault is reached. The remaining triangular space is filled in with smaller arcs. Often, more courses are laid on top of the first one leaning in opposite directions [van Beek 1987].

Domes might be even more advantageous because they only need support at four points, unlike vaults that require continuous support along two walls. Domes can also be constructed without centering using a similar idea to the pitched-brick vaults. First four piers are erected and connected with four arches. The first set of arches will require some centering, however subsequent domes can be built by leaning the arches on the previous domes. Next the spaces between the arches are filled in concentric courses. The construction can be stopped after the completion of any course and the structure will remain stable. Brunelleschi most famously and spectacularly applied this principle at the dome of the Duomo in Florence.

MASONRY CONSTRUCTION SIMULATION

In order to gain some practical experience in the feasibility and challenges of constructing masonry structures, Crew 22 undertook a project to build a masonry dome during our rotation at the Mars Desert Research Station (MDRS).

We decided to construct a pitched-brick vault which obviated the used of centering. Due to the MDRS command's concern for safety and in order to minimize the impact on the land the project was restricted to a vault with a one meter radius, erected directly on the ground.

Three main considerations determined the choice of a site for the project. The primary requirement was to be at the base of a steeply inclined slope, which we could use as a support for the first row of pitched masonry. Second, we wanted to be close to the Hab in order to facilitate the work and to be able to take pictures of the project with the rest of the 'base'. The final objective was to locate the vault in such a way that if the project failed it would not be visible from most vantage points in the area. We found a site to match all of the objectives about 50 meters north of the Hab on the opposite side of a small protrusion of the ridge next to MDRS (Figure 1).

An investigation of the subsurface conditions determined that most of the vicinity of MDRS is covered by a crumbly layer of weathered stone. Relatively hard shale is located 20 – 30 cm below the top crust. This bedrock can still be fractured easily with the mason's hammer to a depth of another half of meter. Balancing the need for stability of the vault and the need for expediency in our tight schedule it was decided to remove the top crust and any loose rock that was knocked out in the process and to lay the foundations on the exposed bedrock (Figure 2).

Material for the masonry units was collected from an outcrop about one kilometer away from the Hab. The location was chosen near an existing road in order to minimize off road travel. The raw material was loaded manually on the ATVs and transported to the pressurized rover (a crew member's SUV), which remained on the main road. The pressurized rover then brought the material to the construction site. Five crew members brought two rover-full shipments of rock to the site in two hours (Figure 3). The other local ingredient was sand, which was sifted from the surface of the main road by one crewmember. Cement and lime were the only materials that were imported from outside the local area. The mixture that was used for mortar comprised of two parts cement, one part hydrated lime and six parts sand. This mixture constitutes Type II mortar and is recommended for southern Utah.

The crew planned the work schedule in two EVA slots. In the morning when temperatures were still below freezing the EVAs concentrated on projects by other crewmembers. On most days the temperature rose past the freezing point in late morning and the afternoon EVAs were dedicated to the masonry project. A summary of the man-hours for each phase of the project is covered in Figure 4. The surveying and excavation tasks were accomplished by one crew member and did not require many man-hours. Gathering of rocks involved the coordinated efforts of the whole crew and was less efficient in terms of man-hours even though in absolute time it was accomplished expediently. Sand, on the other hand, was gathered and sifted by one crewmember, often on the way to an unrelated EVA. We experienced a steep learning curve, once we began the actual construction. The first day five crewmembers went to the construction site, leaving one in the Hab. In one and a half hours we managed to lay only four stones for one side of the foundations. Most of the time there were people standing around without a task. When we began the construction of the first arch we used a team of four. Finally, we determined that the best labor division for the construction of a vault of similar size is a team of three, with one crewmember mixing the mortar and two crewmembers laying the masonry (Figure 5). This configuration allowed us to mix many small batches of mortar that can be used up before it hardens past workability.

One caveat that bears mentioning is that manual mixing of mortar is a dusty process. Possibly even more so on the Martian surface due to decreased atmospheric pressure and increased wind velocity. On a particularly windy day one crewmember was inadvertently exposed to airbourne lime during the construction process. It is recommended that this experiment not be recreated or extended in windy or closely enclosed locations due to the potential dangers of chemical inhalation.

A schedule of all of the materials used for the project is listed in Table 1. Clearly the level of efficiency needs to be greatly improved. The first step that we recommend is to use regular building blocks instead of rough stone. A large portion of the time was spent sorting through the pile of rocks and chiseling them into usable shapes. Additionally a lot of mortar was wasted to fill gaps between rocks that did not fit together well. We estimate that the amount of mortar can be reduced by half or more. Additionally much of the water can be recovered if the operation is conducted inside a closed construction tent where the atmosphere can be controlled and moisture can be condensed.

The foundation and the first two arches of the vault were completed in 64.5 man-hours. On the last day of Crew 22's rotation we completed a third arch working for six man-hours out of Sim. This gave us an opportunity to compare the experience. The main negative effects of the simulation space suits were a decrease in visibility and in communications. Working vigorously in the suits made the visors steam up much more than during science observations. This problem was exacerbated in the afternoon when the sun was low behind the hill next to which we were working and most activities required facing it. Additionally communication was accomplished mainly though gesturing or not at all. Both problems reduced ones awareness of the activities of other crewmembers, thus greatly reducing teamwork. Both of these adverse effects can be eliminated if work is done inside a pressurized construction tent. The weight of the life-support backpacks had a secondary effect on work efficiency, though its role will probably increase if longer work shifts are employed.

It is useful to estimate how many man-hours would be required to complete a vault of useful dimensions. A vault with a radius of 3.5 meters and a length of 4.5 meters can cover a space of roughly 16 m^2. By extrapolating from the efficiency which we achieved at the end of the project of 5.5 man-hours per arch we estimate that such a vault can be completed using 353 man-hours including surveying, excavation, collection of materials and placing of 30 arches necessary to cover 4.5m, see Table 2. Many of the required tasks can be automated, in order to improve efficiency. The robots and machinery will still need supervision and maintenance, however this can be accomplished by fewer crewmembers. We estimate that by excavating and collecting materials using teleoperated robots the same vault can be built using 240 man-hours.

This experiment provides the first attempt to construct masonry structures in a simulated space environment. It is obvious that before making plans to equip the Martian settlers with trowels and shovels there are a great number of problems that will need to be solved. One of the most important challenges is to find an appropriate mortar. Mortar is used to even out stress concentrations by filling in the irregularities between bricks, as well as to hold the individual bricks in place during construction. Originally, mortar will be made by mixing dust and water. If more strength is needed, some additives might be acquired from plant products or will have to be imported from Earth. Eventually, the mortar may be entirely from plant derived polymer extracts. Shaping the brick so successive courses interlock can obviate the second function of mortar. Additionally a temporary inflatable tent will have to be developed, so that work can be performed in a controlled environment without the need for bulky and cumbersome spacesuits. Once the enclosures are completed they can be glazed to make them airtight. Any remaining cracks can be patched up with plant products. A series of plastic sheets can be laid inside the cover material to trap and recover air that might still escape. If further leaks occur, the moisture in the air will quickly freeze thus sealing the crack [Mackenzie 1987], [Petrov 2004].

Future projects in this area can include repeating our experiment using regular masonry units, developing automation processes for as many tasks as possible, and designing and testing a reusable pressurized construction tent, which will allow work in shirt sleeve environment and control of the temperature and pressure during construction.

All of these challenges are awaiting solutions and will provide ample ground for further study by enthusiasts interested in helping to develop the knowledge necessary for humans to survive on Mars.

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TABLES

Table 1

Materials schedule			
Water	36 gal	= 137 Liters	(local)
Sand	540 lb	= 246 kg	(local)
Portland Cement	180 lb	= 82 kg	(imported)
Hydrated Lime	70 lb	= 32 kg	(imported)

Table 2

Projected Man-hours for Full Vault	
Survey	3.0
Excavate by hand	10.0
Collect materials	160.0
Build 30 arches	180.0
TOTAL	**353.0**

FIGURES

Figure 1
Site for the masonry vault project near MDRS.

Figure 2
Excavation of the top crumbly layer exposes relatively solid rock on which the vault was constructed.

Figure 3
Two rover loads of rocks were collected in two hours by five crewmembers

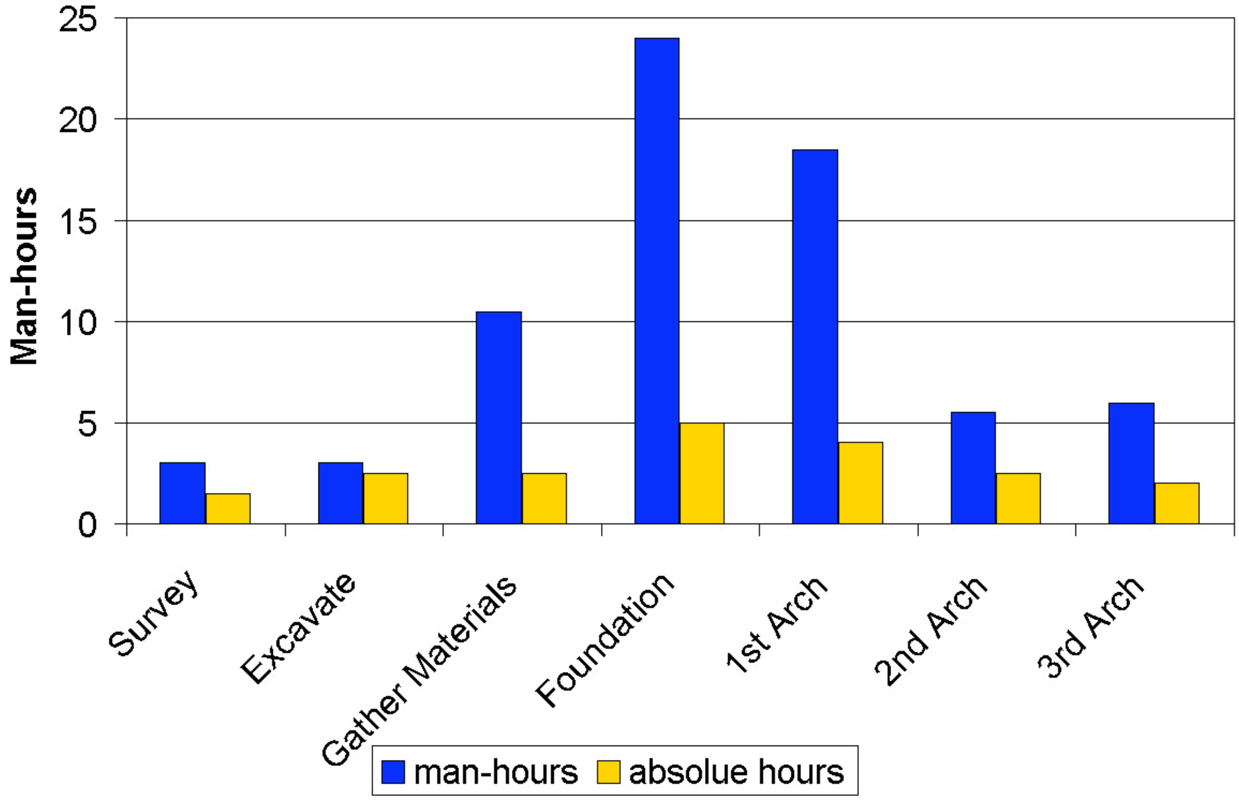

Figure 4
Summary of the man-hours for each phase of the project

Figure 5
Optimum labor division for the construction of a vault of similar size is a team of three, with one crewmember mixing the mortar and two crewmembers laying the masonry

Figure 6
The tools necessary for masonry constructions are simple – mason's hammer, spades, trowels, mixing bucket, and a rope to guide the geometry of the vault.

Figure 7
The first three arches of a vault completed at the end of Crew 22's rotation.

Figure 8
Mars Base with a deployed habitation module, greenhouse, observatory and the first step in the construction of a permanent habitat using local resources.