CONSTRUCTION TECHNIQUE AND STRENGTH OF CONNECTED REGOLITH BAG STRUCTURES

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

Mandeep Singh

Certificate of Approval:

P.K. Raju Thomas Walter Professor Mechanical Engineering	David G Beale, Chair Professor Mechanical Engineering
Royall M. Broughton Professor Polymer and Fiber Engineering	Joe F. Pittman Interim Dean Graduate School

CONSTRUCTION TECHNIQUE AND STRENGTH OF CONNECTED REGOLITH BAG STRUCTURES

Mandeep Singh

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
May 10, 2007

CONSTRUCTION TECHNIQUE AND STRENGTH OF CONNECTED REGOLITH BAG STRUCTURES

Mandeep Singh

Permission is granted to Auburn University to make copies of this thesis at its discretion, upon the request of individuals or institutions and at their expense. The author reserves all publication rights.

Signature of Author

Date of Graduation

VITA

Mandeep Singh, son of Harbinder Pal Singh and Harvinder Kaur, was born on August 2, 1982 in Jamshedpur India. He graduated with a Bacherlor of Engineering degree in Mechanical Engineering in May 2004 from Madras University, India. He entered the graduate program at Auburn University in August 2004, where he worked under Dr. David Beale as a graduate research assistant in Mechanical Engineering department.

THESIS ABSTRACT

CONSTRUCTION TECHNIQUE AND STRENGTH OF CONNECTED REGOLITH BAG STRUCTURES

Mandeep Singh

Master of Science, May 10, 2007
(B.E, University of Madras, India, 2004)

125 Typed Pages

Directed by David G. Beale

Masonry Arches have been used from a long time in construction of bridges, domes and other structures. They are constructed out of voussoirs and their stability is determined by drawing a funicular polygon representing force flow through the structure. If this line remains inside the structure then its stable, otherwise it forms hinges at the locations where the line comes outside of the structure, and collapses.

The work presented in this thesis implements the use of funicular polygons in determining the stability of lunar structures prototypes made out of bags filled with regolith (lunar soil). These structures are made in the shape of a catenary arch using center connected and top connected bags. Various structures are developed at Auburn University and MSFC, to test their stability. Structures made out of top connected bags are found to be more stable, as demonstrated by construction of a simply hanging beam made out of top connected bags. During construction at Auburn University and

MSFC, both the top and center connected bags are filled with vermiculite because of its light weight and also because of lack of regolith on Earth.

These structures are constructed on frames which are removed after the structure is built completely. The structures are designed to be stable under their own load so the frames are not required once the construction is over. They are also designed such that the construction process can be carried out by taking minimum amount of material from Methods of filling the bags with regolith are also investigated and a screw conveyor system is found to be the most reliable. The stability of these structures is found by constructing funicular polygons, under given load conditions, in Solid Edge. This technique of determining the stability is found useful and reliable in construction of lunar structures that are based on masonry arches.

ACKNOWLEDGMENTS

I would like to thank Dr. Beale for his support and advice throughout my research at Auburn University. I would also like to thank Dr. Raju and Dr. Broughton for being on my graduate committee and for their contribution to my thesis. I would like to acknowledge my research mates Manoj Rajagopalan, David Branscomb, and staff of Polymer and Fiber Engineering Jeff Thompson, David Clark who helped me in various stages of my thesis. Finally, I would like to express my deepest gratitude to my parents, my sister and my friends whose love and encouragement has guided me through towards my goal.

Style manual or journal used: Guide to Preparation and Submission of Theses and Dissertations 2005

Computer software used: Microsoft® Word® 2003, Microsoft® Excel® 2003, Microsoft® Visio® 2003, Solid Edge®, MSC®. Working Model

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

Masonry arches have been used from a long time to construct bridges, building, domes etc. Over the years various shapes of masonry arches have been developed ranging from circular, elliptical to catenary etc. They are a classic example of form following function and have been used primarily because of their ability to carry vertical loads as longitudinal load to the abutments of the arch. These longitudinal loads act as vertical and horizontal reactions forces on the abutment, giving the arch its stability. This thesis presents a way of adapting this technique to the development of a lunar structure made out of multi pocket bags filled with regolith. The main objective of this is to be able to construct a lunar structure in the shape of catenary arch with minimum amount of raw materials carried from Earth.

1.1 Scope of thesis

The development of a catenary arch to be made on the moon, using techniques used in construction of masonry arches involves the development of an analysis technique that can reliably predict the stability of such a structure. In this report the technique of finding stability using funicular polygons has been primarily used. Various real structures were made manually in Auburn University and NASA-Marshall Space Flight Center (MSFC) using bags filled with vermiculite. The construction of these structures involved construction of frames to support the structure while construction, filling of bags with vermiculite (sand was not used primarily because of its high weight) and testing their stability. The construction of frames has been discussed in this report along with the various techniques used to fill the bags with vermiculite. These structures were also drawn in Solid Edge and their stability was tested using funicular polygons. The results obtained using funicular polygons can easily be compared to the stability of structures built using bags, as long as the bags behave similar to rigid voussoirs.

1.2 An overview of thesis

The thesis provides a look into the construction of structure to be built on the moon, which can be used to store equipments, machines and can also be used as a habitat. In this regard, chapter 2 presents a brief literature review of various papers published over the year discussing techniques of lunar base construction and also other important parameters involved like site selection, challenges faced, requirements etc. Chapter 3 discusses some lunar structures that have been proposed by various authors. Chapter 4 discusses the experimental setup required for construction of the lunar structure proposed in this thesis. The stitching of bags used for construction, techniques used to fill the bags, construction of frames has been discussed in detail. In Chapter 5, the analytical technique developed using funicular polygons is discussed. A small section is devoted to initial exploratory studies carried to test if Working Model could be used to determine the stability of the structure being developed.

CHAPTER TWO

BACKGROUND

The construction of lunar structures for storing goods, equipments and even for use as a human habitat has been of primary interest, from the time man landed on moon. The design of a lunar structure is based on factors like environment, gravity, materials used, safety, rigidity etc. The design of a lunar structure is important for numerous reasons. For any kind of scientific research on the surface of moon, a lunar structure will be required to store equipments. This structure will also protect the equipments from lunar environment. For human habitation the lunar structure will also need to provide adequate protection from harmful radiations. Designing of such structures involves structural analysis and design. This section reviews only arch structures as determined by using funicular polygon. Detailed description of the funicular polygon technique is discussed in this chapter. The first part of this chapter will deal with the scientific importance of moon. Then a brief overview of various environmental factors and construction techniques of a lunar structure will be discussed.

2.1 Scientific Importance of Moon

The Moon is a suitable platform to carry out observations about the universe, explore even further into space and help us in understanding it even better. The Moon can also act as a source of natural energy and minerals. Setting up of a lunar base has been discussed ever since the first Apollo mission to the moon. After decades of space exploration, setting up of a lunar base is the obvious next step to help us in exploring it even further. Research in site selection and construction of a lunar base is required. The international space stations like Mir are an important step in this direction. Setting up of a lunar base will involve use of regolith and other materials found on moon, therefore reducing the need to carry heavy payloads from Earth. This can be a significant advantage over developing of space station, for which the raw material required needs to be carried from earth.

Development of a lunar base will also give us experience and help us in building base on Mars [2]. With recent discoveries that life forms might have existed on Mars, our interest in sending manned missions to Mars has increased, even though there are lots of challenges associated with it. For one, Mars is around 100 times farther from Earth, than the moon even in its nearest approach [2]. With current technology available, manned missions to Mars will take years to complete. Hence setting up a lunar base would help us in understanding various effects of extended stay in space on human bodies and help us in preparing more efficient and reliable manned missions to Mars. As mentioned before setting up of a lunar base will also help us in exploring space further. There are various questions that need to be answered and it is believed that this can be done only by setting up a base on moon [1]. Some of the important issues that need to be answered are [1]:

- Relationship of earth and moon.
- Origin of moon.
- Presence of water on moon.

- Mineral composition in regolith and the potential of moon being used as a resource hub

2.2 Development Phases

Development of a lunar base has been categorized into three important steps [2]-

- Pioneering phase
- Consolidation phase
- Settlement phase

Pioneering phase

During this phase, the basic aim will be to travel to moon with simple equipments like telescopes, dune buggies, cameras etc. Site selection and understanding of how various factors will affect the lunar base will be the important steps associated in this phase. The dune buggies can be used to explore areas in close proximity while the telescopes and cameras can be used to set up a small observatory.

Consolidation Phase

This phase will involve bringing of life support system, power system, lunar transport system to the moon. These equipments will help in construction of bigger and better observatories.

Settlement Phase

This phase will be characterized by growth in population on the lunar base, efficient observatories running on power obtained from natural resources available on moon.

2.3 Challenges in Designing a Lunar Base

The design of a lunar base does not end with understanding of the phases involved. The conditions found on moon are very different from those found on earth and hence challenges faced by various environmental factors need to be taken into account and addressed before designing of the base. Some of the factors are [7]:

- Temperature
- Atmosphere
- Radiation
- Meteorite Impacts

Temperature

Temperatures on moon can vary drastically between the night and day cycle in moon. During day the temperatures can soar to 380K [7] and during the night they can drop down to 100K [7]. This variation in temperature can cause adverse affect on humans and even on material properties. It was observed that 50 to 100 cm of regolith placed on top of the regolith can reduce the temperature variations observed inside the base. This can be attributed to its low thermal conductivity. Surface of the moon also undergoes large temperature variations during the night and day cycle. Because of this metal structures constructed on the surface can undergo severe thermal stressed because of expansion and contraction. This can considerably reduce the life cycle of a structure.

Atmosphere

The moon’s s atmosphere is considerably different from earth. Moon has very few gases present in atmosphere and quantity of oxygen present is too low to sustain life without other aids. The thin atmosphere also makes moon more susceptible to harmful solar winds, meteorites etc. The thin atmosphere can also prove beneficial as it can allow for experiments to be carried out in vacuum if required.

Radiation

Due to the lack of atmosphere on Moon, harmful radiations coming from sun and other parts of the solar system do not get absorbed and reach the moon’s surface. These radiations are harmful for human body and can cause considerable damage. Solar Winds and Solar Flare are some major sources of radiation on moon. Even in protective clothing, astronauts face a risk from these radiations. Accurate and efficient techniques to predict these events need to be developed. Lunar bases should also be protected from these harmful radiations. It has been found that 400 gm/cm^2 of regolith will be needed to prevent over exposure of humans to these ultra violet radiations [10]. Other materials like lead, water, copper, hydrogen have also been found to act as barriers to radiations. [10].

Meteorite Impacts

Meteorite impacts on Moon are more frequent and a bigger problem than on Earth. This is due to the lack of atmosphere on Moon. As a result, meterorite impacts can cause craters in metal structures. Even micrometeorites can cause considerable damage to the structure over a period of time Meteorites weighing more then 1 gram can cause considerable damage to a structure.

2.4 Requirements of a Lunar Base

After discussing the challenges it can be seen that any lunar base designed should be able to meet some design requirements in order to support life system inside. Some of the issues that a lunar base should be able to address are as follows-

- Gravity
- Vacuum
- Shielding
- Internal Air Pressurization

Gravity

Gravity experienced on moon is around a 1/6 of that experienced on Earth. Therefore during designing of the lunar structure, mass should be taken as important design variable rather then weight [5].

Vacuum

The lack of atmosphere creates construction and maintenance issues that need to be taken care of. Many materials can be unstable in such an environment. The use of hydraulics will be limited because of leakge of oil, vapors etc [5]. Vacuum implies that the only source of heat transport would be radiation [7]. This would affect the design of thermal systems. Vacuum will also increase the friction between moving parts because of the lack of an air layer between them. [5].

Shielding

A lunar base should be able to shield itself against radiations, meteorites etc. as discussed before, regolith can be used as an effective shielding device. This layer of regolith should be able to provide adequate protection from radiation exposure. The amount of radiation exposure should not exceed 5 rem (radiation equivalent man). The extra weight of regolith can be used to balance off the forces due to internal air pressurization.

Internal Air Pressurization

To support life system, oxygen supply and pressure must be maintained inside the structure for human habitation. A human body needs air pressure to balance the internal blood pressure. Internal air pressure of 15 psi is considered safe for life support [5]. The structure should also be designed to be fail safe against leakages.

2.5 Oxygen Production

Since oxygen is the most important requirement for life support considerable research has been done to determine methods of producing oxygen on moon. Regolith is a good source of oxygen as it contains almost 50% of oxygen by weight [13]. Ilmenite ($FeTiO_3$) is present in lunar soil and this can be used to extract oxygen using the following chemical process [14]-

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$
$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

$$FeTiO_3 + C \rightarrow Fe + TiO_2 + CO$$
$$CO \rightarrow C + \frac{1}{2}O_2$$

Equation 1

Various techniques for carrying out this process, known as Ilmenite Reduction [12] have been researched on. Mishra et al. discuss a technique of producing oxygen from regolith using molten salt technology [11]. Design concept of a lunar rover able to carry out the chemical process on Moon's surface has also been developed [12].

2.6 Site Selection

Site selection is an important step towards the construction of a lunar base. The site should be selected on the basis of following factors [1][13]

- Science
- Resources

- Operational Considerations.
- Lighting
- Landscape
- Terrain

Science

A lunar base will be used to carry out various scientific experiments. The soil around the base must be able to support the weight of the telescopes. Settling can occur under the support of a telescope and this can lead to malfunctioning [5]. Moon has two different types of terrain [1]- mare and highland. Both represent two different periods of lunar history and hence are equally important in understanding the moon’s evolution.

Resources

As mentioned before, a lunar base will depend on regolith for shielding purposes and for production of oxygen. The site chosen must have enough amount of Ilmenite for oxygen production. The site must also be able to provide adequate sunlight during day time. A site selected close to the poles of the moon will be hidden from sun for long durations and hence will not prove to be an ideal site location.

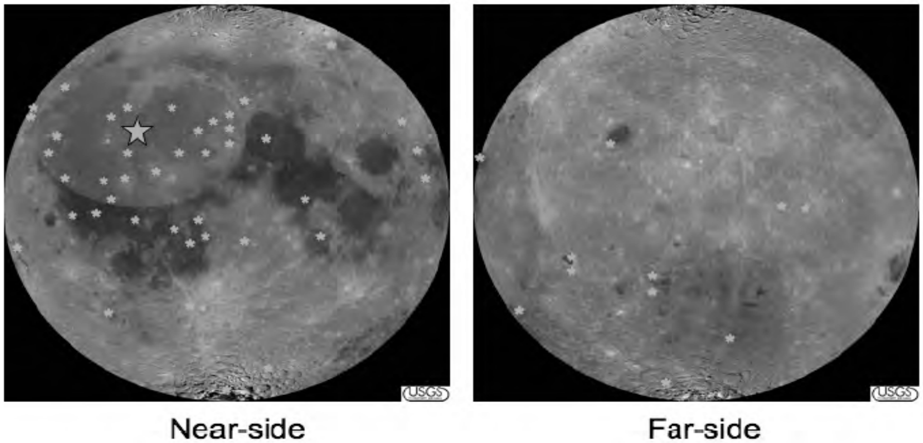
Operational Considerations

The development of a lunar base will also be followed by development of emergency systems that can act immediately during a human crisis. A command module has been proposed [1]. This module will orbit around the moon and will help in evacuating humans back to earth during emergency. The site selected should be easily approachable by this module for quick evacuation. Landing site safety and mobility around the site will also effect site selection.

Lightning, Landscape, Terrain

As discussed before, adequate lighting is required for human survival and for carrying out various experiments. The terrain around the site should not act as a barrier for sunlight but at the same time a site selected around a mountain or crater can help in shielding the site from meteorites. The landscape again should be smooth for ease of construction purposes.

As can be seen, site selection poses quite a unique challenge because of the contradictory nature of some site selection requirements. A site meeting all these requirements will be difficult to find. Various sites have been proposed and each has different scientific importance. Figure 1 below shows some sites selected as suitable based on the requirements [13].



Near-side
Far-side

Figure 1 Proposed Lunar Sites on Moon

2.7 Construction Materials

Various indigenous materials have been proposed for the construction of lunar base [8]. Use of indigenous materials reduces the need to carry heavy pay load from earth to the moon. This also reduces the cost of construction. Some of the materials proposed are as follows.

- Regolith
- Cast basalt and glass
- Ceramics
- Cement
- Metals

2.7.1 Regolith

Regolith is found in abundant quantities on moon and hence can be used easily without having to process it. Lunar Base can also be made by digging in the regolith and creating bunkers to stay in. they can also be used to make structures out of bags filled with regolith. The bags will need to be brought from earth along with a feeding system. These bags can also act as good shielding materials because as discussed before, regolith can help in keeping out harmful radiations very effectively.

2.7.2 Cast Basalt and Glass

These can be produced easily on moon’s surface using cooling molten basalt process [8]. They can be used as structural materials for construction of buildings and pavements.

2.7.3 Ceramics

Ceramics can again be easily produced on moon using lunar soil. Ceramics can be used to make structural materials like bricks, blocks. They also have good thermal insulation and are resistant high temperatures making them ideal to be used on moon.

2.7.4 Cement

Cement can be produced from lunar soil and glass by means of sintering and crushing processes. Water required can also be obtained by reducing lunar oxides with hydrogen [8]. Cement can be used as for making heat insulators, shields, roads, foundations

2.7.5 Metals

Metals can be extracted from lunar soil using various chemical processes. The equipments required for this kind of operation will need to be carried from earth. Metals can be used for construction of railroads, structural support members, bridges.

2.8 Design of Masonry Arches

Masonry arches have been used for about 5000 years [15] and are one of the oldest structural elements in use. The fundamentals of masonry arch are used to design the lunar base and hence a description of masonry arches plays an important role in this thesis.

A masonry arch is a structure of masonry covering an opening and carrying load as longitudinal thrust. Voussoir arch is a type of masonry arch where the arch is composed of independent blocks of masonry [16]. Such an arch is robust because of the fact that it utilizes the strong compressive property of its masonry in transmitting stresses through its geometry [15]

An arch is composed of following parts as shown in Figure 2 below.

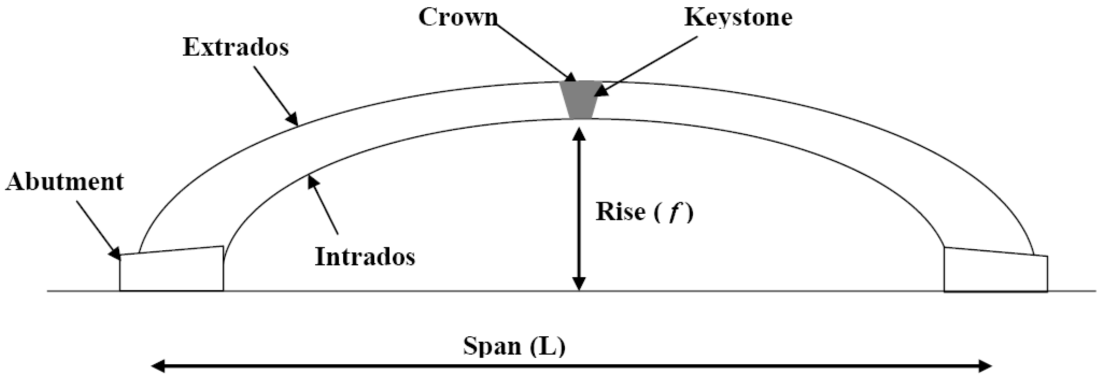


Figure 2 Parts of Masonry Arch.

Intrados

It is the intersection of the soffit with a vertical plane perpendicular to the axis of the arch. Soffit is defined as a material which covers the underside of a building or structure such as an arch, beam, balcony etc.

Extrados

It is the intersection of the outer surface with a vertical plane perpendicular to the axis of the arch.

Crown

It is the highest point on the arch.

Rise

It is defined as the perpendicular distance from the highest point of the intrados to the ground.

Keystone

It is the voussoir at the crown of the arch. It is used to give the arch stability.

2.9 Stability of Arch

It has been found that masonry arches fail due to instability rather than a lack of material strength [17]. This is because of the fact that stresses in masonry arches are much lesser than the crushing capacity of stone. Therefore to determine the stability of a masonry arch, equilibrium approach using geometrical rules can be utilized. Few basic assumptions are used while using this technique [17]-

1. Stone has no tensile strength: This assumption is based on the fact that the stones might have tensile strength but the joints will not and tensile force cannot be transmitted from one portion of the structure to other.
2. The compressive strength of stone is effectively infinite.
3. Sliding failure between bricks cannot occur

The graphical method utilizes the concept of line of thrust or funicular polygon. This is the path which represents the resultants of compressive forces through the stone structure. This line is a resultant of two forces [16]:

- weight of the arch
- Horizontal thrust

Horizontal thrust depends on the weight of the voussoirs and the flatness of the arch. The more flat the arch is, higher the horizontal thrust is [17]. The weight of voussoirs acting on each other creates a line of thrust. For an arch to be stable, this line of thrust should lie within the thickness of the arch [17]. If the line of thrust lies outside the arch, then the joint will tend to open up on the opposite side and area of contact between voussoirs will be reduced. This technique of determining the stability of an arch based on the line of thrust is essentially a geometric technique. Figure 3 shows the line of thrust (LT) acting inside an arch as a result of the horizontal thrust (HT) and weight (W).

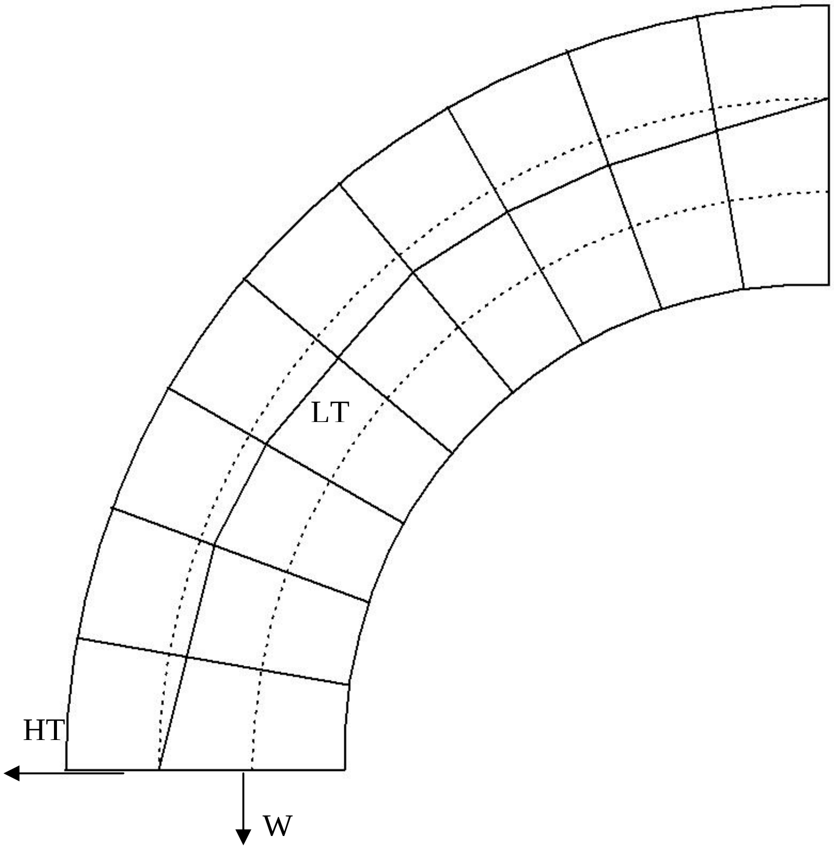


Figure 3 Line of thrust lying inside the arch

The failure of an arch is caused due to the formation of hinges. Whenever the line of thrust goes outside the arch, a hinge is formed [17]. The number of hinges required for collapse can be calculated. If a structure has three hinges then it becomes a statically determinate structure. If there are four hinges, the structure acts as a mechanism and the arch fails [17].

If the structure is stable under given external loads, various positions of the thrust lines are possible. If a thrust line is found to be lying inside an arch for a given set of external loads, then it can be assumed safely that the structure is safe. This line of thrust need not be the actual line of thrust. For the same structure, with same external loads, a line of thrust can be found to be lying outside the arch, but this cannot make the structure unstable.

It was also found out that an arch will turn itself into a statically determinate structure if there are any imperfections present in the structure [17]. This can be seen in the figure below.

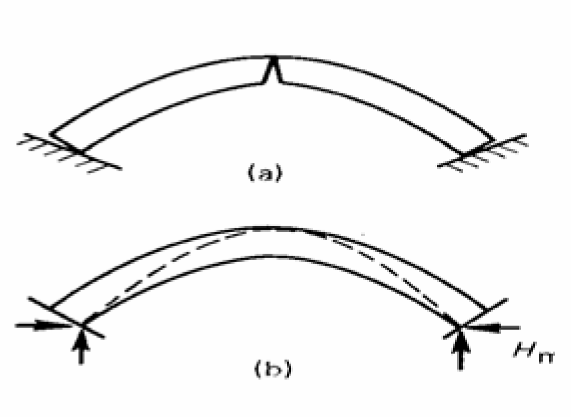


Figure 4 a. Formation of hinges b. Line of thrust acting through the arch

As can be seen in Figure 4a the shape of the arch is fixed by the shape of the voussoirs, and if the shape implied by the geometry of abutments is different then the arch will accommodate itself to those abutments and will form hinges in doing so. In the figure above, the arch forms a statically determinate structure because of presence of three hinges.

2.10 Design of Voussoir Arches

As discussed in previous section if a line of thrust can be found that stays inside the arch, then it can be assumed to be stable for that set of load. This line of thrust can be found using graphical methods. Following are some of the parameters needed for this graphical method

2.10.1 Shape of the Arch

Masonry arches are designed in the shape of a catenary. A catenary is defined as the shape formed by a chain suspended between two fixed ends and hanging under the force of gravity. It is shaped in the form of a parabola. Figure 5 shows a simple catenary.

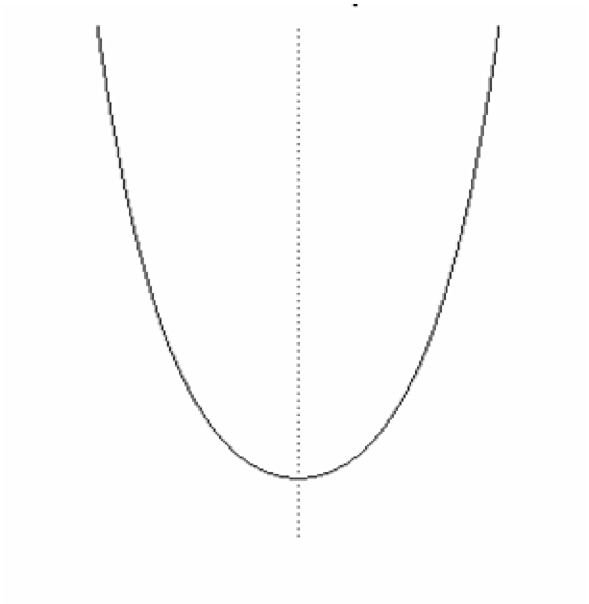


Figure 5 Catenary

Catenary is better defined using the following equation [18] -

$$x(t) = t$$

$$y(t) = a\cosh(\frac{t}{a})$$

Equation 2

a determines the shape of the catenary. As *a* changes, the catenary opens up or closes. The arch length of the catenary also is important and is defined using the following equation [18]:

$$s(t) = a\sinh(\frac{t}{a})$$

Equation 3

s is the arch length of the catenary and it is important in finding the surface area while designing the arch.

2.10.2 Thickness of Masonry Arch

The line of thrust should always lie inside the thickness of the arch (h) and hence it plays an important part in designing of the arch. Various equations have been suggested to calculate the thickness of the arch based on span (S) and/or the rise (f) [15]-

$$h = \sqrt{36650S}$$
$$h = 220\sqrt{f}$$
$$h = 82 + 182\sqrt{\frac{s}{2} + f}$$
$$h = \sqrt{40000S}$$

Equation 4

Spalding [16] and Taha [15] talk about these equations in detail. The effectiveness of each equation depends on the safety factor required for a particular arch. Any of the equations can be used to design an arch and then the line of thrust can be developed for that configuration. The most suitable design will be one in which the line of thrust lies well within factor of safety.

2.10.3 Horizontal Thrust

It has been discussed before that a masonry arch tends to settle down according to the geometry of the abutments and forms a three pinned arch. This three pinned arch is a statically determinate structure. For the construction of funicular polygon, the following parameters are involved

a. The amount of horizontal thrust
b. External forces acting on the structure
c. Weight of the voussoirs
d. Span of the arch
e. Height of the arch

Parameters like external force, weight, span and height of the arch are known. The value of horizontal thrust needs to be determined. In case of the three pinned arch, half of the arch can be taken with forces acting on it as shown in the figure below.

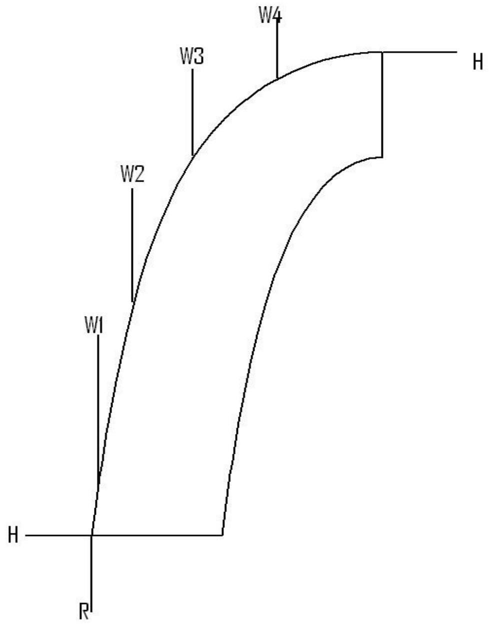


Figure 6 Catenary arch with loads acting on it

H= Horizontal thrust acting on the arch that needs to be calculated

R= Reaction force acting due to the weight of the voussoirs and external force acting on the arch

W1, W2, W3, W4= External Forces acting on the arch

Using momentum about point O, the reaction forces and horizontal thrust can be calculated. In this report Solid Edge has been used extensively to design the arches and construct a funicular polygon. This is done by using the horizontal thrust values obtained after analyzing the structure and the load acting on the structure. Other important factors that need to be known are the span of the arch, the height of the arch and the point of application of the loads.

To demonstrate the method of constructing a funicular polygon using Solid Edge an example is used which is shown in Figure 7. The vertical lines represent the point of application of the load acting on the arch. Since the arch is symmetric about its center, it is enough if funicular polygon is constructed for just one side of the arch. It can be mirrored using Solid Edge to fit the other half of the curve.

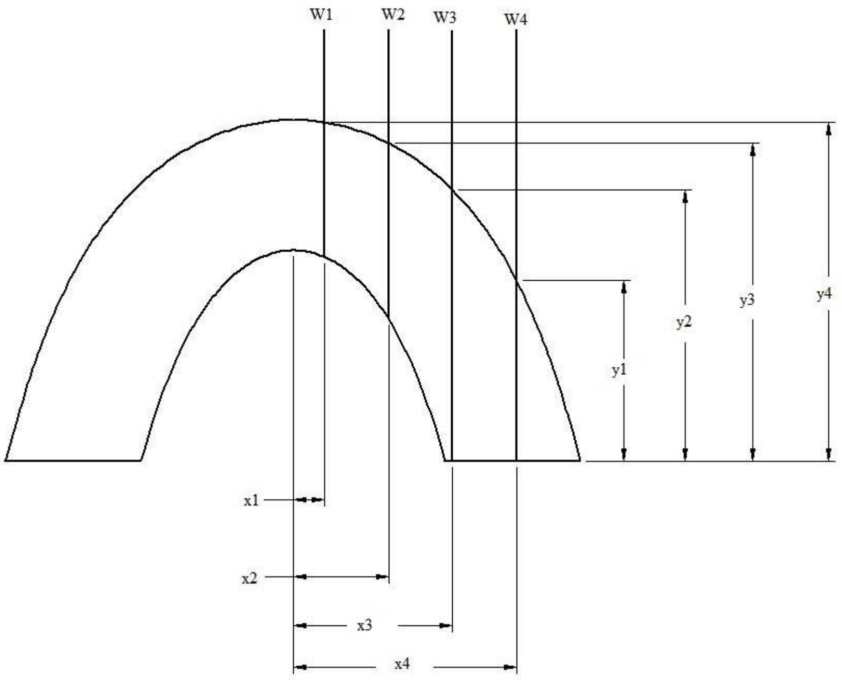


Figure 7 Catenary arch with dimension (in)

W1, W2, W3 and W4 are the loads acting on the structure and (x1, y1), (x2, y2) etc are the co-ordinates of the point of application of loads. The horizontal thrust is found to be *h.* Now before constructing the funicular polygon, a force diagram is constructed as shown in Figure 8. *h* is the horizontal line and the loads W1, W2 etc are drawn perpendicular to *h*. Then a line is drawn starting from *h* to each of the loads as shown in Figure 8.

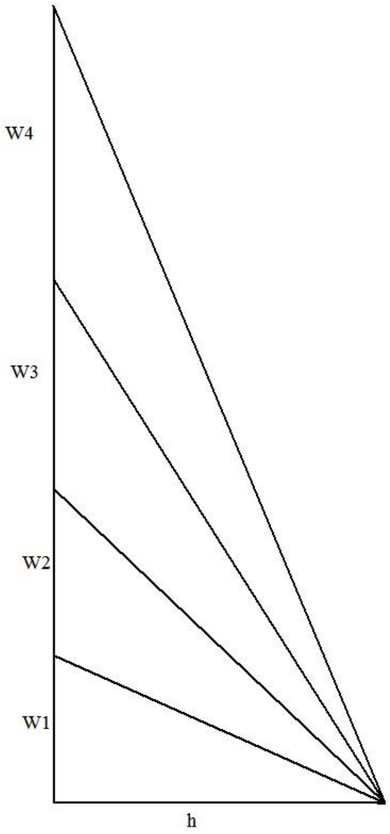


Figure 8 Force Diagram for the catenary

Using the force diagram, the funicular polygon can be constructed in the catenary arch shown in Figure 7. To start of, a line parallel to the line connecting W4 to *h* is drawn in the catenary starting from within the base of the arch on the right side. This line is drawn till it intersects the line drawn through the first line of force which is W4 in this case. This is shown in Figure 7

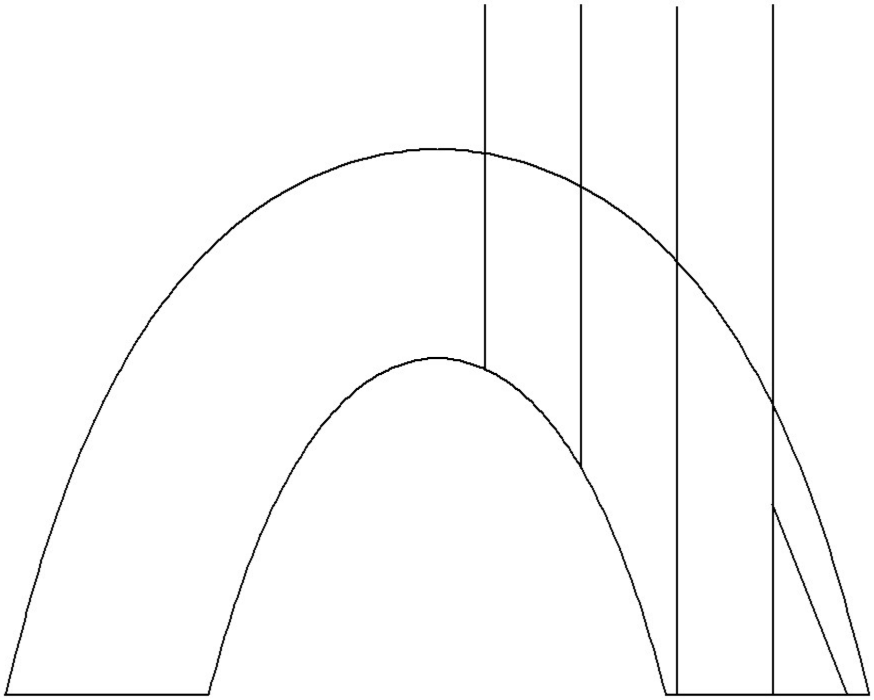


Figure 9 First line drawn parallel to the line connecting *h* and W4

It can be seen that the first line is drawn from somewhere in between the thickness of the arch. As has been discussed before, that if any funicular line is found to be inside the thickness of the arch, then the arch can be said to be stable. Hence it is enough if we can draw a funicular line that lies within the arch in Solid Edge to show that an arch is stable. If no such line is found, then the arch is unstable. Using trial and error process, it can be seen if any funicular line will lie within the thickness of the arch. In this example, the first line is drawn from somewhere in between. For the next step, another line, parallel to line joining *h* and W3, is drawn from the point where the first line intersects the line of force W4. This line extends till it intersects the line of force running through W3. This is shown in Figure 10.

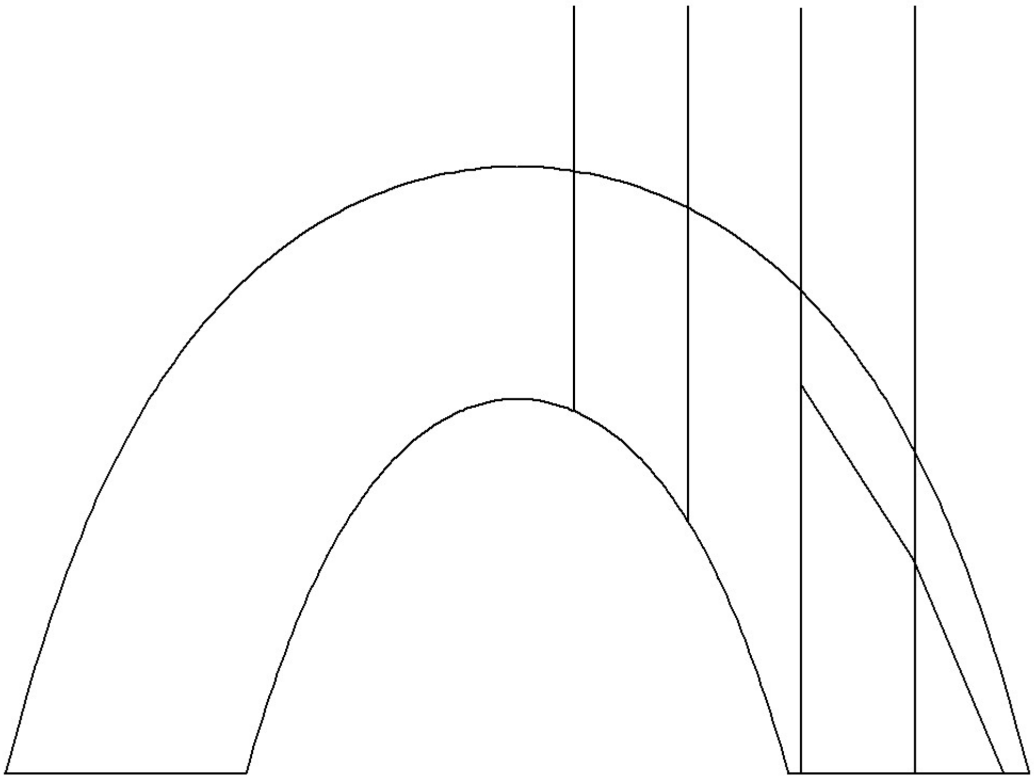


Figure 10 Second line drawn from the first intersection point to W3

Proceeding in a similar fashion, parallel lines can be drawn to lines connecting W1 and W2 to *h.* In this manner a funicular polygon is obtained which lies inside the arch in this case. Figure 11 shows the completed funicular polygon constructed for this example, which shows that this configuration is stable.

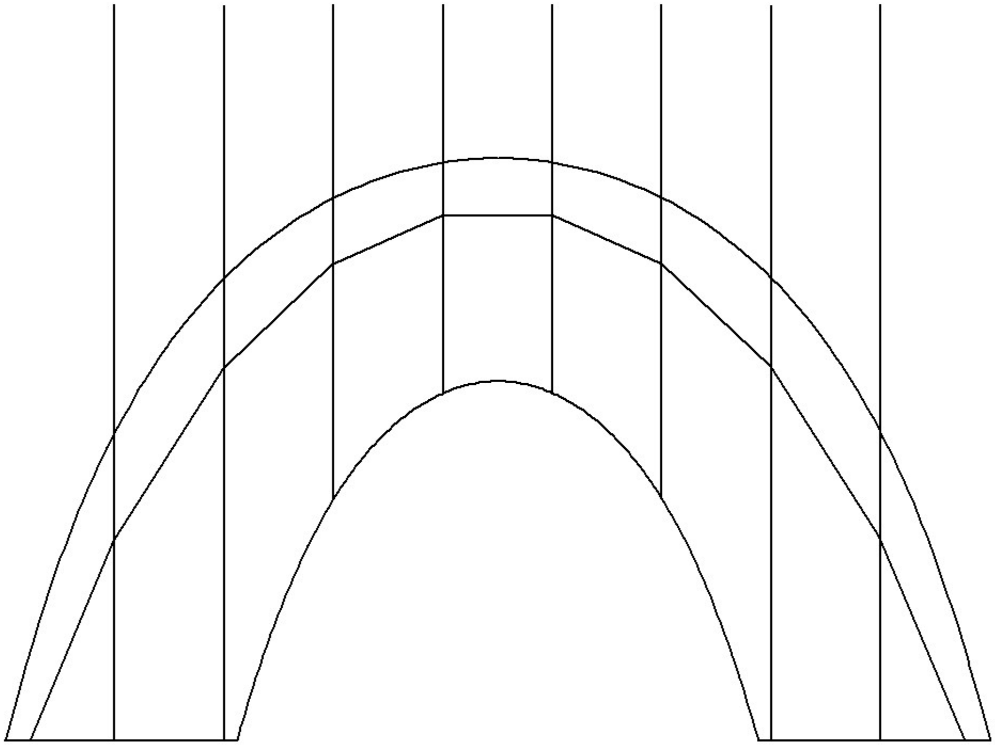


Figure 11 The completed funicular polygon lying inside the arch

This way a funicular polygon can be constructed for any catenary shape structure if the loads acting on it and its dimensions are provided.

2.11 Research Objective

The design of a lunar base involves various steps. In this case the lunar base is being designed in the shape of a catenary arch consisting of regolith bags acting as voussoirs. Just like in masonry arch, the funicular polygon principle is used to determine the stability of the lunar base. This thesis attempts to see how well this principle translates to a structure made of regolith bags. A structure made of regolith bag is different from one made using masonry because regolith has lower compressive strength than compared to masonry, and this must be taken into account while designing the structure. Also the bags tend to slip on each other while in masonry arch, slippage is almost negligible. Another difference is that the bags are connected to each other, either as top connected or center connected, while in masonry arch, the voussoirs are not connected to each other with a fabric link.

Another objective of this thesis is to test various shapes of structures made out of different types of bag to determine the best possible structure. To help in this objective, spread sheets and simulation package like MSC. Working Model is explored to determine the stability.

Various techniques for filling of bags with regolith are also discussed. Each process has its own advantages and disadvantages and the best technique is also proposed. A brief overview of the material used for the bags and the stitching technique is also discussed.

In this chapter the research that has been done previously on development of structures on the moon has been discussed. The various phases of development of a lunar structure have been discussed along with the challenges involved in development of a lunar base. Site selection is an important step in developing a lunar base and the process involved in selecting a good site has also been discussed. The later part of the chapter discusses masonry arches and their stability. This is useful in understanding how the masonry arch technique can be used to design a lunar base which is one of the research objective of this study.

CHAPTER THREE

LUNAR STRUCTURES

Numerous lunar structures have been proposed and in this chapter we’ll look at a few of them. In the previous chapter we have discussed some of the essential requirements and constraints faced by a lunar structure. Various structural concepts have been proposed to satisfy these requirements [19], some of which are concrete structures, metal structures, pneumatic structures, hybrid structures. Various research tools and decision making science have been proposed to determine the efficiency of a structural concept [19]. Some of the tools used for this purpose are Operation Research and Decision Science [20]. A numeric scoring system to evaluate a structure has also been proposed [21]. This scoring system evaluates eight structural concepts, which are [21]-

- Inflatable
- Framed/Rigidized Foam
- Polygonal Framed
- Hexagonal Framed
- Square Module
- Spherical Hybrid
- Semi cylindrical Hybrid
- Rigid Tower

These techniques can be used to determine the viability of a concept which is an important step leading up to the construction of structure.

The eight types of structures listed above are basic design concepts and any type of structure developed will fall under them. Some of the structures developed are discussed in the following sections.

3.1 Cable Structures

Cable structures similar to cable bridges have been used extensively on earth because they have the advantage of carrying loads efficiently through axial tension [23]. Some of the properties that make a cable structure a viable option are [23]

- They are easily transportable and easy to erect
- They carry loads efficiently using tensile stresses.
- They can be prefabricated on earth and carried to the moon.

Three different types of cable structures have been developed for the moon. They are- Small Span Systems, Medium Span Systems, and Long Span Systems. These structures have been developed for two modes, one in which internal pressure is maintained and one in which internal pressure cannot be maintained because of leakage in the structure. These structures are therefore designed to keep the structural integrity intact in both the modes [23].

3.1.1 Small Span System

A cable reinforced fabric structure was developed. For the first mode during which internal pressure is to be maintained, the fabric will be active in supporting the structure. For the other mode, a three hinged arch is proposed. Figure 12 displays the structure developed [23]

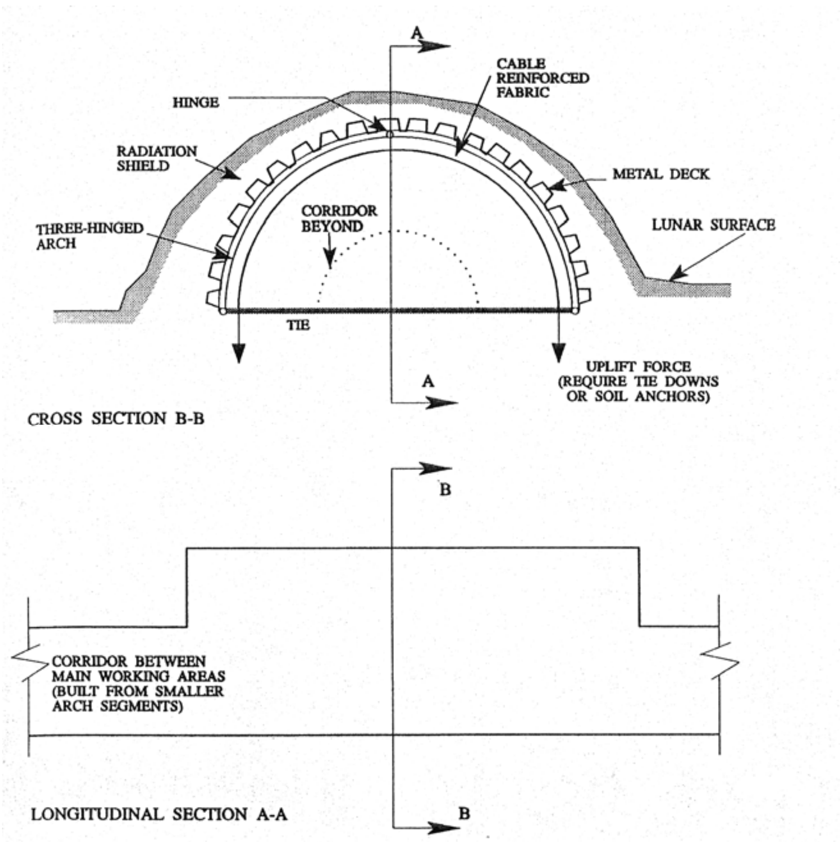


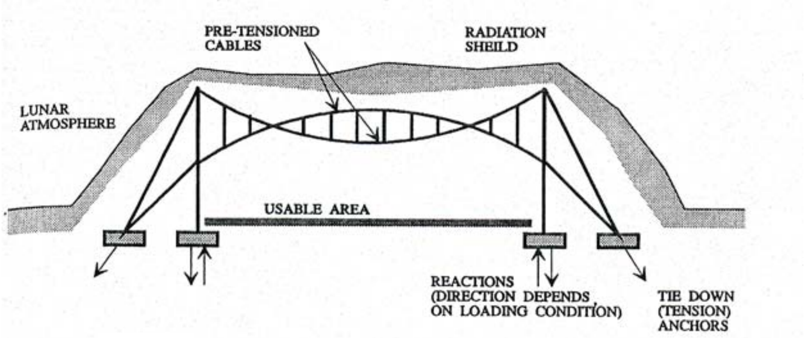
Figure 12 Small Span System

The use of various indigenous materials available on moon has been discussed in the construction of these lunar bases [22].

As can be seen from the figure the structure is circular in shape. This limits the span of the structure because with larger span, the structure will become higher and more unstable [23].

3.1.2 Medium Span Structure

In medium span structures pretensioned cables are used to extend the structure beyond the dimensions of a small span structure [24]. Configurations like convex, concave, convex-concave were discussed, but the convex-concave configuration was chosen to be more suitable for lunar structures [23]. Figure 13 shows such a structure developed [23].



Pretensioned, Convex-Concave System

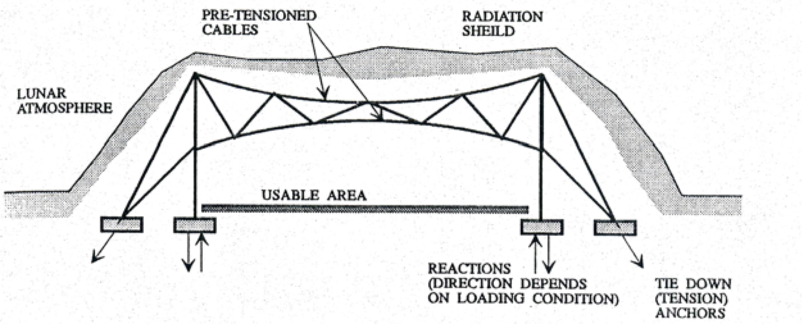


Figure 13 Medium Span System

The figure shows that the roof is made out of a concave-convex cable system. The advantages of this system are that it is much lighter because of extensive use of cables. Also it is much easier to construct [23].

3.1.3 Long Span Systems

Tension cable systems are again used for designing of larger lunar bases. Floor supports are used to resist the compressive forces [23]. This system will offer lots of usable space and it has been designed to function reliably in both modes. Figure 14 shows a long span structure in more detail [23].

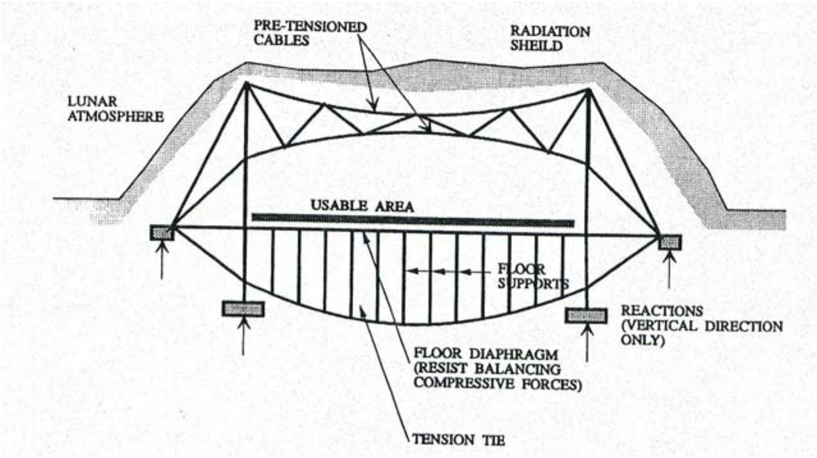


Figure 14 Long Span Systems

3.2 Mobile Lunar Bases

Various mobile lunar bases have been discussed [25][26]. These lunar bases can be constructed by assembling two or more of mobile modules together. While moving to a different location, each module can relocate to the new location easily using robotic legs or wheels. One such structure discussed in [26], uses three modules docked together to form a 4 person shelter for 45 days. This structure can dissemble and relocate to a new site of interest easily. Each module consists of crew quarters, power systems and other life support systems. Each module is equipped with 6 legs powered by electric motors, giving the module three degrees of freedom. These legs also act as structural supports when the modules dock with each other and form a habitat. Figure 15 shows the proposed habitat [26] made out of three modules and assembled in the form of a T. this configuration allows more modules to be added to the habitat.

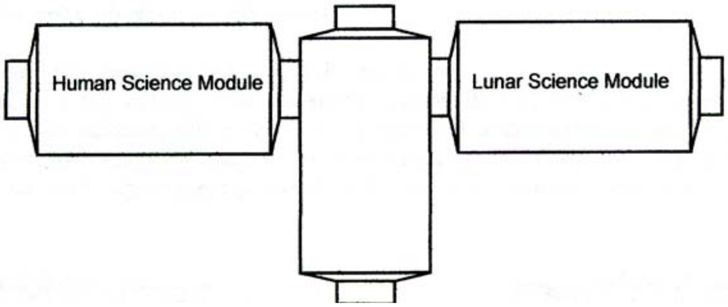


Figure 15 Habitat made out of three modules

Each module has been designed to provide the required radiation shielding to its occupants. These modules are also designed to protect the occupants from meteorite impacts [26].

3.3 Inflatable Structures

Inflatable structures in form have also been proposed [19] as permanent lunar base concepts. This concept is made up of inflatable, pressurized tensile structures. Regolith is used to provide radiation shielding. Air needed for inflating the structure can be carried from Earth in form of high pressure gas or cryogenic liquid [27]. Cryogenic Air is a more viable option because of its higher density. While relocation of the base, air can either be discharged to the moon or it can be stored for future use. Storing it and using air again, will reduce the costs involved with bringing air from earth. For removing air from the structure, water must be first removed from it. This can be done using a HVAC system. After that a cryo pump can be used to store the air in cryogenic containers [27]. An example of an inflatable structure is shown in Figure 16 below [19].

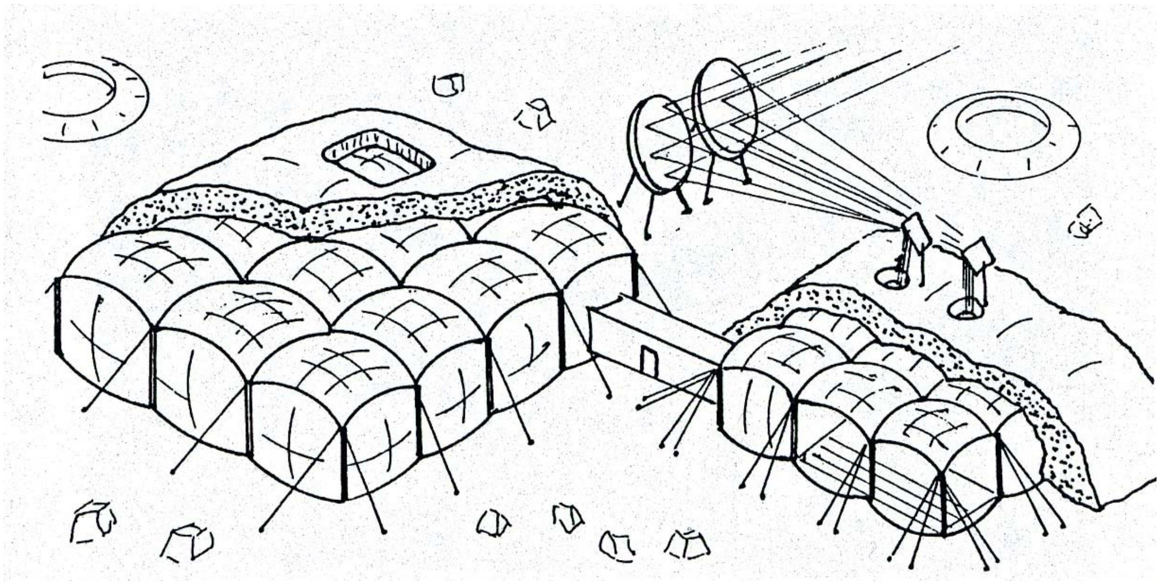


Figure 16 Inflatable Structures

In this chapter we have seen three different types of structures- Cable Structures, Mobile Structures and Inflatable Structures. This thesis aims at developing a structure made of regolith bags, stacked on each other. Such a structure has been in development [28] and is used as an emergency shelter and for other purposes. These structures are made of bags filled with sand and piled on each other, are connected using barbed wire. These structures are cheap in construction and provide adequate protection on Earth. Figure 17 shows some of the structures developed by the Cal Earth Forum [28].

Figure 17 Cal Earth Structure Concepts

The structures proposed in this thesis are similar in principle to the structures shown above. Different geometric configurations were evaluated and as discussed in previous chapters, the strength of each configuration was also evaluated.

CHAPTER FOUR

EXPERIMENTAL SETUP

In this chapter we’ll discuss about the various construction steps involved in erecting the structures. They can be categorized into following steps:

- Design and construction of frame needed to support the structure
- Filling of the bags with vermiculite
- Mounting of the bags on the frame and adjusting them as per the dimensions developed from the CAD model
- Removal of the frame

Each construction steps has various steps involved in it and they’ll be discussed with respect to each structure. Various different techniques were also used to fill the bags. Advantage and disadvantage of each technique will also be discussed.

4.1 Types of Bags

The following types of bags were used in design and construction of the lunar structure-

4.1.1. Center Connected Bags

These bags are connected by a stitch running through their center as shown in Figure 18. The materials used for the bag and the stitching technique will be discussed in a later section. These bags assume circular cross section on filling completely with vermiculite and look like stacks of balls placed on each other. The final shape these bags assume depend on the amount of vermiculite filled in each bag. If the bags are tightly packed then they assume circular shape as shown in Figure 18. If they are not completely filled the vermiculite inside the bags remains loose. The amount of vermiculite required inside each bag depends on the structure size and dimensions and will discussed in more detail in the later sections.

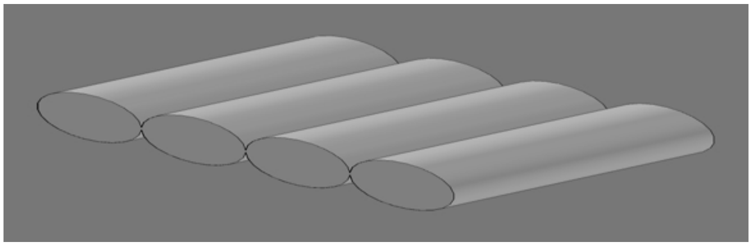


Figure 18 Center Connected Bags

4.2.2. Top Connected Bags

These bags are connected by fabric running on top as shown in Figure 19. Each bag forms a “tooth” in this structure. On filling the bags with vermiculite, the shape they assume is based on the amount of vermiculite poured into them. If the bags are tightly packed, they start assuming a round shape, very similar to the shape of bags shown in Figure 18. But since the bags are top connected, the fabric on top stretches and the distance between the bags on top becomes less than the distance at the center of the bags. This is not desirable as it makes the structure difficult to construct. On the other hand, a partially filled bag can be made into a shape of a rectangle and this way it becomes easier to the pile the bags on each other. A structure made out of a top connected bags is shown in Figure 20

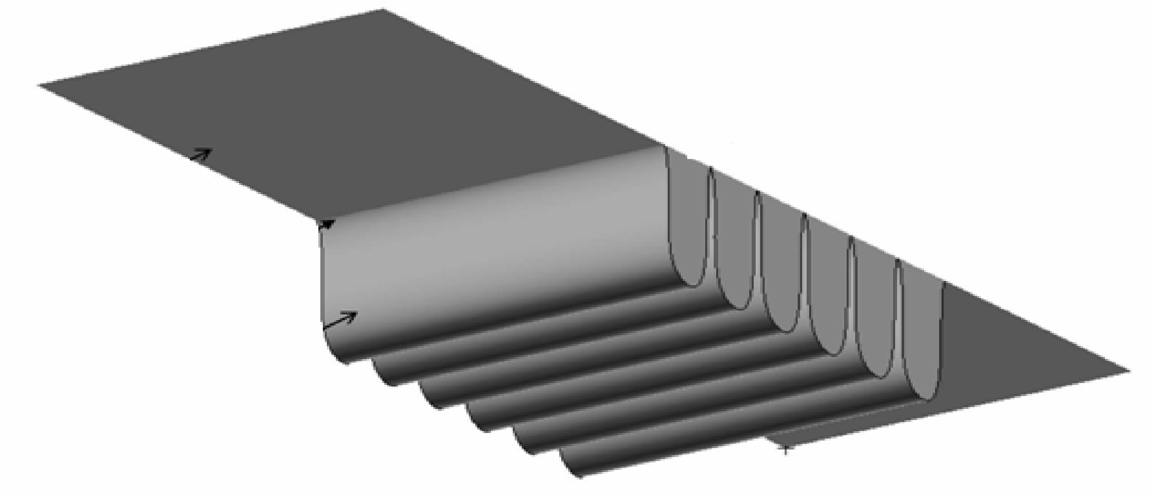


Figure 19 Top Connected Bags

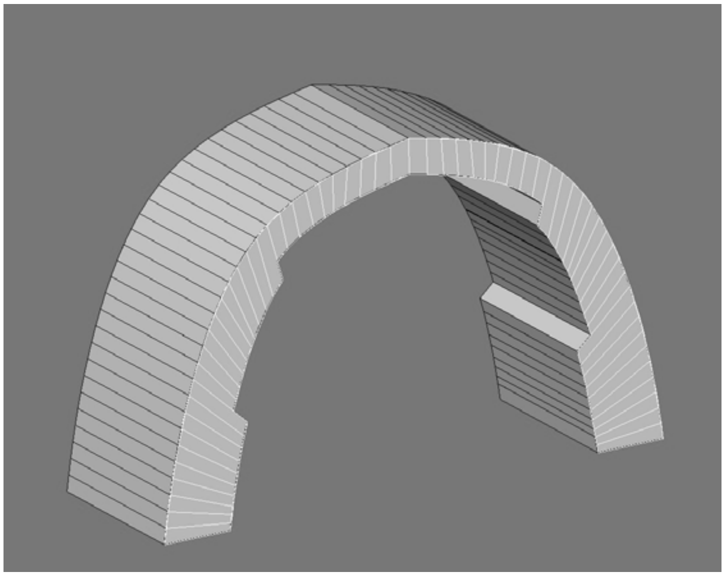


Figure 20 Structure made out of Top Connected Bags

4.2 Stitching Techniques and Materials used for Bags

Nylon was used in the construction of the bags of both type discussed above. For the top connected bags, different portions of fabric were cut out for and then stitched together. The bottom part of the bag is first constructed and then the top is stitched onto it. Two stitches were used for the construction of the bags. The top stitch was made up of double bonded polyester and the bottom stitch was made out of Kevlar. Figure 21 shows an image of the stitch. Zippers were used on one side of the bag, to keep an end accessible for pouring vermiculite into the bags. The zippers can withstand temperatures in the range -73^{0}C to +260^{0}C. They act as a sealing membrane and can withstand pressure of up to 700psi.

Figure 21 Stitch

For the center connected bags again nylon was used. These bags were constructed by stitching together two pieces of fabric. One end was closed and the other end was left open for pouring vermiculite. After filling the bags the open end is taped shut. This is not an optimum technique as the taped end can open up very easily and cause leakage of vermiculite.

4.3 Techniques used for Filling Bags

Filling the bags with vermiculite was a very time consuming process. Different techniques were used with little or no success before deciding on the best way to fill bags. Before discussing the techniques used for filling bags, the properties of vermiculite will be discussed.

4.3.1. Vermiculite and its Properties

Vermiculite was used instead of sand or regolith primarily because of its light weight in this project. Vermiculite has been extensively used in various industries for around 80 years [29]. The chemical formula for vermiculite is $(MgFe,Al)_3(Al,Si)_4O_{10}(OH)_2.4H_2O$ [30] and it is primarily composed of the following minerals [29]

Table 1 Vermiculite Chemical Composition

ELEMENT	PERCENT BY WEIGHT
SiO_2	38-46
Al_2O_3	10-16
MgO	16-35
CaO	1-5
K_2O	1-6
Fe_2O_3	6-13
TiO_2	1-3
H_2O	8-16
OTHER	0.2-1.2

Vermiculite is found primarily in Australia, Brazil, China, South Africa [29] [30]. It is a non toxic material which expands on the application of heat in a process called exfoliation [30]. After this process vermiculite becomes lightweight, non-combustible and a good insulator [29]. Hence it has found use in a variety of applications like [29] [30]

- Fire protection
- Fertilizer
- Pesticide
- Acoustic Finishes
- Absorbent packing
- Used in swimming pools to provide smooth pool base
- Furnace insulation

4.3.1.1 Safety Aspects of Vermiculite

Vermiculite has been proved safe to work with and poses no serious health risks on exposure [29]. The only serious health risk is when there are traces of asbestos present in vermiculite. The presence of asbestos can be found out through the Material Safety Data Sheets provided by the manufacturer. These sheets will inform the user about the material composition of vermiculite and will also provide information about any hazardous materials present in vermiculite and their safe handing and disposal [29].

Inhalation of vermiculite can cause minor coughing, sneezing [29]. This can be prevented by using dust respirators. Safety glasses should also be used to prevent minor eye irritations because of vermiculite.

4.3.2 Manual Filling of Bags

Initially, considering the small size of the bags used, manual filling the bags was the cheapest and fastest way available. In this process, the bags were filled with vermiculite using a funnel attached to a hole in the bag. The vermiculite was then poured into this funnel using a scoop. The bags were held upright at 90^{O} during this process. This technique works very well for center connected bags, because the round shape required for such a structure is achieved easily, because vermiculite settles down due to gravity given the erect positions of the bag. For a top connected bag this technique does not work very well as the bags attain a round shape instead of the desired rectangular shape. Figure 22 shows the bags erect and taped shut after filling them with vermiculite.

Figure 22 Center Connected Bags Filled with Vermiculite

Advantages

- Easy and cheap technique for filling small bags
- Minimum equipment is required

Disadvantages

- Not suitable for filling large bags
- Not suitable for filling Top Connected bags
- It is a tiring process and requires minimum of 2-3 persons

4.3.3 Filling of bags using Sand Blower

Figure 23 Sand Blower

Sand blower was used to fill the bags with vermiculite. Figure 23 shows an image of the sand blower used. The sand blower used was a pneumatic type. It was connected to air supply and it was then filled with vermiculite. A schematic of the sand blower is shown in Figure 24

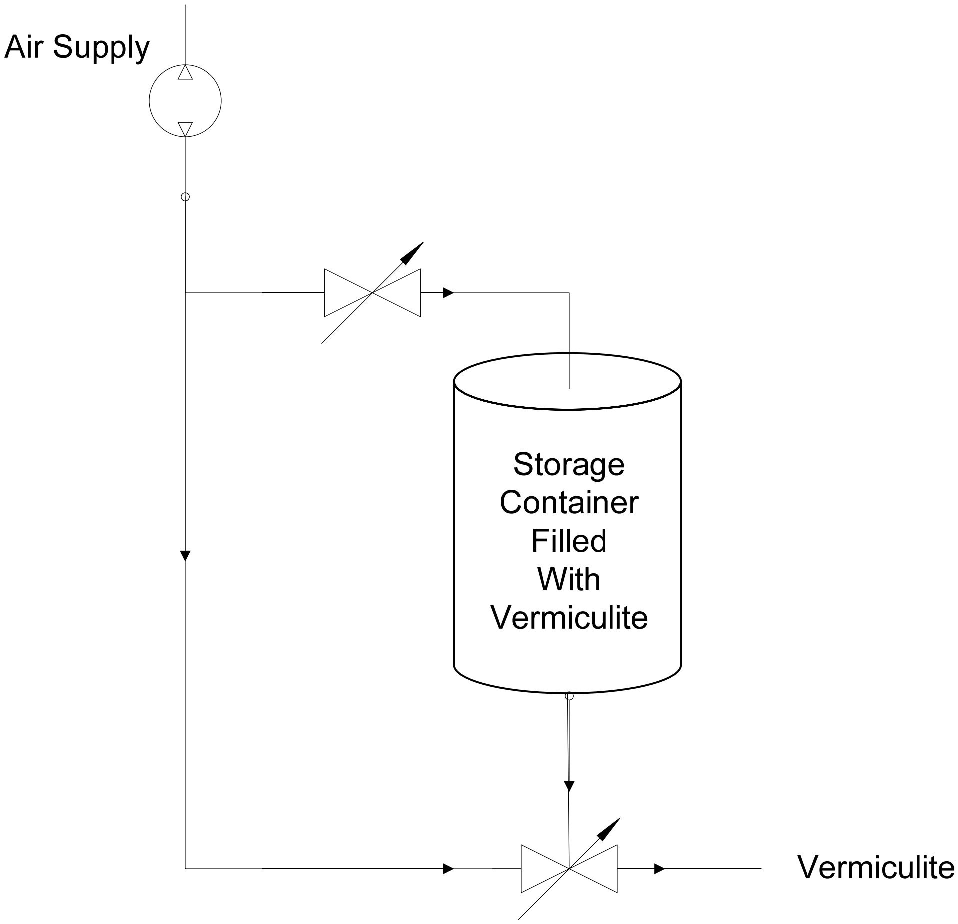


Figure 24 Schematic of Sand Blower used

As can be seen from the figure above the top of the cylinder is connected to an air supply. The cylinder is filled with vermiculite. The cylinder has a hole at the bottom through which the vermiculite can flow. When the air supply is switched on, air flows through as indicated by the directions shown in the figure. The vermiculite flows through the hole in the cylinder and into the valve. Here it mixes with air blowing through and comes out through a pipe as shown above. This end is inserted into the bag to fill them up.

Advantages

- It’s a fast technique of filling the bags
- This technique only requires a couple of people to fill the bags. Ideally one should be enough
- The equipment setup is pretty cheap and easy to construct.

Disadvantages

- The vermiculite that comes out is usually at a very high speed mixed with air. Hence when the outlet pipe is inserted into the bag, the vermiculite stirs up the contents of the bags inside. This causes lot of vermiculite to escape out of the bag. This is not ideal for filling the bags fast
- A lot of air also is accompanied with vermiculite. This is not desired as it blows out the vermiculite present inside the bag, through the hole on top.
- This technique causes vermiculite to blow out into the face of the operator and hence it has some health concerns.

This technique was not used extensively as the amount of the vermiculite leaking through the bag during filling, was more then the amount of vermiculite going inside the bags.

4.3.4 Leaf Blower

A leaf blower was also used to try and fill the bags. This leaf blower is designed to suck up leaves from its inlet hole using a fan and then blow them out into a bag attached to its other end. The inlet hole was instead attached to the bottom of a cylinder filled with vermiculite using pipes and fixtures. On switching it on, the fan was able to blow out vermiculite through the outlet and into the bags. This technique is very similar to the one where a sand blower was used. Figure 25 shows a leaf blower used for filling the bags.

Figure 25 Leaf Blower

Advantages

- This is also a fast technique of filling the bags
- The leaf blower is easily available and cheap
- A maximum of 2 people are required for this technique

Disadvantages

- This technique is very similar to sand blower technique and hence, even here a lot of vermiculite is blown out of the bag
- While operating the leaf blower, electric shocks were experienced. This was supposed to be caused by static charges transmitting through vermiculite.

Hence proper safety measures need to be taken while operating the leaf blower.

- There is a risk of the motor, operating the blower, burning out due to the friction created between vermiculite and the fan attached to the motor.

This technique was not very successful in the filling the bags because of reasons discussed above. Because of the shock experienced, a leaf blower powered by a gasoline engine was also tried. But it was not very successful because it was blowing out vermiculite at a high velocity and also it was seen that, the fan blowing the vermiculite out was getting stuck because of the weight of vermiculite acting on it. Another configuration was tried in which the leaf blower was attached upside down, to the bottom of a tank filled with vermiculite. This configuration is very similar to the one shown in Figure 26, but instead of the auger, a leaf blower was fixed. This was done to make the filling process easy but similar disadvantages as discussed before were encountered.

4.3.5 Screw Conveyor System

A screw conveyor system was purchased from Hapman industries. Also known as Auger this system consists of a helicoid screw conveyor attached to a motor. The helicoids screws rotate, powered by the motor. When vermiculite is poured into the screw system it is carried through and into the bags. The screw is enclosed in a pipe and this pipe is inserted into the open ends of the bag. Vermiculite is filled in a container and this container is placed on top of the screw conveyor system. When the vermiculite drops on the helicoid screw, its gets carried forward due to rotation of the screws. The pipe used here was around 12 ft long. The pipe can be inserted till up to 1 ft inside the bag. The bags are placed horizontally on the ground, and vermiculite is brought in by the screw system. Filling bags this way is easier but it was time consuming. The screws system could not be used for long durations at a time because the pipe heated up due to the friction between vermiculite and helicoid screw.

Figure 26 Screw Conveyor System- Image shows a motor attached to helical screw running inside the tube. The container is filled with vermiculite. When vermiculite pours into the screw it is carried through the pipe and into the bags.

Advantages

- A relatively easy system of filling the bags
- Less number of people required to fill the bags

Disadvantages

- The equipment required is complex and expensive.
- Its takes a while to assemble the system
- Not easily transportable like leaf blower or sand blower
- The pipe heats up because of the friction and hence the system has to be stopped frequently.

4.4 Frames

Frames were used as temporary centering to mount the bags on. The advantage of using a frame is that it makes the construction of the structure easy. Also it gives temporary support to the structure during construction. Frames are also helpful in giving the desired shape to the structure.

Different frames were developed for different bag structures. The frames were made out of aluminum or wood. Both were used primarily to reduce the weight of the frames.

4.4.1 Frame for 8 Bag Structure

This frame was made out of aluminum plates bend in the shape of a desired catenary arch. Figure 27 shows an image of CAD model of the frame designed for construction of this structure, whereas Figure 22 shows the frame made out of aluminum with bags on top if it. The shape of the three catenary supports on the frame was defined by the arch length, which is given by Equation 3. The arch length is important because the whole bag should be able to rest on the frame. Using Solid Edge, the shape was designed such that the total arch length of the catenary was equal to or more than the length of the bags. These bags were filled manually and then mounted on the structure.

The frame was then removed and structure was able to stand on its own as shown in Figure 28.

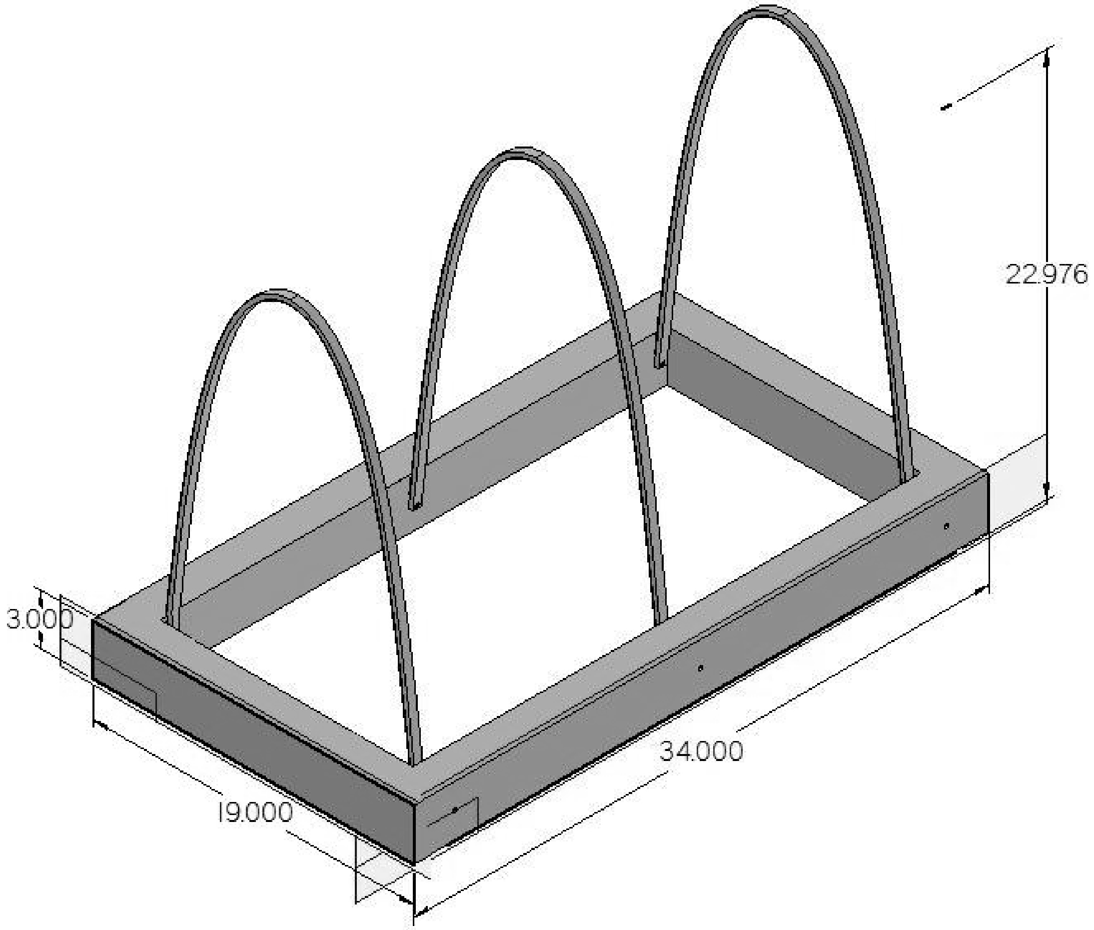


Figure 27 Frame for 8 Bag structure with dimensions (in)

Figure 28 Structure without frame

4.4.2 Frame for 16 Bag Center Connected Structure

The 16 bag structure was made out of center connected bags. The frame designed was again made out of aluminum plates bend into the shape of desired catenary. The shape of this frame is very similar to the one shown in Figure 27, the only changes being in the dimensions. Figure 29 below shows the frame made for 16 bag structure

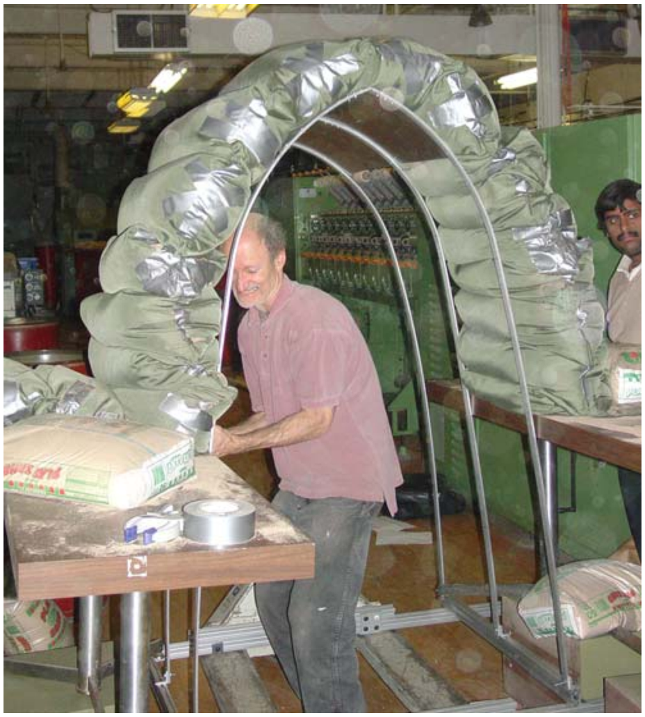


Figure 29 Frame for 16 Bag structure

The bags were filled manually and were then mounted on the frame as shown in the figure above. After all the bags were mounted, the frame was removed. The Figure 30 below shows the structure standing under its own weight without the support of the frame.

Figure 30 Structure without the frame

During construction of this structure it was observed that mounting the bags on the frame was a tedious process because of the weight of the bags. A better way of approaching this would be to use a pulley lever system to lift the bag from the middle and place it on the frame and then adjust the bags so that they confirm to the arch’s shape.

4.4.3 Frame for 60 Bag Top Connected Structure

The frame for this structure was made out of wood. The frame was made in such a way so that it could be used to mount different structures of different sizes. Wood was primarily used to reduce the weight of the structure and its costs. The bags used were around 30 feet long and the structure made out of the bags was around 10 feet high. Hence the frame designed for supporting this structure had to be big and strong enough to hold the structure. This frame consisted of 2 parts. Each part was designed to support one half the structure. Each part consisted of 4 vertical posts arranged in the corners of a square. The Figure 31 below shows the structure in more details

Figure 31 Frame for 60 Bag Structure

Wooden plates were then fixed to two opposite sides of the frame. Rods were run through these plates. Each rod was used as a support for mounting the structure on. The design of this frame was such that it could support a structure made out of either 46 bags or 60 bags. Another structure was made out of bags that were 1/3rd the size of bags shown in Figure 31. This structure was designed to support this structure also. A CAD image showing how a structure resting on its frame would like is shown in Figure 32

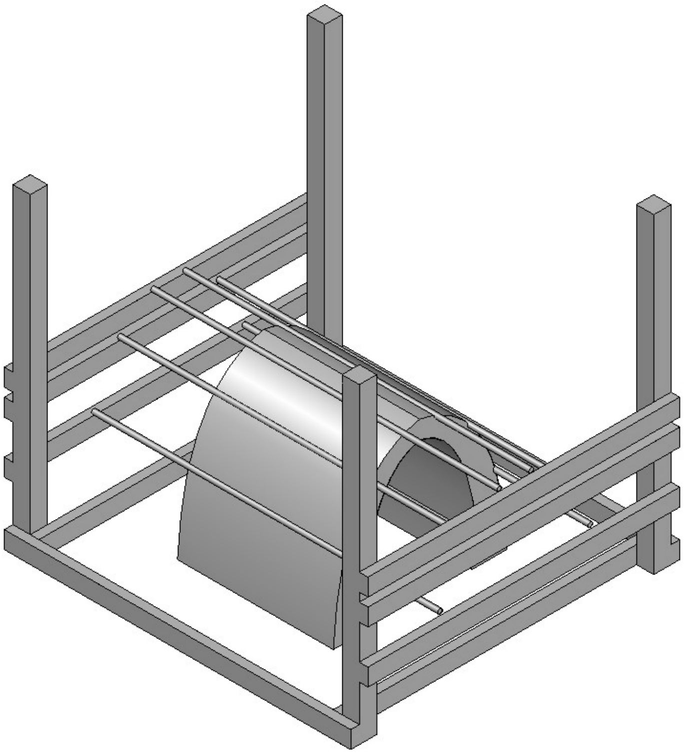


Figure 32 46 bag structure resting on its frame

CHAPTER FIVE

ANALYTICAL TEST OF STABILITY

The stability of the structures made was tested by analytical method and computer simulations. In this chapter, both these techniques will be discussed. Working Model, MSC. Marc was used primarily for computer simulation of the arch and some of the models developed are discussed in this chapter.

Funicular polygons, which have been discussed in previous chapter, were used to test the stability of the arches under different load and boundary conditions. Funicular polygon is the line of thrust acting through the arch. If the line of thrust goes outside the arch then the structure is unstable. The line of thrust can be found by using the following parameters

- Forces acting on the structure
- Span of the structure
- Height of the structure

For constructing the force polygon, the horizontal thrust needs to be found and this can be found using force equations and moment equations of the loads acting on the structure. Once the horizontal thrust has been found, the force polygon can be constructed and then the funicular polygon can be constructed.

5.1 Exploratory study to build a Working Model brick element from Springs and Dampers

MSC. Working Model was used in the initial stage to try and model a structure made out of various element or body types available in Working Model. Working Model is essentially a 2D simulation software, which can be used to model various physical problems. It also allows the user to change various properties associated with the elements available. Therefore, by using Working Model, the aim was to see how a structure made out of sand bags would behave under different load conditions. In this section we will discuss various models developed.

In Working Model, there are no element types available to model sand or regolith. Hence each bag was assumed as compressible. Springs and rigid bodies were used instead to model the bag. Figure 33 shows a single bag. The four corners of the bag are made out of rigid bodies. They are attached with springs to each other. A body is suspended in the middle of the bag and 4 springs are attached diagonally to the 4 corners as shown in the figure. The body suspended in the middle is used so that a mass can act in the center of the body. In Working Model, springs cannot be given any mass, hence in order that a mass acts in the middle of the bag, a small rigid body was placed and suspended with strings. Without a mass acting the center, it was difficult to approximate the model as bag.

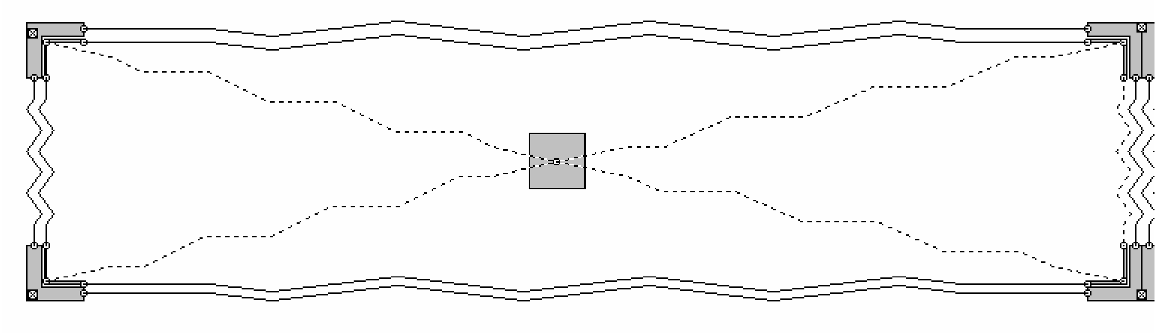


Figure 33 First Working Model Brick Element developed using springs, dampers and rigid bodies

Figure 33 shows that the model is made up of 4 rigid bodies on the corner, attached to each other with springs. 4 more rigid bodies were placed inside to model soil. Hence the 4 rigid bodies on top connected with springs can be called the “fabric” of this model or the bag. The rigid bodies were given L- shape as can be seen in an enlarged image in Figure 34. L-shape was given so that, while running the simulation under load of gravity, the inner rigid bodies could rest on the outer rigid bodies. This was an approximation of soil settling inside the bags. The 2 outer rigid bodies on the left were fixed to the ground. Hence the model constructed was that of a cantilever beam.

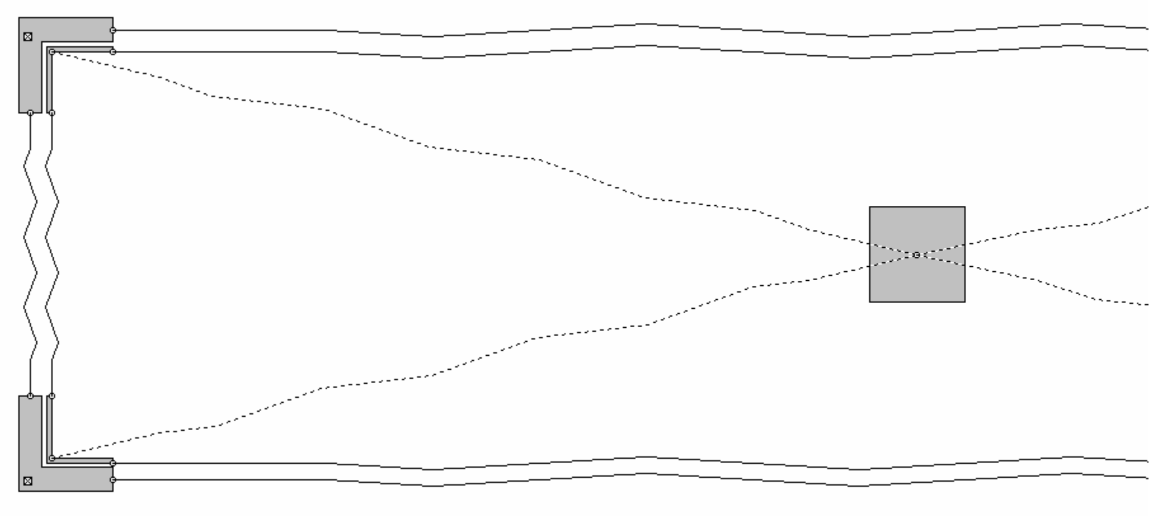


Figure 34 A closer look at the model developed

There were a total of 3 bags made in this model glued to each other as shown in Figure 35. The properties of the springs and rigid bodies present in this system were chosen at random to start of with and then varied to test how the model works.

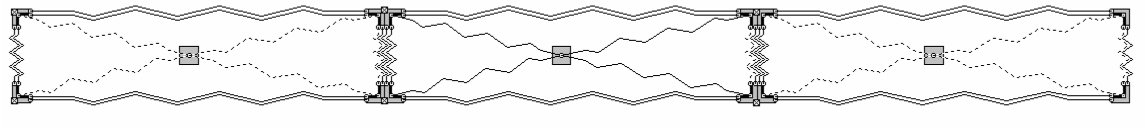


Figure 35 A set of 2 brick elements fixed together to act as a beam

It was seen that under the force of gravity, the model starting failing as the free end of the structure became unstable. As can be seen in Figure 36, the free end of the model has bent down due to the force of gravity. The properties associated with springs and rigid bodies were varied, but the end result was the same. The failure of this model can be associated to some of weakness present in Working Model. Springs in Working Model have no contact properties and hence a rigid body can pass through a spring in Working Model. This limits the use of springs as fabric, because they won't be able to hold any rigid body inside them.

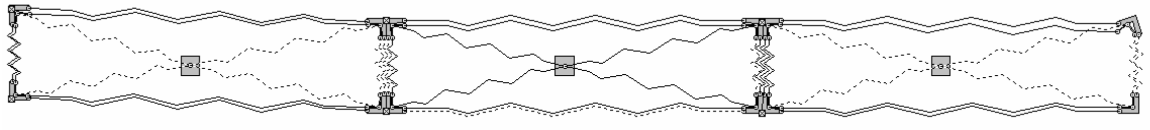


Figure 36 The Model falling down under the load of gravity

Since springs have no contact properties, another model was developed where 2 more rigid bodies were attached as shown in Figure 37. Springs were still attached to the model because they helped in modeling the stretching of fabric under load. The 2 rigid bodies on the top and bottom acted as a barrier since they had contact properties.

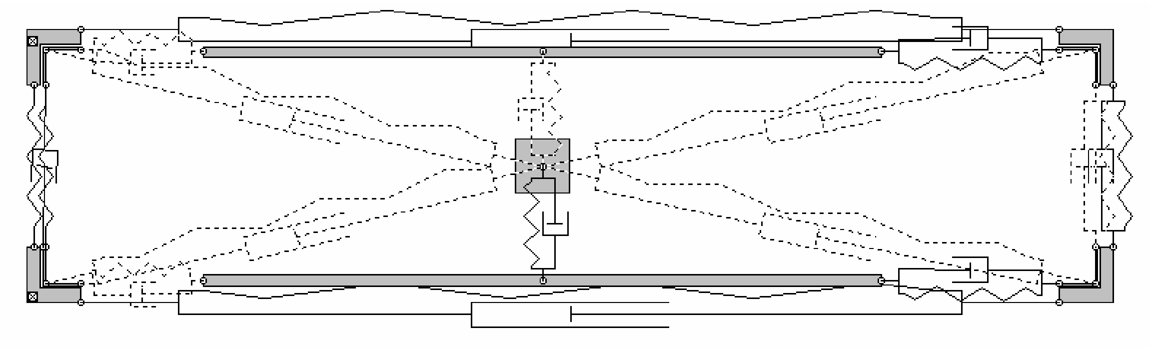


Figure 37 Next model developed with rigid elements on top.

On simulating this model it was observed that it became highly unstable. As shown in Figure 38, the free end of the model starts falling down. The 2 rigid bodies attached to the model also are unstable. The properties of springs and rigid bodies were modified and similar results were obtained.

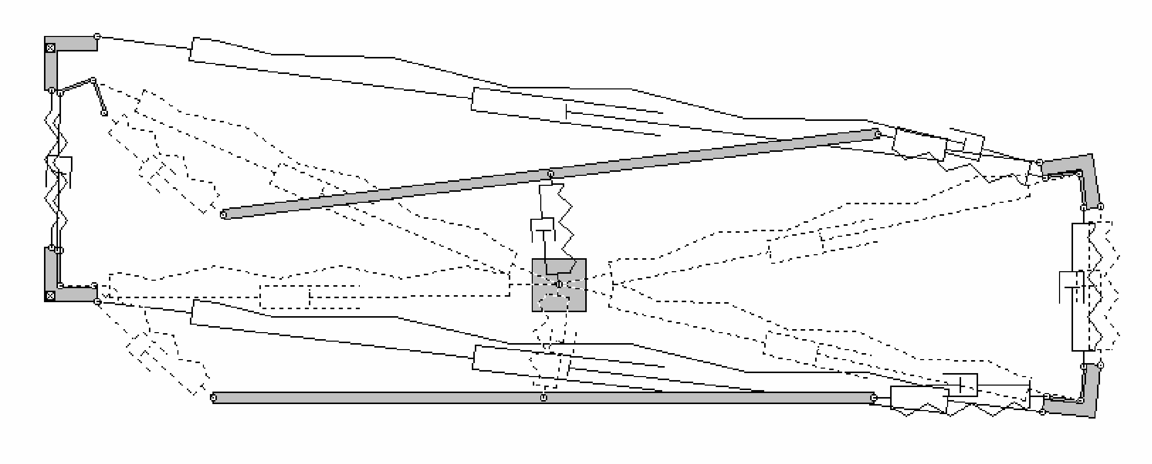


Figure 38 Model failing under the load of gravity

Figure 39 shows a graph plotted for the displacement of the right most body in the y axis. Since the slope of the graph keeps on increasing it can be seen that the model is unstable. Figure 38 shows that the L-shaped rigid bodies on the inside also act unstable and start to hinge on the outer L-shaped body. To prevent this from occurring another model was developed where the L-shaped bodies on the inside were replaced with balls.

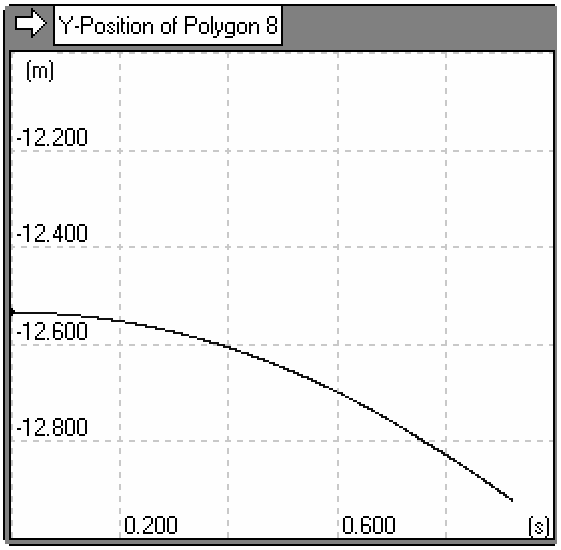


Figure 39 Graph showing the y-position of the model

Figure 40 shows a model with more rigid bodies attached to it. The L-shaped bodies on the inside were replaced with balls to prevent them from hinging around the outer L-shape bodies. Also 6 rigid bodies were added to the top and bottom part of the model as can be seen in Figure 40. These bodies act as the fabric in a sand bag.

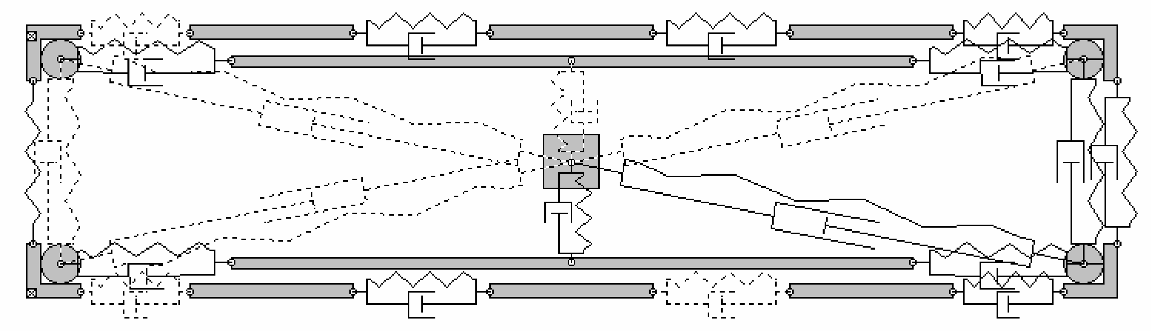


Figure 40 Next model developed with rigid bodies on both the outside and inside. The outer bodies are used to model bag and inner bodies are used to model sand

On simulating this model, stability was observed as shown in Figure 41 and the graph in Figure 42 shows that the system oscillates.

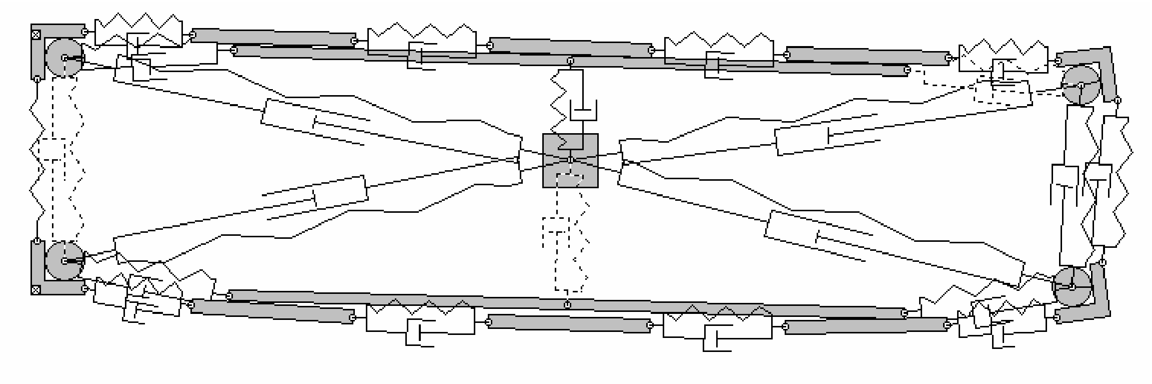


Figure 41 The model vibrates under the load of gravity.

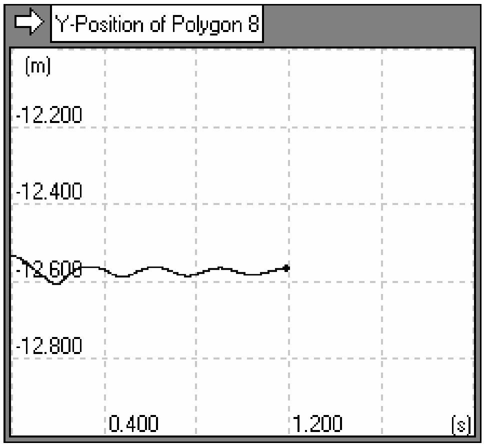


Figure 42 Graph showing the oscillatory motion of the model

The previous model was a success as it did not fall down under the load of gravity and instead remained stable. Next another model was created based on the previous model, but the springs inside were replaced by circles of equal dimensions and properties. This was done to model the sand particles inside the bag and to see how well Working Model was able to simulate multiple bodies. Figure 43 shows the model developed. Another difference from the previous model is that the springs connecting the rigid bodies on the inside of the model were replaced by rigid bodies on all 4 corners. 2 rigid bodies were placed on each side and connected to each other using a sliding joint. This was done so that all the 4 sides could elongate or compress under load.

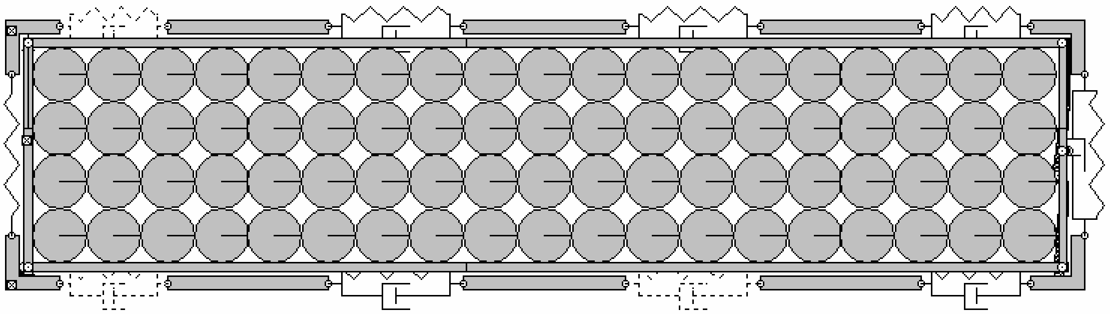


Figure 43 Model with balls to simulate sand packed inside bags

On running the simulation it was observed that the model failed under the load of gravity. Also, due to the presence of numerous bodies, the simulation took a huge amount of time. Figure 45 shows a graph for the displacement of top right L-shaped rigid body's displacement along the y-axis. As can be seen, the body along with other bodies in the system keeps falling and hence this model is a failure.

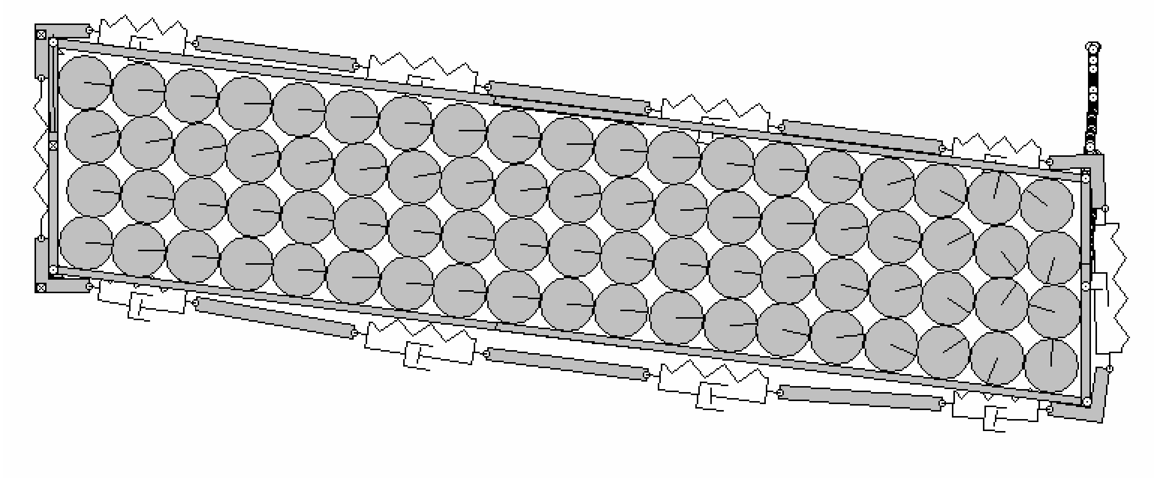


Figure 44 Model failing under the load of gravity

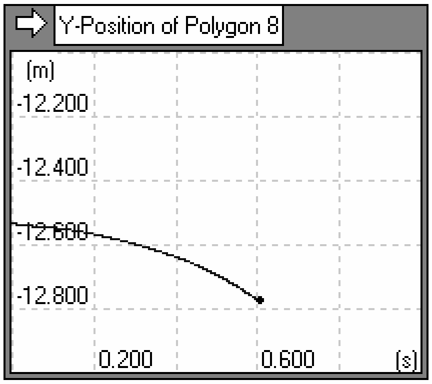


Figure 45 Graph showing the y-position of the model

All the above models were developed to see how a bag filled with sand would act under the load of gravity if hung like a cantilever beam. This was done to get some insight into how well Working Model would be able to simulate a sand bag and what kind of approximations can be made. It was observed that Working Model has limited use in simulating such a model because of the following reasons

1. Only rigid bodies can be simulated in Working Model. To simulate compression of a body, springs can be used but springs have no contact properties, hence it becomes difficult to model the contact between 2 deformable bodies.
2. It was seen that Working Model has limitations when it comes to modeling the friction between 2 or more bodies. A very high friction value between 2 bodies should be able to prevent them from sliding on each other under suitable load conditions. But in Working Model sliding could not be prevented even after giving very high value of friction of coefficient. This limits the way the model is developed as in case of masonry arch it is assumed that voussoirs don’t slide on each other.

A simple model of a masonry arch was developed in Working Model, where each bag was approximated as 4 rigid bodies in corner of the bag attached to each other using springs. Figure 46 shows the model created to simulate a masonry arch. The 2 ends of the structure are fixed to the ground. As can be seen, bags are joined to each other using a common spring. This is done because in a masonry arch it assumed that the voussoirs don’t slide on each other.

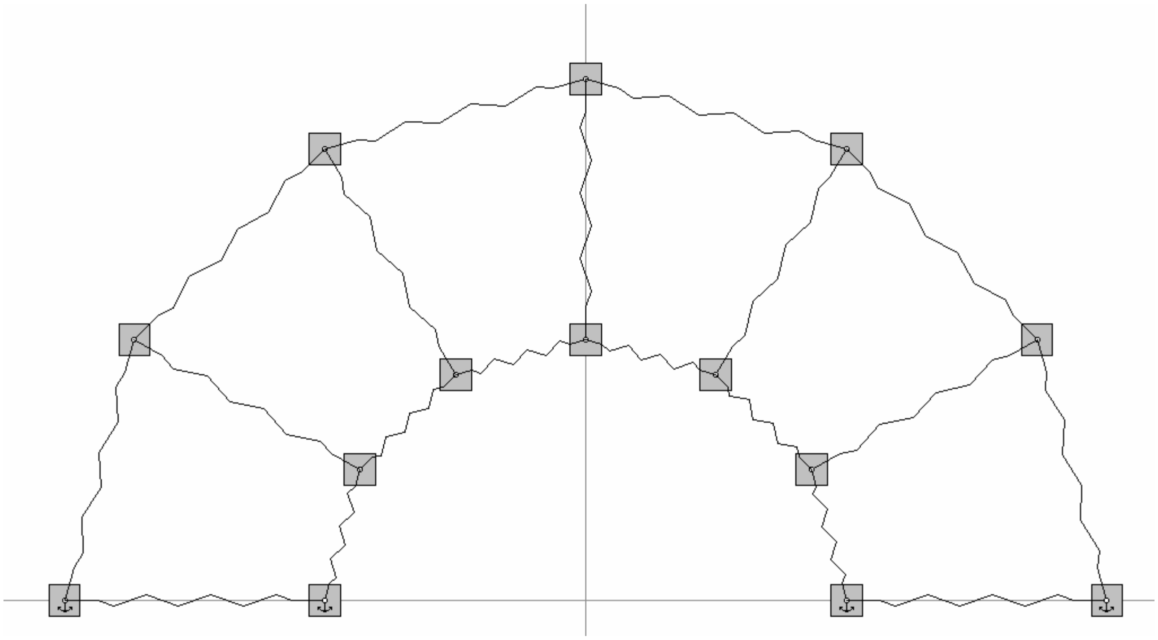


Figure 46 Arch Constructed using springs and rigid bodies

The properties of the springs were chosen at random first to see how the model simulates. On simulating under the load of gravity it was observed that the system oscillates and settles around the position shown in Figure 47. The advantage of this model is that the bags are compressible because of the presence of springs. This approximates the regolith structure very closely. The disadvantage of this model is that it fails when more bags are used instead of 6 used in this case.

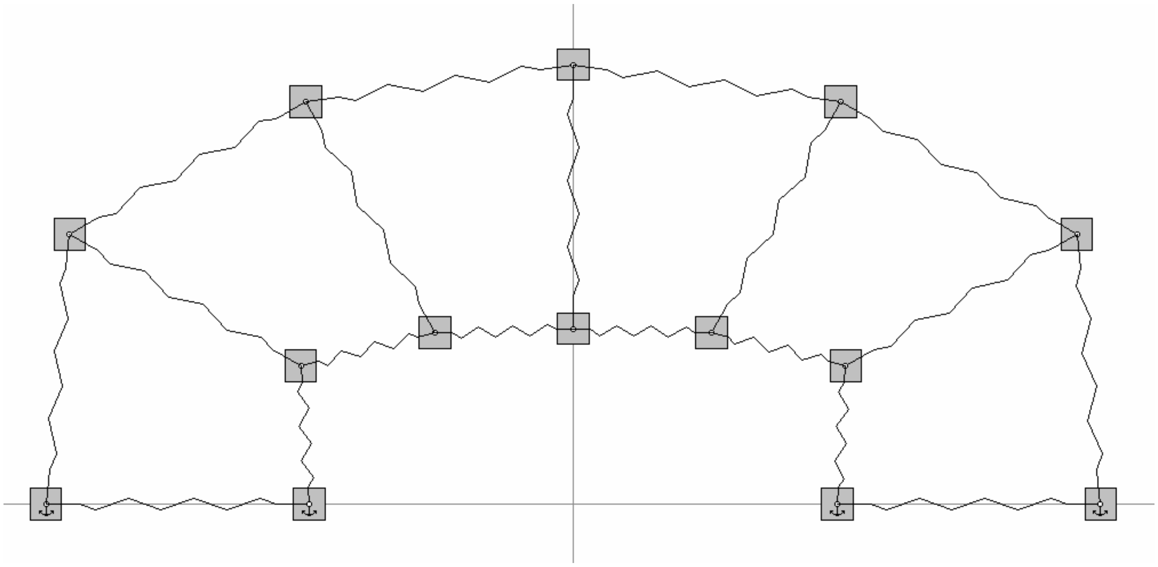


Figure 47 Arch stable when simulated in Working Model

5.2 Excel Spread Sheet for Funicular Polygon

To calculate the horizontal thrust, as discussed before, reaction forces on the structure, span of the structure and height of the structure are needed. An excel spreadsheet was developed to calculate the horizontal thrust. A sample excel spread sheet is shown in table below.

Table 2 Excel Spread Sheet

	W_1	W_2	W_3	W_4	W_5
x_i(in m)	0.157988	0.118542	0.078994	0.039522	0
y_i(in m)	0.112522	0.184404	0.22479	0.24323	0.245618
W_i(in N)	140	107	85	75	0
ΣW_i	140	247	332	407	407
$W_i x_i$	22.11832	12.68397	6.71449	2.96418	0
$\Sigma W_i x_i$	22.11832	34.80229	41.51678	44.48096	44.48096

H	113.5244				

This spread sheet can be better explained with the help of Figure 48 shown below

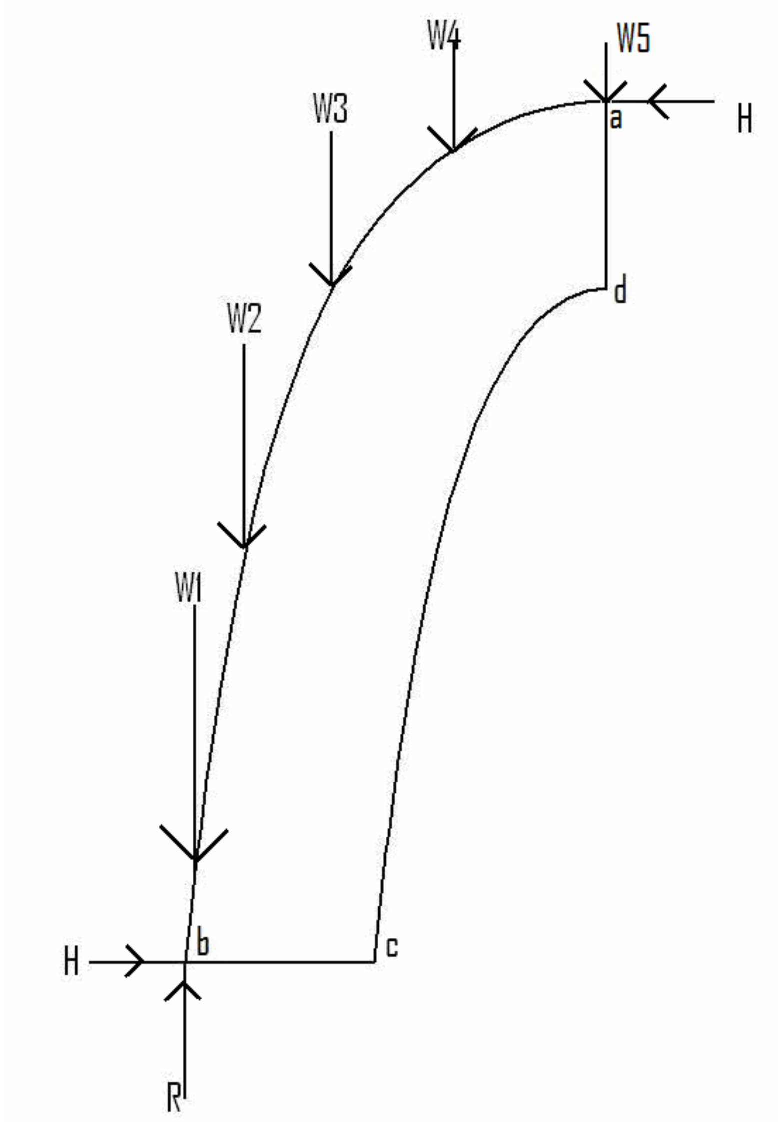


Figure 48 Arch with various loads acting on it

In this image only half an arch is shown as it is assumed the arch is symmetrical along the axis, both in shape and in force distribution. W_1, W_2, W_3, W_4 and W_5 are the forces acting on the structure. The first row "x_i" is the distance along the x axis from the point of action of force to the middle of the arch denoted by line *ad*. The second row "y_i" is the vertical distance from the point of application of force, which is along the y axis, to the bottom of the arch denoted by point "*b*". The third row "W_i" is the force acting at each point in Newton. The fourth row "ΣW_i" is the cumulative value of the forces. Similarly the fifth column is the product of the force and distance along the x axis. The next row "$\Sigma W_i x_i$" is the cumulative sum of the previous row. These variables are required to calculate the horizontal thrust. The horizontal thrust is calculated using the following equation

$$H = \frac{(\sum W_i * x1) - (\sum W_i x_i)}{y}$$

Equation 5

Here "*x1*" is half the span of the arch or the distance between points "*a*" and "*b*" along the x axis and "*y*" is the vertical distance between points "*a*" and "*b*". This equation is found from statics by calculating the momentum of the structure about the point "*a*". The force equations satisfying the equilibrium position can also be found. These 2 equations when solved give the solution for H. The equations and the solution can be found in the Appendix.

5.3 Stability of 8 Bag Structure

The construction of the 8 bag structure has been discussed in previous chapters. The 8 bag structure was filled with vermiculite using manual technique and mounted on a frame as shown in Figure 27. After mounting the frame was removed and the structure was able to stand under its own weight as shown in Figure 49. External loads in the form of sand bags were also applied to the structure to test its stability. Funicular polygons were developed for the structure with load and no load.

The structure was mounted on the frame and the frame was then removed. The bags were tightly stacked up against the frame and they were stacked in such a way that both the ends of the bag rest on ground. The frame was then removed and it was observed that the structure was able to stand on its own without any support from the frame. An image of the structure made is shown below.

Figure 49 Center Connected Bags with no Load

Length of base= 18 in

Height = 16 in

The image shows that the bag is able to stand on its own. Extra weight was also added to this structure to test its stability. Sand bags weighing 150 lbs were added on top of the structure and it was observed that the bag was still able to support itself. A little compressive flattening at the contact between bags was observed, but the amount of flattening depended upon the amount of vermiculite filled inside the bags and the load on the bag. The bags were tightly packed in this case. Because of this the compression of bags was not very high. Slipping was not observed between the bags and this was in agreement with the masonry arch theory as discussed in chapter 2. The presence of stitches between the bags gives an extra degree of stability to the structure. The funicular polygon was drawn for this configuration of the arch with 150 lbs weight acting on it and is shown in Figure 50. It was seen that the line of thrust stays inside the structure and hence confirming the results obtained from this experiment.

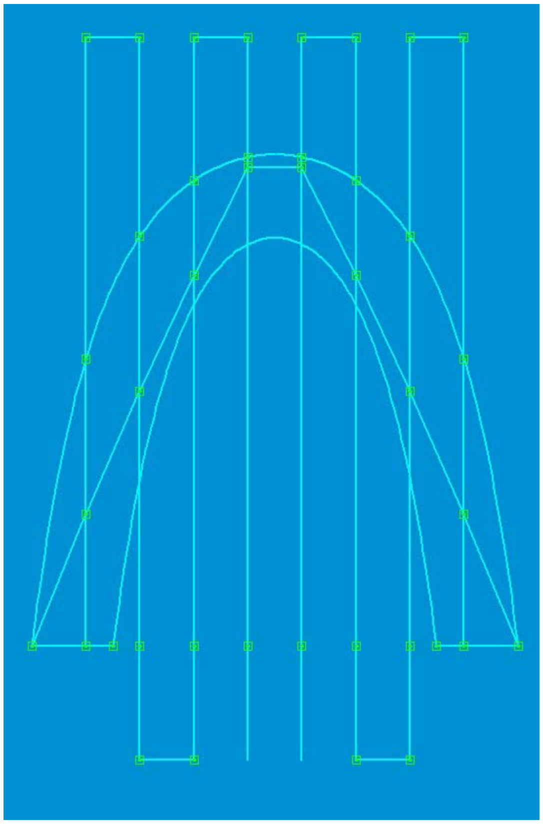


Figure 50 Funicular Polygon for 8 bag structure with 150 lbs weight on it

Another configuration was tested, where the length of the base was reduced and hence the height was increased. On adding weight to the structure it was seen that the bags settle down into an “M” shape configuration by forming hinges as shown in Figure 51. This structure was also observed to be stable, as it was still able to support itself with external weight acting on it, in “M” shape. An image of this new configuration is shown below.

Figure 51 8 bag structure forming M-shape when loaded

Funicular polygon drawn for this configuration is shown below

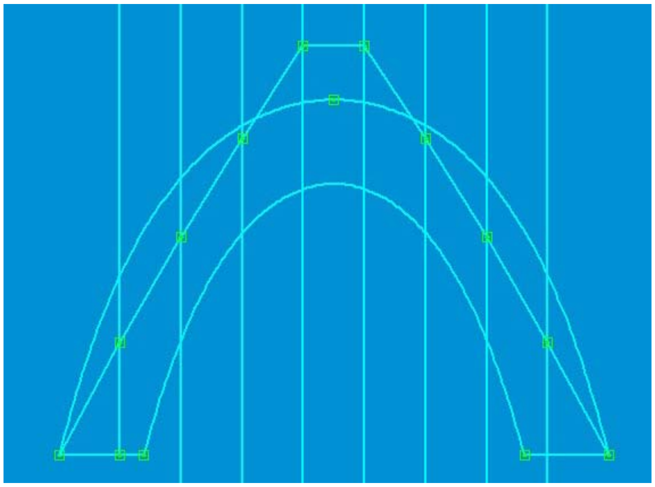


Figure 52 Funicular polygon of loaded 8 bag structure

It can be seen from the funicular polygon that the line of thrust goes outside the structure making it unstable, but in this case, the bags remain stable. This can be compared to a masonry arch, where the arch would fail if the funicular polygon goes outside the structure. The masonry arch fails because hinges are formed and they make the structure unstable. The voussoirs in the arch are not connected to each other and hence when hinges form, they open up at the location of the hinge. But with the structure made out of 8 pocket bag, even though the funicular polygon shows the structure is unstable, the structure does not fail and instead goes into an m-configuration. The m-shape shows the location of potential hinges in the structure. The location of the hinges is at the top of structure where the bags go into m shape. Since these bags are center connected, the hinge is not able to separate the bag and therefore the structure does not fail. It was noticed that addition of extra weight lead to the collapse of the structure. this shows that the m-shape configuration can be assumed to be a stable shape but the factor of safety reduces here considerably.

5.4 Stability of 16 Bags Structure

The structure constructed out of 8 bags was very small compared to the final structure desired. Due to the small size and less number of bags it performed favorably and in line with results obtained from funicular polygon analysis. For the next step, a bigger structure was desired. For this 16 center connected bags were stitched. The dimension of each bag is as follows

Length = 3 ft

Width= 6 in

The bags were filled using manual technique discussed in chapter four. Each bag took a lot of time to be filled and 2 person were needed, one to hold the bag and the other to pour the vermiculite in. These bags were considerably larger than the small 8 bags and also heavier. Because filling the bags was performed manually, the bags were not able to be packed tight initially. This was done to help in reducing the weight of the structure. After all the 16 bags were filled, the structure was mounted on a frame discussed in chapter 4. The weight of the bags was considerable and hence 3-4 set of hands were required to lift the bags from the floor and mount them on the frame. For mounting purposes a lever pulley system was considered, which could lift the bags from the middle and mount them on the frame, but was not implemented. Another approach was the use of a belt running through the middle of the bags to lift them up. As shown in Figure 53, a buckle was riveted to the middle of each bag. The idea was to run a belt through all these buckles and then to pull the belt from 2 ends in such a manner that the bags would rise up from the middle. The belts had to be pulled from under the bag such the when pulled the force exerted would act towards the center of the bag. The idea was to bring the ends of the bag together using the belt, which would then make the other pocket stack on each other because the belt ran through buckles placed in the middle of each pocket. This technique can be better visualized as bending a bar from its middle by exerting force on its ends, acting towards the center. When the ends of the bar are fixed such that they can only move in one plane, the force exerted would cause the middle of the bar to rise and bend. But this technique did not work out because of the weight of each pocket. A huge amount of force needed to be applied to lift the bag and also, the bags were not stacking on each other as easily as thought of.

Figure 53 Buckle on each pocket, fixed using rivets.

For manually mounting the bags on the frame, the bags were first lifted and mounted on the frame. Then starting from one side, each bag was compressed against the table. In this manner, the bags were packed tightly against each other increasing the area of contact between them as shown in Figure 54. This was done to all the bags. At the ends, sand bags were placed to prevent the structure from slipping on the table.

Figure 54 Bags stacked on each other.

After mounting the bags in the first trial it was noticed that the bags at the top of the structure needed to be packed more tightly with vermiculite as they were not compressing against each other and making the structure unstable. Hence the bags were pulled down and the top 5 bags were packed tightly (to around 3/4th of its volume). After this the bags were mounted on the frame again. This structure looked a little more stable than the previous one. But after the frame was removed, the structure stood for a while and then collapsed within few minutes. Figure 55 shows the structure standing on its own without the help of a frame.

Figure 55 16 bag structure standing without frame

The funicular polygon in Figure 56 developed for this structure also shows similar results. As can be seen, the funicular polygon goes out on top of the structure and hence it fails. During the construction process difficulties were faced in stacking the bags on each other. This made it difficult to keep the bags in desired position against the frame while stacking them up. On the top where the bags were tightly packed, the desired catenary shape was not assumed as can be seen in Figure 55. This is because the bags were packed tightly. This made the bags less compressible because of which they couldn't be stacked on each other at top. This showed that the bags on top needed free volume to compress against each other.

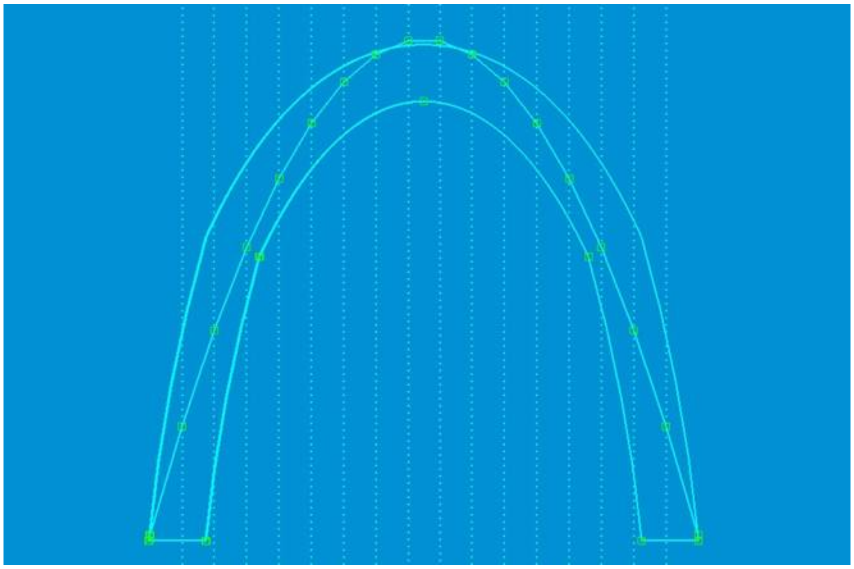


Figure 56 Funicular polygon developed for the 16 bag structure

Working with this center connected bag showed the in stability of a structure made out of such bags. Hence top connected bags were used for next set of experiments.

5.5 Stability of 46 and 60 Bags Structure

A 60 bag structure was discussed in previous chapter. The 60 bag structure was not easy to be handled by hands. So a smaller structure made out of bags which were 1/3rd the size of the actual bags. This helped in reducing the weight of the bags after they were filled with vermiculite. To make the construction of the structure even easier, only 46 bags were used instead of 60. As discussed before this structure is made out of 3 bags of different sizes. There are 10 bags of each size in one half of the structure. So starting from the top, 23 bags were taken on each side. The remaining bags were stacked up against the sides of the structure and they helped the ends in sticking to the ground.

For filling the bags, first manual technique was used. It didn't work out because of the large number of bags present. Next leaf blower and sand blower were used to fill the bags but were soon dismissed because of the problems discussed in chapter four. Finally the screw conveyor was used to fill the bags. This technique took a long time to fill each bag and also the conveyor system would become very hot due to friction as discussed in previous chapters. Because of this manual technique was again used to fill the bags up.

To form a catenary arch after the bags were filled; a drum was placed under the middle of the bags that is around the 23rd and 24th bag. This drum was placed on a jack which could be raised or lowered. When the jack was raised, the bags would rise from the middle and form a catenary arch shape. But a problem was encountered because the jack could not be raised higher enough. Also the bags were tightly packed. Because of this, each bag assumed a round shape instead of the rectangular shape desired. This caused the bags to roll on each other and the ends of the structure assumed a circular shape. Because of lack of time and manpower, this structure could not be developed further. But funicular polygons were developed for this structure and were found to be stable. Figure 57 shows a funicular polygon developed for a 46 bag structure with no external forces acting on it.

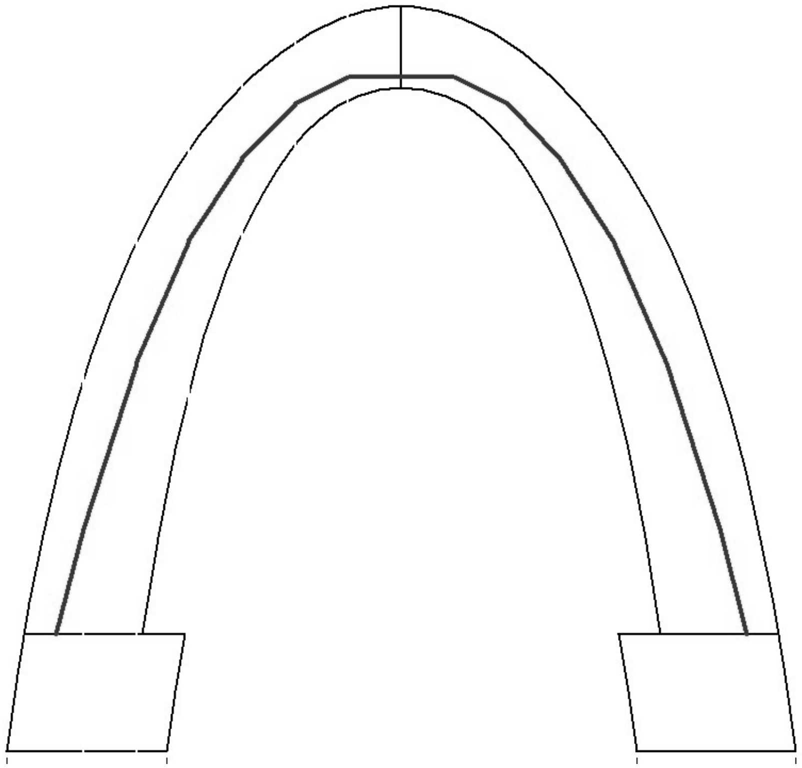


Figure 57 Funicular Polygon for 46 bag structure.

5.6 Stability of 60 Bags Structures

The construction of the 60 bags top connected structure was carried out in MSFC. This was the final structure to be developed. A top connected bag was used after it was observed in previous experiments that a structure made out of center connected bags would be more unstable. To test the stability of a top connected bag, a small 6 bag piece of fabric was made in Auburn University and tightly packed with vermiculite. One end of this bag was then fixed and the other end was left free as in a cantilever beam. It was observed that the bags were able to support their own weight and did not collapse under the load of gravity. Figure 58 shows the cantilever beam made out of top connected bags.

Figure 58 Top Connected bags acting as cantilever

On closer look it was seen that the fabric on top of the structure goes into tension and the bags start compressing onto each other. If the same structure was made out of a center connected bag, then gravity would make the beam fail, because there would be no tension on top of the bags to hold them upright. Also in center connected bags, each pocket tends to roll on each other under the load of gravity. On the other hand, rolling of packets on each other is prevented by the top layer of fabric in top connected bags. Figure 59 shows a CAD image of the structure discussed above. As can be seen, the rolling of pockets on each other is not possible because of the top layer of fabric and also because of the shape of the bags. The structure shown in Figure 59 looks different from that shown in Figure 58. This is because while performing the experiment, the bags assumed a slight circular shape and didn't remain in a perfect rectangular shape as desired. This was primarily due to the settling of vermiculite due to gravity. The walls of each pocket, being made of fabric, would stretch a little bit and form a circular shape. Since each pocket has a fixed distance between them, the circular shape of the pockets increases the distance and causes the fabric on top to go into tension. And since the pockets push against each other, they start compressing.

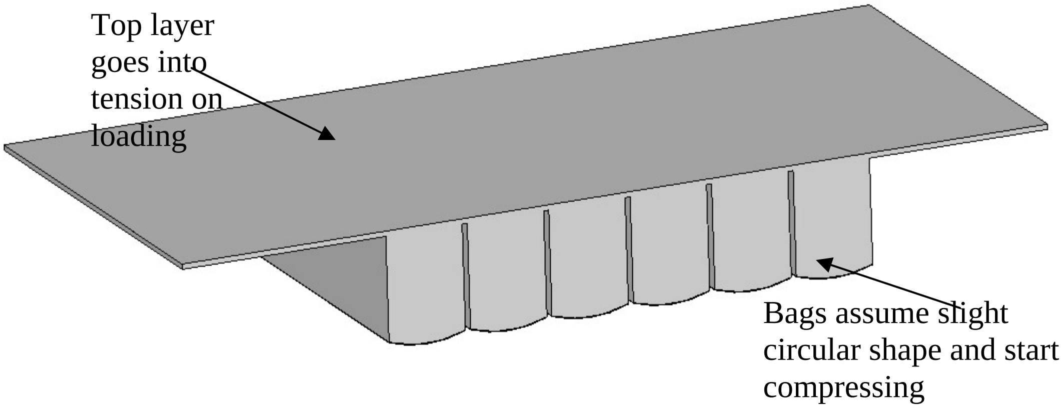


Figure 59 CAD image of top connected cantilever beam

The tension on the top layer and compression between the bags keeps the structure from failing. This cantilever beam experiment shows the stability that can be achieved by using top connected bags, because of the ability of the top layer to resist tensile loads.

The 60 bags constructed for this structure consisted of 3 bags of different dimensions, each type being 20 in number. So each half of the structure consisted of 10 bags of each kind. The dimensions of each set of bags is as follows

- 20 pockets at the bottom measuring 6” x 2’ in cross-section.
- 20 pockets above the bottom pockets, measuring 6” by 1.5’ in cross-section.
- 20 pockets that form the crest of the arch, measuring 6” by 1’ in cross-section.

Before constructing the structure analysis was performed on a series of 60 bag structures each with different dimensions. It was observed that taller configurations would be more stable, and would be able to support more weight. The first structure that was analyzed is shown in Figure 60.

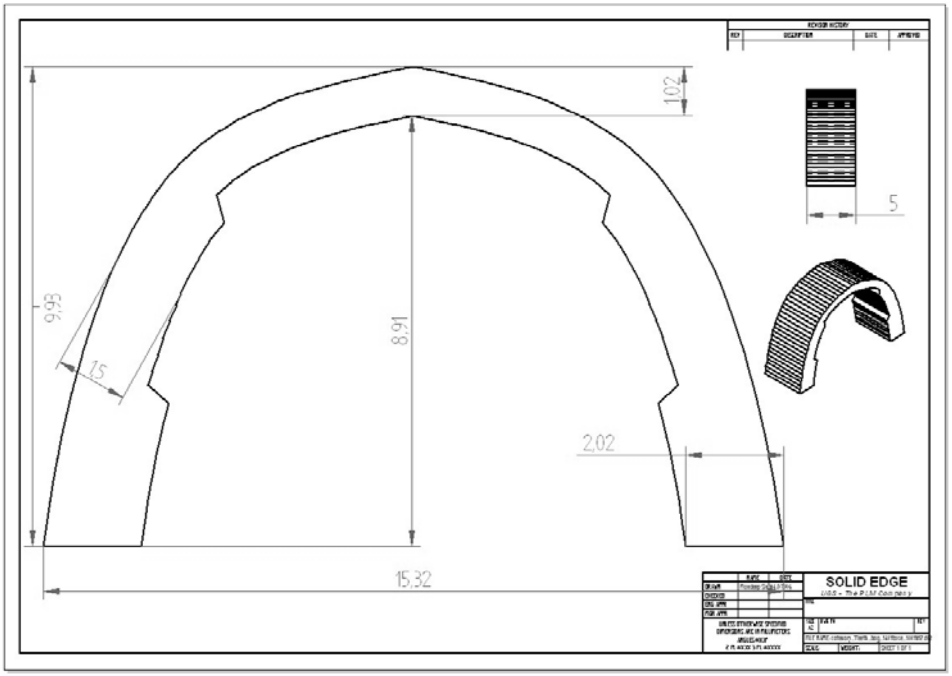


Figure 60 Front View with Dimensions (ft)

Funicular polygon was developed for this structure with no external load acting on it. Figure 61 shows the funicular polygon, and it can be seen that the bag will form hinges between the 15th and 16th bag. Assuming that the bags are symmetric, the hinge would form on the other side of the structure too. These hinges will tend to open towards the outside of the bags. But because of the presence of a layer of fabric on top, the formation of these hinges will be prevented. Hence this configuration might be stable.

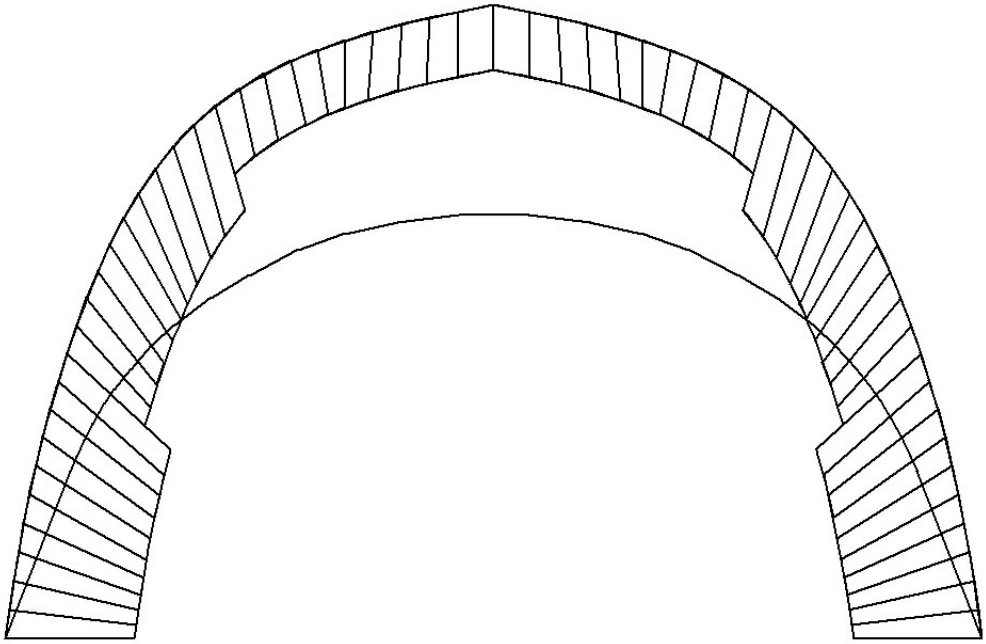


Figure 61 Funicular polygon for 60 bag structure

Another funicular polygon was made for this structure, under the same load, by starting the construction of the polygon from middle of the structure instead of the ends of the structure as in the previous case. The funicular polygon developed for this case is shown in Figure 62

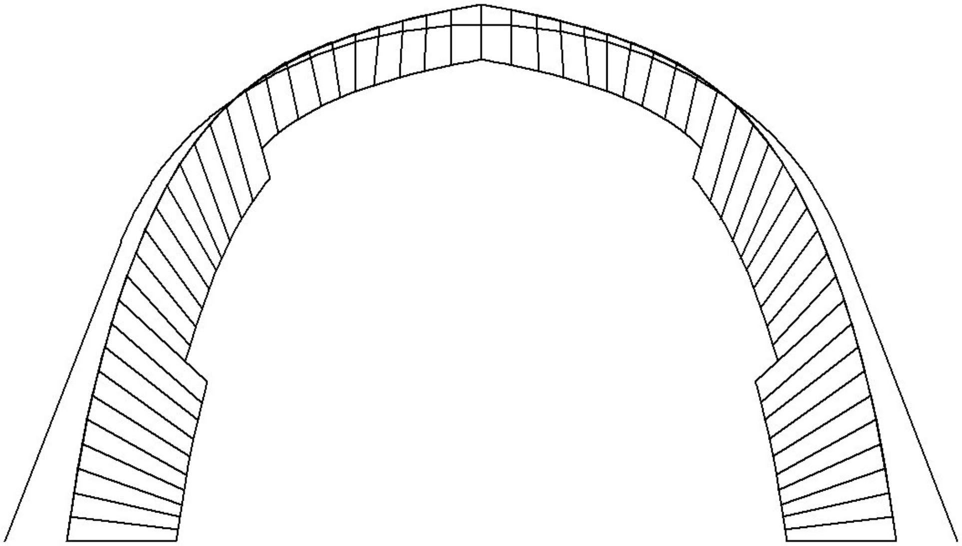


Figure 62 Another possible configuration for 60 bag structure.

This shows that hinges will form around the 20th and 21st bag. Since these hinges will open towards the inside of the structure where there is no fabric present, this structure might fail. Since both the funicular polygons developed for this model go out of the structure, it can be assumed that the structure will be unstable. Therefore this structure was not developed further.

Another model was developed where, the height of the structure was increased and the width was reduced. This configuration is shown in Figure 63.

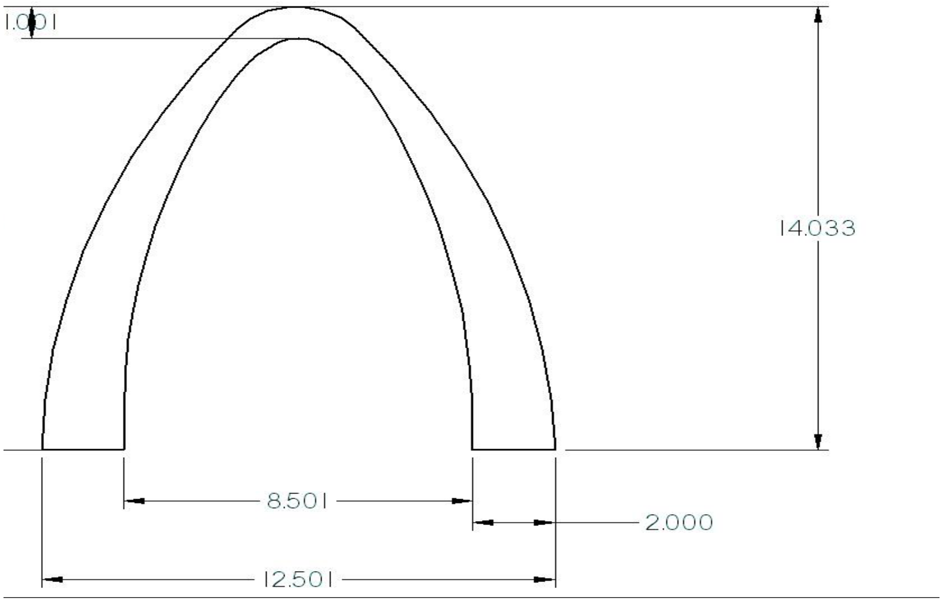


Figure 63 60 Bag structure with dimensions (ft)

The funicular polygon developed for this configuration lies inside the arch and hence shows that this configuration can be stable. The funicular polygon is shown in Figure 64.

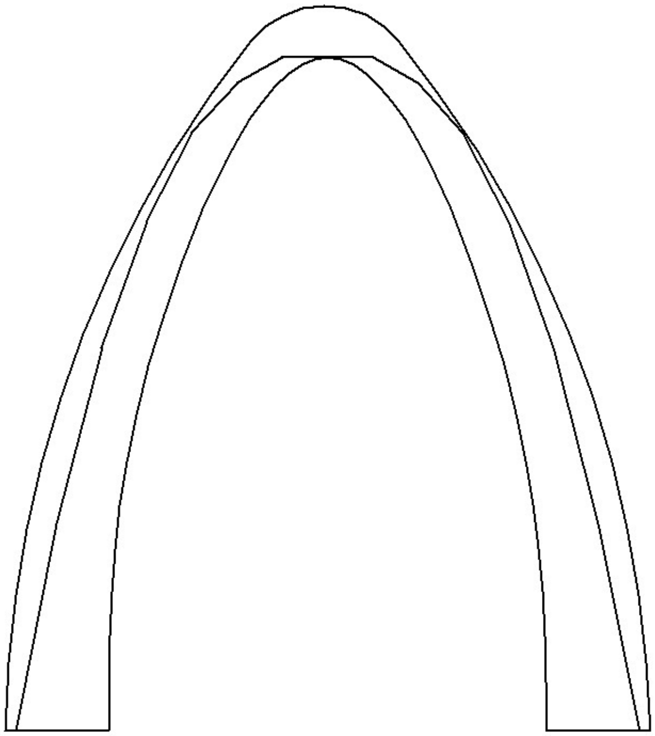


Figure 64 Funicular Polygon

This shows that the arch becomes more stable on increasing the height of the structure. Since the length of the bags remains the same, increasing the height causes the ends to come closer as can be seen clearly by comparing Figure 64 and Figure 62. Because of this the distance between bags on each side decreases. And as we go towards the top bags, the reduced distance causes the bags to get more tightly packed against each other. More tightly bags on top makes it difficult for the bags to start failing from the top and this gives the taller structure more stability.

5.6.1 Erecting the Structure

Only 46 of the 60 bags were used when building at MSFC. This was done because the remaining 14 bags could be used a strong foundation to hold the structure and also, with 46 bags the structure was more manageable. Figure 65 shows a stable structure, designed to be stable. Only 3 large bags were present as bottom bags. A wooden frame in Figure 66 was constructed and the structure was erected on this frame. Pipes were placed at 5 points on the frame in the shape of an approximate catenary. The positions of these points were determined from Figure 65, which shows the catenary shape build in Solid Edge. This shape corresponds to the actual catenary being constructed out of 60 bags. Table 3 shows the x and y co-ordinates of the points shown in Figure 65.

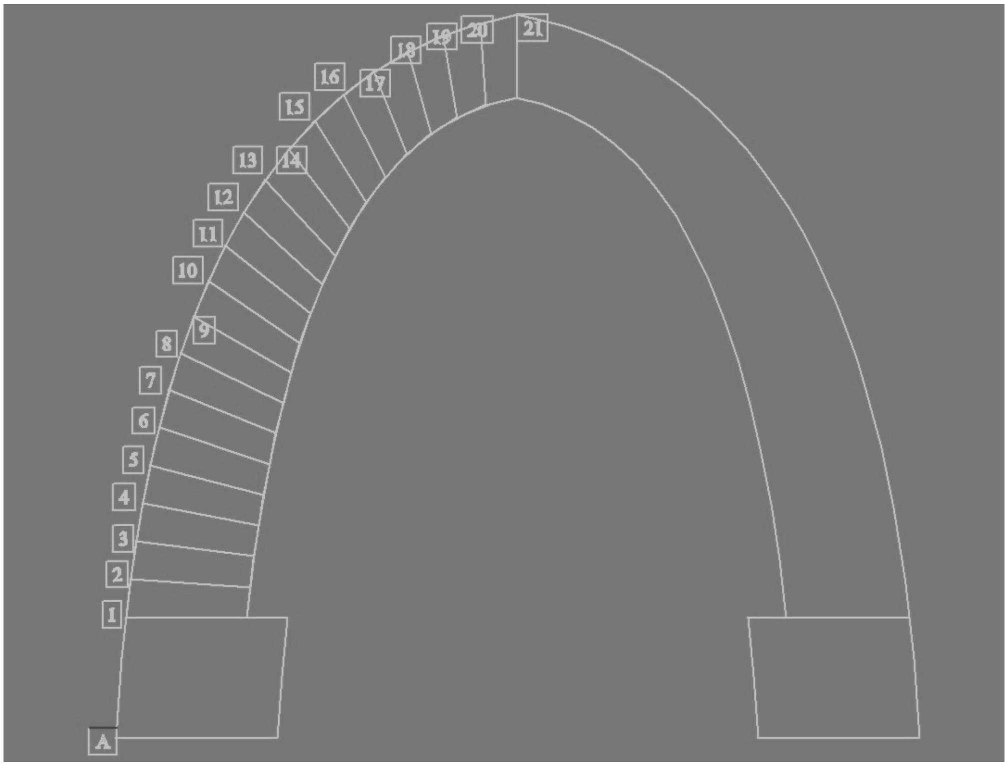


Figure 65 CAD Model Template to Guide Erecting

Table 3 Co-ordinates of points shown in Figure 65

POINT	X	Y
A	**0**	**0**
1	1.45	18
2	2.151	23.746

3	2.985	29.475
4	3.9	35.18
5	5.1	40.857
6	6.4	46.49
7	7.9	52.08
8	9.6	57.61
9	11.59	63.06
10	13.806	68.411
11	16.31	73.63
12	19.129	78.687
13	22.29	83.536
14	25.817	88.127
15	29.724	92.399
16	33.56	95.88
17	38.66	99.73
18	43.65	102.65
19	48.913	105.087
20	54.39	106.955
21	60	108.287

Assuming that the structure is symmetric, the position of the pipes is given by the following x, y co-ordinate values-

Actual Pipe Locations: Lower Level Pipes: x=14.5”, y=70”

2nd Level Pipes: x=25.7”, y=88”

Top Pipe: x=60, y=108”

Figure 66. Air-Filled 46 Bag Structure, 5 pipes guiding bag filling.

After airfilling the bags, filling of bags with vermiculite proceeded from bottom bags up. Bags were filled using a Hapman Flexible Screw Conveyor System. The white pipe contains a helicoid screw (without a center core tube), rotated by a motor that feeds and forces vermiculite into the bags. The white pipe was inserted into the bag to within 1 foot of the bag end, and the motor turned on to rotate the screw. As vermiculite flowed out, the tube was slowly and incrementally pulled from the bag. This operation was labor-intensive, required human assistance to distribute the vermiculite as it came out of the tube into the bag (Figure 67).

Figure 67: Big Filling Process

Lower bags were filled and formed to a near rectangular shape as shown in Figure 67, while trying to provide bag angle as the structure grew which can be seen by the angle obtained by the black zippers.

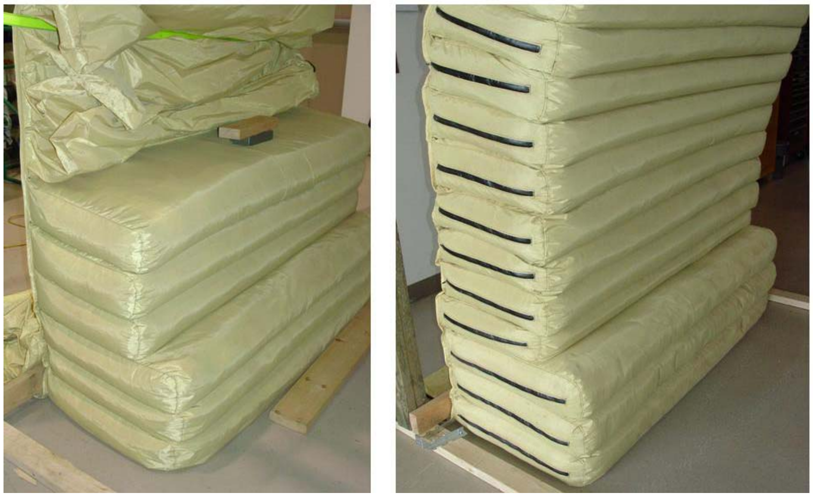


Figure 68. Rectangular Packed Bags

Filling of the top 20 bags required a different technique. Unfilled bags which hang down from the top fabric cannot be filled with a rectangular shape. This is because due to gravity and the looseness of the bag the vermiculite will settle at the bottom of the bag making it round in shape. Therefore the top 20 bags must be filled to capacity with vermiculite, which causes them to round. The top three bags couldn't be filled because with the topmost bags were nearly touching each other. This left no place for the top three bags. The maximum amount of material that could be placed in a bag was restricted by the Helicoid Screw System, which was limited to a relatively low compaction pressures because of the stiffness and strength limitations of the relatively flexible and shaftless helicoid. Low compaction pressure contributed to the top three bags not filling at pressures below desired. The final erected prototype is shown in Figure 69 (front view) and Figure 70(rear view). In these figures the pipes have been removed and the structure is able to stand on its own. It was noticed that the structure settled around 2" once the top 3 pipe supports were removed.

Figure 69. Front View

Figure 70. Rear View.

Upon review of the standing structure and the process of erecting, the following observations were made-

1. The left side of the structure in Figure 69 (right side in Figure 70) is the "good side". It was built and maintained a catenary shape very near design specifications, except for the topmost bags.
2. The right side of the structure in Figure 69 (left side in Figure 70) is the "bad side". Here several flaws were observed that were a result of bags not filled to capacity
3. Figure 71a shows that several bags on the bad side with a flattened profile that lost the catenary-shape curvature. Bags slipped downward despite attempts to erect the structure with a catenary shape; bags slippage was visible and occurred over a several second interval. Slippage is attributed to a shortage of vermiculite due to incomplete packing, which did not occur on the good side; the vermiculite

grains may slide (shear) with respect to each other inside the bags. This situation is correctable (but difficult given that zippers are only on one end) by hand loading more vermiculite through an open zipper and forcing material into the bag with a plunger. A simpler fix would have been to have used an auger-type system which deposits vermiculite under higher pressure than the helicoid.

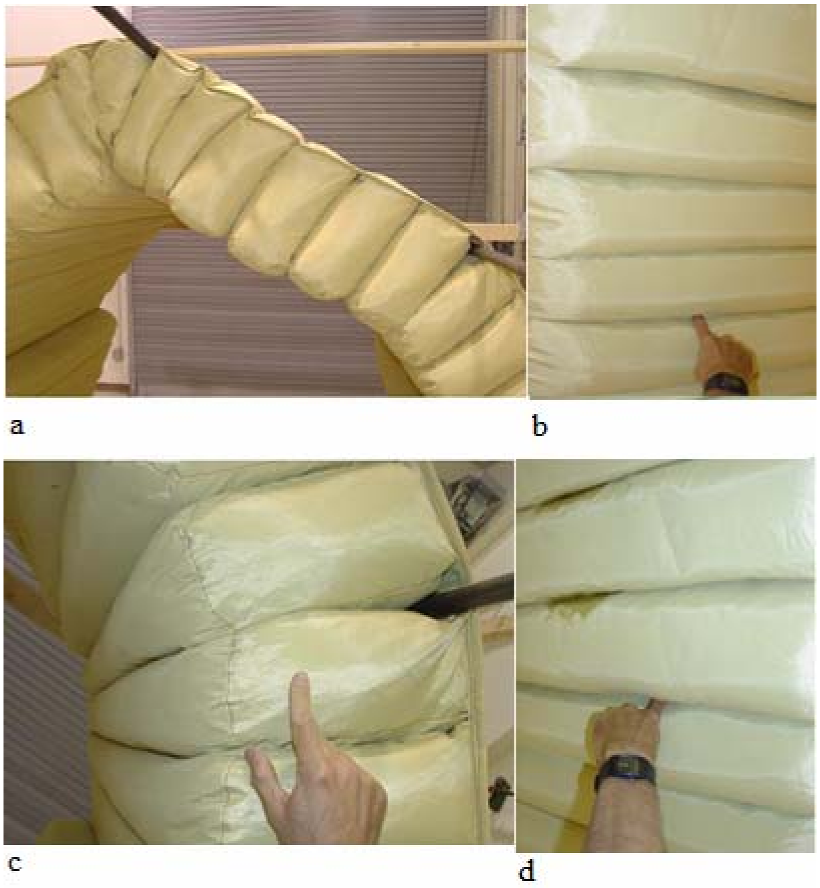


Figure 71 Closer views of structure

Figure 71b shows a tightly filled bag; it bulges and exhibits a hardness which can be felt by applying finger pressure. Tightly filled bags are necessary to create bags with sufficient vermiculite strength. Part of the internal bag pressure is a result of loading from the bags above.

4. Figure 71c shows another characteristic of a well-built structure with tight bags. Here it is difficult to insert a finger between the bags, implying that the bags are tightly packed with respect to each other. Compressive and shearing loads are transmitted without failure across the fabric boundary, from bag-to-bag.
5. Figure 71d show a characteristic of inadequately packed bags. Here it is easy to insert a finger between the bags – this may imply the beginnings of hinge formation. The bags themselves are loosely packed - by applying finger pressure the bags easily indented. The dark patch in the figure represents glue that was placed in-between the bags as an experiment. The glue did not appear to affect the structure. If the glue had affected the structure, the glued fabric would have been in tension, and this was not the case.

This shows that a catenary arch can be constructed from regolith top connected bags by using proper techniques and analysis. The funicular polygon proved to be reliable in estimating the stability of the structure.

CHAPTER SIX

CONCLUSIONS AND SUMMARY

This thesis presents the process involved in construction of a lunar garage made out of multi pocket bag filled with regolith. The theory and principle behind Masonry Arches was adopted to be used in the design and construction of lunar base. Various techniques were developed and tested at Auburn University and MSFC to develop a better understanding of the various issues involved in constructing such a lunar base. Analytical methods of finding structures stability were also developed. This chapter presents a brief summary of various methods discussed previously in this thesis.

6.1 Thesis Summary

For the testing and construction of lunar base, two types of bags were developed. One was center connected bags and the other was top connected bags. As the name suggests, the center connected bags were made by stitching together pockets through their center whereas in a top connected bag, pockets were stitched onto a layer of fabric. This fabric ran through the top and all the pockets hung freely on the bottom.

The first structure was developed out of 8 pocket center connected bags. These bags were filled with vermiculite and mounted on a frame. The structure made, was found to be stable. The analytical solution developed using funicular polygons also showed the structure as stable. The next structure developed was made out of 16 pocket center connected bags. Filling of bags manually with vermiculite was a tedious and tiresome process. The structure constructed was not very stable and the funicular polygon developed for this structure showed similar results. The next structure constructed was made out of 5 pocket top connected bag. The bags were filled manually and a cantilever beam was constructed using this bag. The cantilever beam was constructed to show the extra stability and bending strength top connected bags would provide over center connected bags. The stability of the cantilever beam proved this. This showed that structures made out of top connected bags would offer more stability. So the next structure was developed using top connected bags. A 60 pocket bag was used to develop this structure. Because of the large number of pockets present, manual filling of pockets with vermiculite was ruled out. Other methods like using a sand blower, a leaf blower etc were tested but were found unsuitable. Finally a screw conveyor system was purchased and used for filling the bags. This method, though more efficient then other methods, was still very labor intensive and involved the manual spreading of the vermiculite inside the bags. For this structure, it was decided that only 46 bags would be used. This reduced the time needed to fill the bags, and also the remaining bags were used as foundation support for the structure. The funicular polygons developed for this structure showed a stable configuration and this was confirmed after erecting the structure, as it could stand on its own under the load of gravity.

6.2 Future Research and development

Finite element analysis of the structure can provide more accurate results for test of stability of a lunar structure. Hence future work can involve the development of finite element models of the structure that could be tested by applying appropriate load conditions and boundaries. There are various difficulties in developing such a model, as a model developed using soild elements and membrane elements can prove to be very complex. An approximate model, needs to be developed

A lot of techniques were used to fill the bags with vermiculite, and the screw conveyor system was found to be the most suitable. Better techniques can be developed as even the screw conveyor system had its shortcomings. If a lunar structure is to be made on the moon, a proper and more reliable technique of filling the bags with regolith needs to be developed. The collection and storage of regolith on the moon is another area of research. Also, the ability of the structure to shield harmful radiations on the moon’s surface need to be looked into and is an area of active research. Another area of research is the development of support frames that are needed during the construction of the lunar structure. Frames that could be easily assembled on the moon’s surface and which can be adapted easily to fit various structures need to be developed.

REFERENCES

[1] L.A. Taylor, Dong-Hwa S Taylor, "Considerations for return to the moon and lunar base site selection workshops", *Journal of Aerospace Engineering*, April, pp. 68-79, 1997

[2] H.J. Smith, A.A. Gurshtein, W. Mendell, "International Manned Lunar Base: Beginning the 21st Century in space", *Science and Global Security*, vol. 2, pp. 209-233, 1991

[3] H.H. Schmitt, "Business approach to lunar base activation." , *Space Technology and Applications Int.,* vol. 654, pp. 1061-1066, 2003

[4] H. Benaroya, "An overview of lunar base structures: past and future", *AIAA Space Architecture Symposium,* Houston, Texas, Oct. 10-11, 2002

[5] H. Benaroya, L. Bernold, K.M Chua, "Engineering, Design and Construction of Lunar Bases", *Journal of Aerospace Engineering,* vol. 15, no. 2, pp. 33-45, 2002

[6] J. L. Klosky, S. Sture, Hon-Yim Ko, F. Barnes, "Geotechnical Behaviour Of JSC-1 Lunar Soil Simulant", *Journal of Aerospace Engineering,* vol. 13, no. 4, pp. 133-138, 2000

[7] G.B. Ganapathi, J. Ferrall, P.K. Seshan, "Lunar Base Habitat Designs: Characterizing the Environment, and Selecting Habitat Designs for Future Trade offs", Jet Propulsion Laboratory, May 1993.

[8] S. Matsumoto, T. Yoshida, H. Kanamori, K. Takagi, “Construction Engineering Approach for Lunar Base Development”, *Journal of Aerospace Engineering,* vol. 11, no. 4, pp.129-137, 1998

[9] P. Eckart, “Lunar Base Parametric Model”, *Journal of Aerospace Engineering,* vol. 10, no. 2, pp.80-90, 1997

[10] J.H. Adams, R. Silberberg, C.H, Tsao, J.R. Letaw, “Radiation Transport of Cosmic Ray Nuclei in Lunar Material and Radiation doses”, *Lunar Bases and Space Activities of the 21st Century,* pp. 663, 1985

[11] B. Mishra, M. Duke, D.L. Olson, J. Roubidoux, J. McDermott, D. Tordonato, “Low Temperature Molten Salt Electrolysis For Oxygen Production from Lunar Soil”, Space Resources Roundtable VII: LEAG Conference on Lunar Exploration, pp. 66, 2005

[12] McCoy Bonnie, “Lunar Oxygen Production Detailed Design Review”.

[13] The Artemis Project- *http://www.asi.org/*

[14] Lunar Oxygen Production Plant: Specification Sheet- *http://www.tsgc.utexas.edu/tadp/1995/spects/o2.html*

[15] M.M R. Taha, “Design of Masonry Arches,” ENCI 595.05

[16] F. P. Spalding, “Masonry Structures”, New York, John Wiley & Sons, Inc. 1921

[17] J. Heyman, “The Masonry Arch”, New York, Halsted Press, 1982

[18] Wolfram Mathworld- *http://mathworld.wolfram.com/Catenary.html*

[19] Task Committee on Lunar Base, “Overview of Existing Lunar Base Structural Concepts”, *Journal of Aerospace Engineering*, vol. 5, no.2, pp.159-174, 1992

[20] H. Benaroya, M. Ettouney, “Framework for Evaluation of Lunar Base Structural Concepts”, *Journal of Aerospace Engineering*, vol. 5, no.2, pp. 187-198, 1992

[21] R.M. Drake, P.J. Richter, “Concept Evaluation Methodology for Extraterrestrial Habitats”, *Journal of Aerospace Engineering*, vol. 5, no. 3, pp. 282-296, 1992

[22] L.S Bell, M. G. Fahey, T.K. Wise, P. C. Spana, “Indigenous Resource Utilization in Design of Advanced Lunar Facility”. *Journal of Aerospace Engineering*, vol. 5, no. 2, 1992.

[23] M. Ettouney, H. Benaroya, N. Agassi, “Cable Structures and Lunar Environment”, *Journal of Aerospace Engineering*, vol. 5, no. 3, 1992.

[24] F.K, Schleyer, “Analysis of Cables, Cable Nets and Cable Structures”, Cambridge,The MIT Press

[25] D. V. Smitherman, Jr. , V. Dayal, D.J. Dunn, II, “Architecture for a Mobile Lunar Base Using Lunar Materials”, *Space Technology and Applications International Forum*, vol. 813, pp. 1022-1029, 2006

[26] D. Smitherman, M.Rais-Rohani, D. Dunn, D. Perkinson, “Hybrid Robotic Habitat for Lunar Exploration”, *Space Technology and Applications International Forum,* vol. 746, pp. 1078-1087, 2005

[27] J.M Hines, C.E Miller, R.M. Drake, “Mechanical Equipment Requirements for Inflatable Lunar Structures”, *Journal of Aerospace Engineering,* vol. 5, no. 2, 1992

[28] Cal Earth Forum, *http://www.calearth.org/*

[29] The Vermiculite Association, *http://www.vermiculite.org/*

[30] Vermiculite, *http://en.wikipedia.org/wiki/Vermiculite*

APPENDIX A

Excel Spread Sheets developed for 8 bag structure for different load conditions

x(in m)	0.26129	0.186614	0.111938	0.037262	0
y(in m)	0.210439	0.317322	0.37084	0.393141	0.397942
W(in N)	140	107	85	75	0
$\Sigma \boldsymbol{W}$	140	247	332	407	407
$\boldsymbol{W}x$	36.58057	19.96768	9.514713	2.794635	0
$\Sigma \boldsymbol{W}x$	36.58057	56.54825	66.06296	68.8576	68.8576
H	170.5789				
x(in m)	0.26129	0.186614	0.111938	0.037262	0
y(in m)	0.210439	0.317322	0.37084	0.393141	0.397942
W(in N)	140	107	85	150	0
$\Sigma \boldsymbol{W}$	140	247	332	482	482
$\boldsymbol{W}x$	36.58057	19.96768	9.514713	5.58927	0
$\Sigma \boldsymbol{W}x$	36.58057	56.54825	66.06296	71.65223	71.65223
H	226.8756				
x(in m)	0.26129	0.186614	0.111938	0.037262	0
y(in m)	0.210439	0.317322	0.37084	0.393141	0.397942
W(in N)	140	214	85	150	0
$\Sigma \boldsymbol{W}$	140	354	439	589	589
$\boldsymbol{W}x$	36.58057	39.93535	9.514713	5.58927	0
$\Sigma \boldsymbol{W}x$	36.58057	76.51593	86.03064	91.61991	91.61991
H	267.0339				
x(in m)	0.26129	0.186614	0.111938	0.037262	0
y(in m)	0.210439	0.317322	0.37084	0.393141	0.397942
W(in N)	400	107	85	150	0
$\Sigma \boldsymbol{W}$	400	507	592	742	742
$\boldsymbol{W}x$	104.5159	19.96768	9.514713	5.58927	0
$\Sigma \boldsymbol{W}x$	104.5159	124.4836	133.9983	139.5876	139.5876
H	275.666				

Excel Spread Sheet for 16 bag structure

big sang bags-no load-16 bags supported									
mass of each bag= 100*5*5*pi*27*(0.0254)^3									
3.475									
Weight									
34.09									
x(in m)	0.653	0.566	0.4785	0.3912	0.3039	0.217	0.129	0.0422	0
y(in m)	0.2627	0.375	0.4258	0.4469	1.334				
W(in N)	40	40	40	40	40	40	40	40	0
Σ***W***	40	80	120	160	200	240	280	320	320
W*x*	26.119	22.63	19.138	15.647	12.157	8.667	5.178	1.6876	0
Σ***W****x*	26.119	48.75	67.886	83.533	95.691	104.4	109.5	111.22	111.22
H	94.19								

Excel Spread Sheet for 60 bag top connected structure

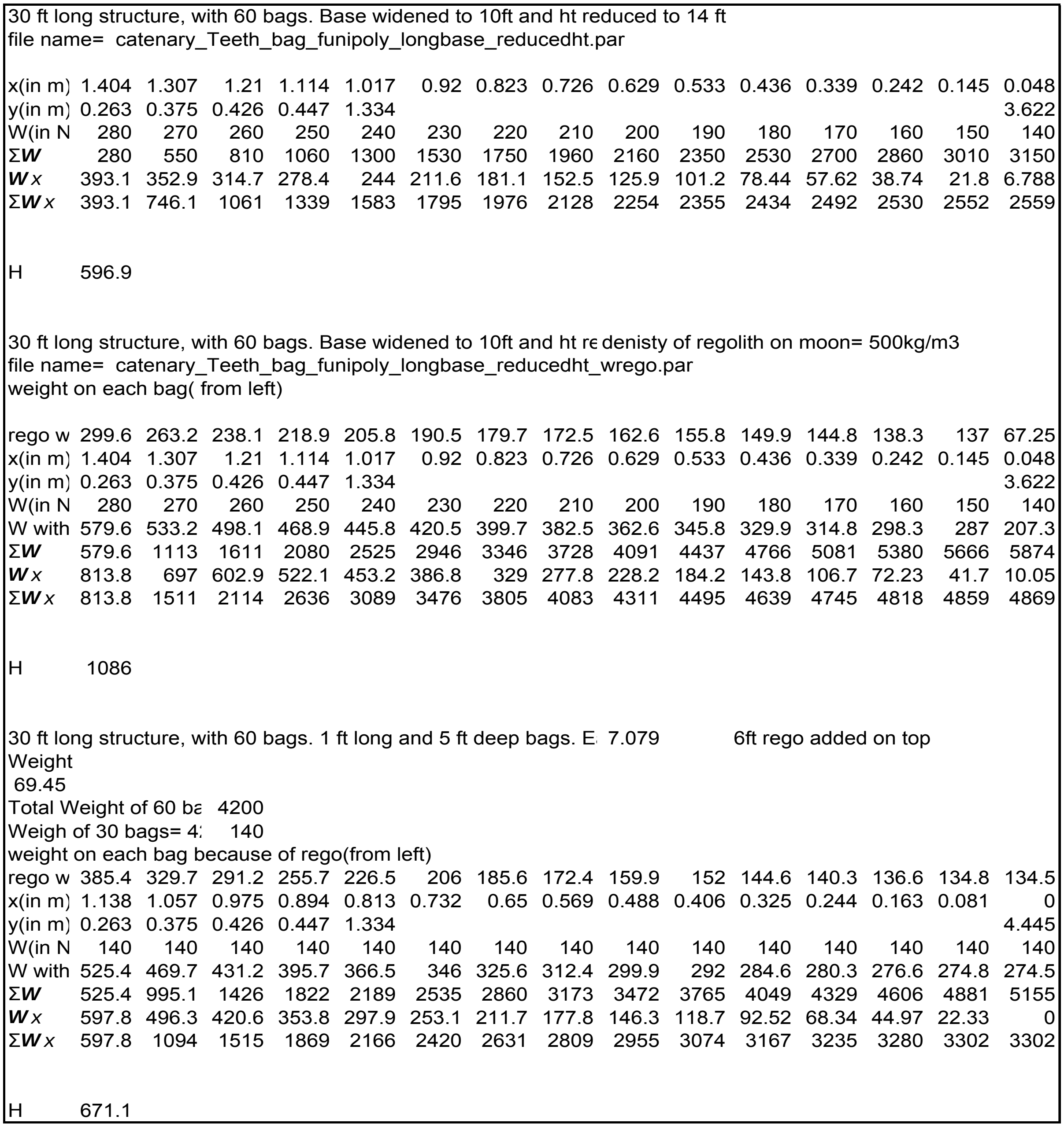
File Name= catenary_Teeth_bag_nasa_presentation_funipoly.par
30 ft long structure, with 60 bags. 1 ft long and 5 ft deep bags. E 7.079
Weight
69.4
Total Weight of 60 4200
Weigh of 30 bags= 140

x(in m	1.14	1.057	0.975	0.894	0.813	0.732	0.65	0.569	0.488	0.406	0.325	0.24	0.1626	0.081	0
y(in m	0.26	0.375	0.426	0.447	1.334										4.445
W(in	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140
Σ***W***	140	280	420	560	700	840	980	1120	1260	1400	1540	1680	1820	1960	2100
W*x*	159	147.9	136.6	125.2	113.8	102.4	91.03	79.65	68.28	56.9	45.52	34.1	22.758	11.38	0
Σ***W****x*	159	307.2	443.8	569	682.8	785.2	876.2	955.9	1024	1081	1127	1161	1183.4	1195	1195
H	307														

File Name= catenary_Teeth_bag_nasa_presentation_funipoly_thickbase.par
30 ft long structure, with 60 bags and wide base. 30 vertical forces assumed.

x(in m	0.94	0.889	0.838	0.787	0.737	0.686	0.635	0.584	0.501	0.417	0.334	0.25	0.1669	0.083	0
y(in m	0.26	0.375	0.426	0.447	1.334										4.445
W(in	280	270	260	250	240	230	220	210	200	190	180	170	160	150	140
Σ***W***	280	550	810	1060	1300	1530	1750	1960	2160	2350	2530	2700	2860	3010	3150
W*x*	263	240	217.9	196.9	176.8	157.7	139.7	122.7	100.1	79.29	60.09	42.6	26.705	12.52	0
Σ***W****x*	263	503.2	721.1	918	1095	1252	1392	1515	1615	1694	1754	1797	1823.6	1836	1836
H	451														

Excel Spread Sheet for 60 bag top connected structure



30 ft long structure, with 60 bags. Base widened to 10ft and ht reduced to 14 ft
file name= catenary_Teeth_bag_funipoly_longbase_reducedht.par

x(in m)	1.404	1.307	1.21	1.114	1.017	0.92	0.823	0.726	0.629	0.533	0.436	0.339	0.242	0.145	0.048
y(in m)	0.263	0.375	0.426	0.447	1.334										3.622
W(in N	280	270	260	250	240	230	220	210	200	190	180	170	160	150	140
Σ**W**	280	550	810	1060	1300	1530	1750	1960	2160	2350	2530	2700	2860	3010	3150
W*x*	393.1	352.9	314.7	278.4	244	211.6	181.1	152.5	125.9	101.2	78.44	57.62	38.74	21.8	6.788
Σ**W***x*	393.1	746.1	1061	1339	1583	1795	1976	2128	2254	2355	2434	2492	2530	2552	2559

H 596.9

30 ft long structure, with 60 bags. Base widened to 10ft and ht re denisty of regolith on moon= 500kg/m3
file name= catenary_Teeth_bag_funipoly_longbase_reducedht_wrego.par
weight on each bag(from left)

rego w	299.6	263.2	238.1	218.9	205.8	190.5	179.7	172.5	162.6	155.8	149.9	144.8	138.3	137	67.25
x(in m)	1.404	1.307	1.21	1.114	1.017	0.92	0.823	0.726	0.629	0.533	0.436	0.339	0.242	0.145	0.048
y(in m)	0.263	0.375	0.426	0.447	1.334										3.622
W(in N	280	270	260	250	240	230	220	210	200	190	180	170	160	150	140
W with	579.6	533.2	498.1	468.9	445.8	420.5	399.7	382.5	362.6	345.8	329.9	314.8	298.3	287	207.3
Σ**W**	579.6	1113	1611	2080	2525	2946	3346	3728	4091	4437	4766	5081	5380	5666	5874
W*x*	813.8	697	602.9	522.1	453.2	386.8	329	277.8	228.2	184.2	143.8	106.7	72.23	41.7	10.05
Σ**W***x*	813.8	1511	2114	2636	3089	3476	3805	4083	4311	4495	4639	4745	4818	4859	4869

H 1086

30 ft long structure, with 60 bags. 1 ft long and 5 ft deep bags. E 7.079 6ft rego added on top
Weight
69.45
Total Weight of 60 ba 4200
Weigh of 30 bags= 4 140
weight on each bag because of rego(from left)

rego w	385.4	329.7	291.2	255.7	226.5	206	185.6	172.4	159.9	152	144.6	140.3	136.6	134.8	134.5
x(in m)	1.138	1.057	0.975	0.894	0.813	0.732	0.65	0.569	0.488	0.406	0.325	0.244	0.163	0.081	0
y(in m)	0.263	0.375	0.426	0.447	1.334										4.445
W(in N	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140
W with	525.4	469.7	431.2	395.7	366.5	346	325.6	312.4	299.9	292	284.6	280.3	276.6	274.8	274.5
Σ**W**	525.4	995.1	1426	1822	2189	2535	2860	3173	3472	3765	4049	4329	4606	4881	5155
W*x*	597.8	496.3	420.6	353.8	297.9	253.1	211.7	177.8	146.3	118.7	92.52	68.34	44.97	22.33	0
Σ**W***x*	597.8	1094	1515	1869	2166	2420	2631	2809	2955	3074	3167	3235	3280	3302	3302

H 671.1

Excel Spread Sheet for 46 bag top connected structure under different load conditions

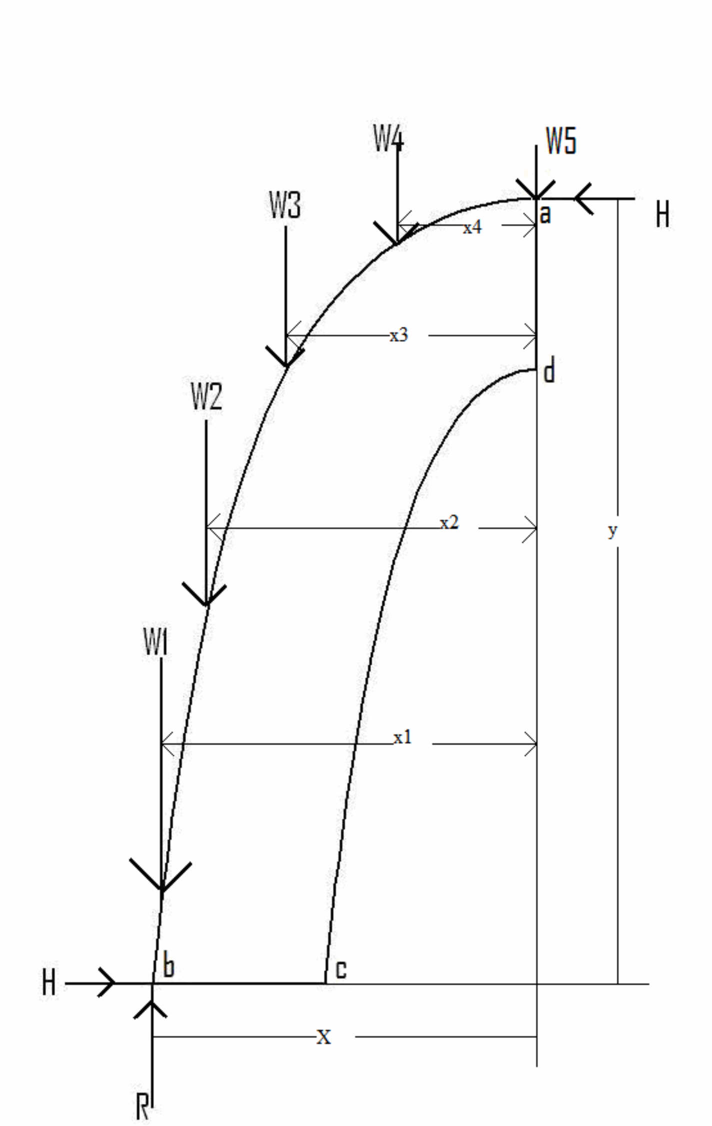
File name= catenary_Teeth_bag_10ftbase_8ftht_fpoly.par											
weight of 18 in bag=	95.49										
weight of 12 in bag=	63.66										
x(in m)	1.438	1.4	1.347	1.276	1.181	1.111	0.918	0.743	0.506	0.177	0
y(in m)											2.43
W(in N)	192	192	192	192	192	128	128	128	128	128	0
$\Sigma\mathbf{W}$	192	384	576	768	960	1088	1216	1344	1472	1600	1600
$\mathbf{W}x$	276.2	268.8	258.7	245	226.7	142.2	117.5	95.15	64.8	22.61	0
$\Sigma\mathbf{W}x$	276.2	545	803.6	1049	1275	1418	1535	1630	1695	1718	1718
H	390.8										

weight of 18 in bag=	95.49						
weight of 12 in bag=	63.66						
x(in m)	1.259	1.049	0.839	0.629	0.42	0.21	0
y(in m)							2.293
W(in N)	316.7	316.7	316.7	212.2	212.2	212.2	0
$\Sigma\mathbf{W}$	316.7	633.3	950	1162	1374	1587	1587
$\mathbf{W}x$	398.6	332.2	265.7	133.5	89.03	44.53	0
$\Sigma\mathbf{W}x$	398.6	730.7	996.5	1130	1219	1264	1264
H	477.9						

weight of 18 in bag=	95.49						
weight of 12 in bag=	63.66						
x(in m)	1.229	1.025	0.82	0.615	0.41	0.205	0
y(in m)							2.881
W(in N)	316.7	316.7	316.7	212.2	212.2	212.2	0
$\Sigma\mathbf{W}$	316.7	633.3	950	1162	1374	1587	1587
$\mathbf{W}x$	389.3	324.4	259.6	130.4	86.95	43.48	0
$\Sigma\mathbf{W}x$	389.3	713.8	973.3	1104	1191	1234	1234
H	410.8						

APPENDIX B

Derivation of Equation 5



where,

H= Horizontal thrust acting on the arch

R= Reaction force due to the vertical loads acting on the arch

x= half the span of the arch

W_1, W_2, W_3, W_4, W_5 = Vertical loads acting on the arch

x_1, x_2, x_3, x_4, x_5= x_1 is the distance on x-axis between W_1 and the line "*ad*". Other distances are defined similarly

y= The vertical distance between point *"a"* and point *"b"*

Calculating the moment about point *"a"* gives

$$(W_1 * x_1 + W_2 * x_2 + W_3 * x_3 + W_4 * x_4 + W_5 * x_5 + H * y - R * X = 0$$

Now from force equilibrium we get

$$(W_1 + W_2 + W_3 + W_4 + W_5) = R$$

Solving these 2 equations we get

$$H = \frac{(W_1 + W_2 + W_3 + W_4 + W_5) * X - (W_1 * x_1 + W_2 * x_2 + W_3 * x_3 + W_4 * x_4 + W_5 * x_5)}{y}$$

This can be written as

$$H = \frac{(\sum_{i=1}^{5} W_i) * X - (\sum_{i=1}^{5} W_i * x_i)}{y}$$, which gives us Equation 5

APPENDIX C

Model of some structures developed for 60 pocket top connected bags

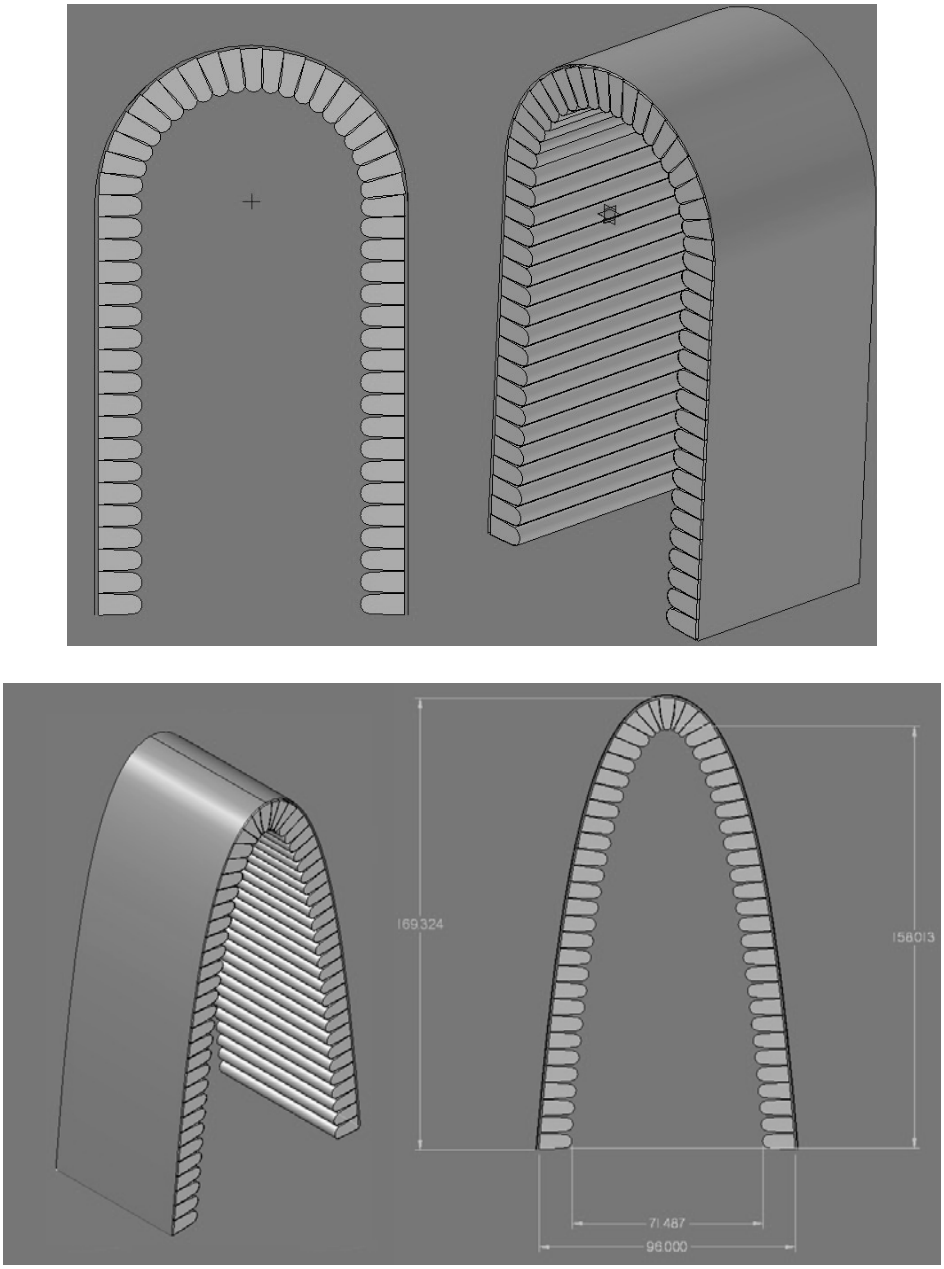


Figure showing the position of each bag on the 46 bag structure developed at MSFC