FIBROUS TECTONICS

by
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Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Architecture Studies

at the
Massachusetts Institute of Technology
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00 /// ABSTRACT

The inherent possibilities of composites present an exciting frontier in architecture that has remained largely untapped. In light of the current computational capacities and new digital tools in manufacturing, composites are just beginning to re-situate themselves in the field of architecture. Efficiency and durability coupled with a load bearing capacity make a strong case for the use of composites as a primary building material.

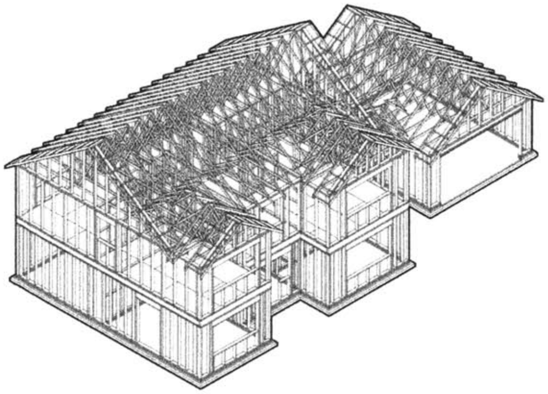
We now possess the computational and digital manufacturing tools that make the development of a composite building viable.On a holistic level, the research has concerned itself with an overarching focus on developing a composite building which minimizes the required costs and labor while simultaneously creating the potential for customized forms. Based on the concepts of mass customization, when the workflow from digital conception to digital production is seamless, a variety of composite structures can be produced at no greater expense. This potential for an efficient "one off" composite architecture empowered by digital manufacturing and computation, is where the research is positioned

At present, the research has been focused on exploring surface composite structures through a reinvention of the 'mold'. This approach has involved using inflated bladders, rather than traditional molds of milled foam or aluminum in order to produce composite structures. In doing so, the benefits of inflatables are all encompassing. Not only do they allow for inexpensive transportation and rapid deployment, but they also lend themselves to the production of large scale structures through the simple use of air and pressure, thus minimizing both material and effort. This lies in stark contrast to traditional composite manufacturing techniques which require molds to be milled out of solid aluminum blocks or high density foam volumes, whereas inflatable molds are easily heat seamed and inflated. When considering issues of scalability, traditional molding techniques demand significantly more labor, material, and with that, overarching costs. Inflatable molds however, require only more air.

Coupled with the rethinking of molding techniques is a consideration in the technological methodologies in order to produce such composite structures. The research looks to the new developments in the composite industry, such as Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM). These processes greatly simplify the manufacturing of composites and eliminate much of the manual labor traditionally associated with composite structures. By taking advantage of the existing vacuum bag used for compaction while producing composites, the VARTM process pulls resin through the bag under vacuum pressure, thus wetting out the fibers and eliminating typical layup deficiencies while producing a nearly weightless composite structure.

CONTENT

01 // THESIS



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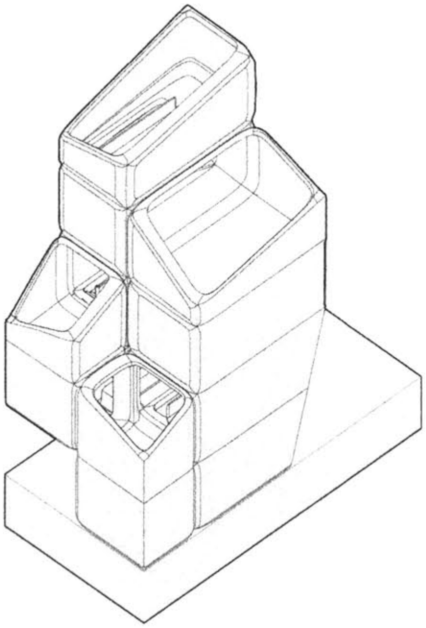
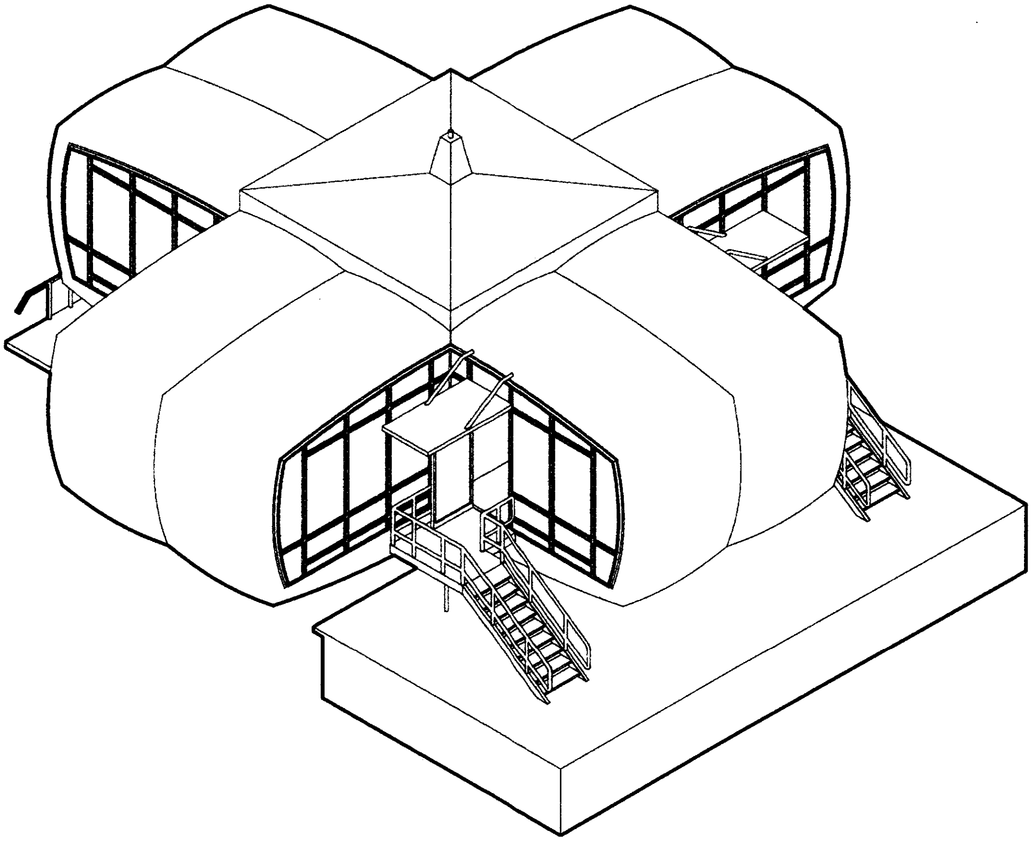


1.1 /// Research Question

How can we make composite materials mainstream in architecture?

My thesis has evolved over the last two years through full-scale exploration of composite manufacturing techniques. My work thus far, has been to develop a composites workflow that can be effectively applied within the field of architecture. Composite materials are readily used in other fields, but have remained primarily underdeveloped in architecture. This is due to the unique requirements of architecture, such as site constraints, varying programs, and clients, as opposed to the requirements needed in the automobile or aeronautics industries. The research combines pneumatic molds with the process of VARTM (vacuum assisted resin transfer molding) in order to reduce production costs, increase efficiency, and produce functional variance.

Monsanto House of the Future 1958



1.2 /// Why Composites

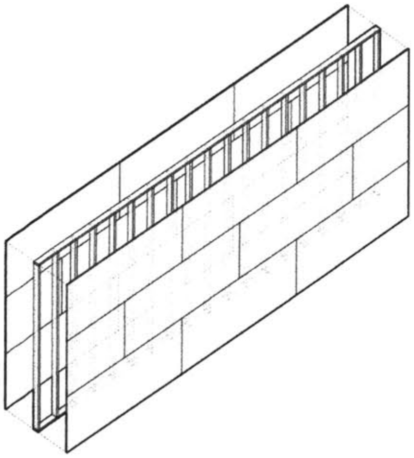
Composites are built upon the premise that distinctive material categories can be combined, to form a greater material that is more than the sum of its individual parts. In other words, by combining the material properties, some which are strong in tension and others which are strong in compression, a superior material can be created. The first composite ever produced was adobe brick. It combined straw, which is a fiber and therefore strong in tension, with mud, which is strong in compression as a matrix. Adobe construction provides excellent thermal mass and is extremely durable and accounts for some of the oldest standing structures in the world.

1.21. Monsanto House

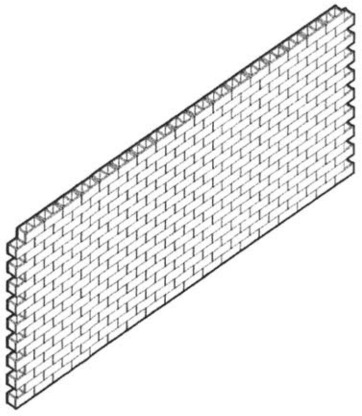
The Monsanto House of the Future, designed by Marvin Goody & Richard Hamilton, was the first of very few precedents for high-performance, composite buildings. Sponsored by Monsanto, petrochemical company, the Monsanto House was built in 1958 from fiberglass composites and challenged the accepted notions of building materials and construction. The form of the house was based on a requirement that all the composites sections could be produced using the same mold resulting in the biaxial symmetry. Due to the one-off nature of the house, and the manually intensive and expensive construction, it was not a viable housing concept at the time.

When the Monsanto House was scheduled for demolition in 1967, the process proved to be immensely difficult and took over two weeks. The wrecking ball bounced off of the exterior composite shell, unable to destroy the home. In order to remove the house, it was deconstructed, and cut into many pieces to be removed.

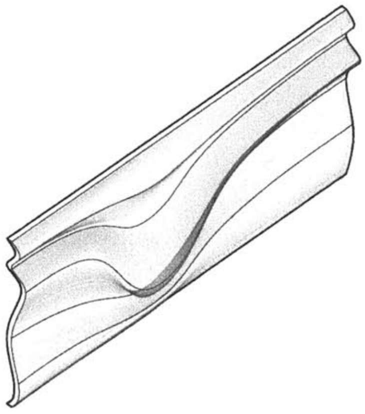
WOOD STUD WALL
WEIGHT 840 LBS



CMU WALL
WEIGHT 5800 LBS



COMPOSITE WALL
WEIGHT 230 LBS



1.3 /// Composite Advantages

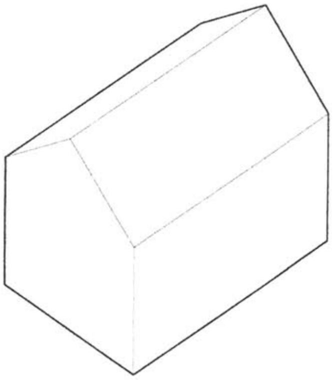
Composite materials present many advantages and possibilities that make them compelling within the field of design. However, it is important to note that being a material which has been adopted from other fields, composites require a disparate set of criteria for their application within architecture. Rather than imitating methods of evaluation from other industries, architects and designers must form their own. For example, in the field of high end sailboats where composites have been used for many years, companies spend millions of dollars in order to achieve a lighter product by only a few hundred pounds. However in there is chance to negotiate a wide variety of trade offs in order to efficiently and economically tailor these new materials specifically to the needs and interests of the field of architecture.

In relation to traditional building materials, composites transcend many of the typical concerns. The most widely known advantage is the strength to weight ratio whereby resulting composite structures are able to achieve supreme thinness and unparalleled lightness. This ultralight advantage simplifies transportation of materials to site and their subsequent handling. This means, an entire building can potentially be brought to site at one time and then erected into place with minimal equipment. Architects have been limited by the capacity of traditional building materials, but composite materials extend these limitations.

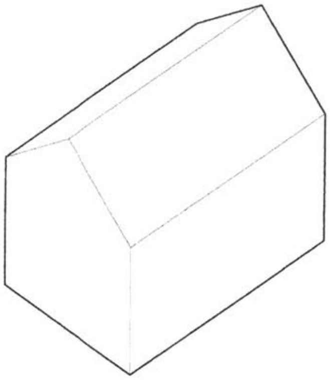
1.3.1 Lightweight

High performance composite materials boast an extreme strength to weight ratio which can be accredited to the tensile strength of glass and carbon fibers. The weight of building materials has a great effect on how they can be used in architecture. The lightweightedness of composite materials could allow for rapid building construction, while reducing the amount of equipment needed to move materials around the building site. This lightness also simplifies the shipping of materials to the building site, reducing transportation costs and number of deliveries.

There is a significant weight difference between typical building materials and plastics. A typical wood stud construction, of 12 ft x 24 ft made of 2" x 4" wood studs on 16" increments, clad in plywood sheathing and drywall, weighs approximately 840 lbs. In comparison a typical CMU wall of the same dimensions weighs approximately 5800 lbs. This does not include the rebar or infill concrete that would be required to make it structural and load bearing. In contrast, a composite wall, again of the same dimensions, consists of three to seven composite layers on both sides of a 2" inch thick foam core. Its weight is only a few hundred of pounds. Until we begin to build with these new materials however, it is impossible to fully understand the implications that such reduced weight may have on architecture and construction.



2015 C.E.



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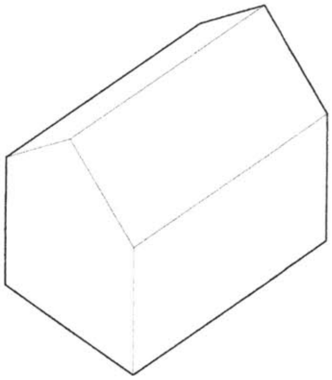

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1.3 /// Composite Advantages

1.3.2 Long Lifespan

Another important advantage of composites is the extremely long life span that requires little or no maintenance.

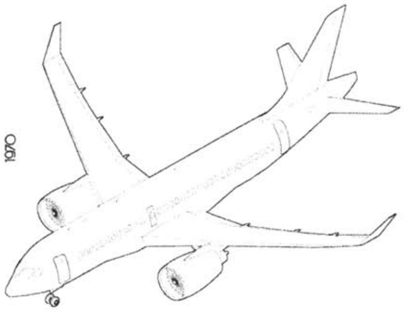
The matrix that transfers the loads between the fibers in a composite are made of polymers. Some polymers can be reheated and recycled, but their inability to biodegrade is highly criticized. This long lifespan however, can be considered an advantage. Polymers are infamous for polluting our oceans and shores ie. Great Pacific Garbage Patch, they are resistant to weather, chemicals, water, etc., and have a tendency to be indestructible and impossible to dispose of.

When plastics were first introduced into mainstream American culture the world was in a very different place; oil was cheap and plastic was unlimited. The introduction of plastic during this environment lead to a mentality and culture that has been ingrained. Driven by the idea that plastic is cheap and disposable, it has become a representation of the excessive. Plastic has become a synonym of cheap and a description of poor quality, "plasticy". However, it is important that these misconceptions clouding the reputation of plastic are cleared, and its true value redefined.

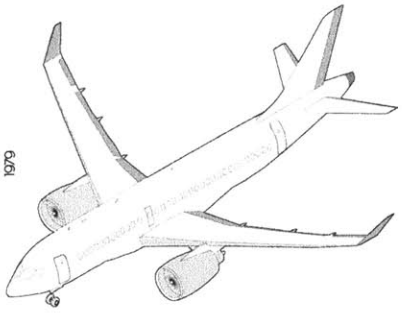
We consume plastic at incomprehensible levels, from our daily use of plastic bags and tupperware, to packaging and bottles. It is as though we do not realize that it is one of the longest lasting materials created. Other materials such as wood rot and even steel will rust.

The shift in many airlines companies to use composites and polymers results primarily from their long lifespan with very little maintenance resulting in immense cost savings over aluminum.

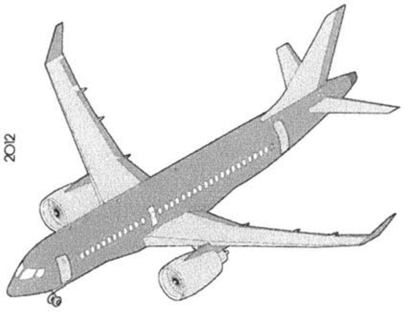
BOEING 747
PARTS : 6 MILLION
ASSEMBLY 4 MONTHS



BOEING 767
PARTS : 3.1 MILLION
ASSEMBLY 3 WEEKS



BOEING 787
PARTS : 10 - 15
ASSEMBLY 3 DAYS



1.3 /// Composite Advantages

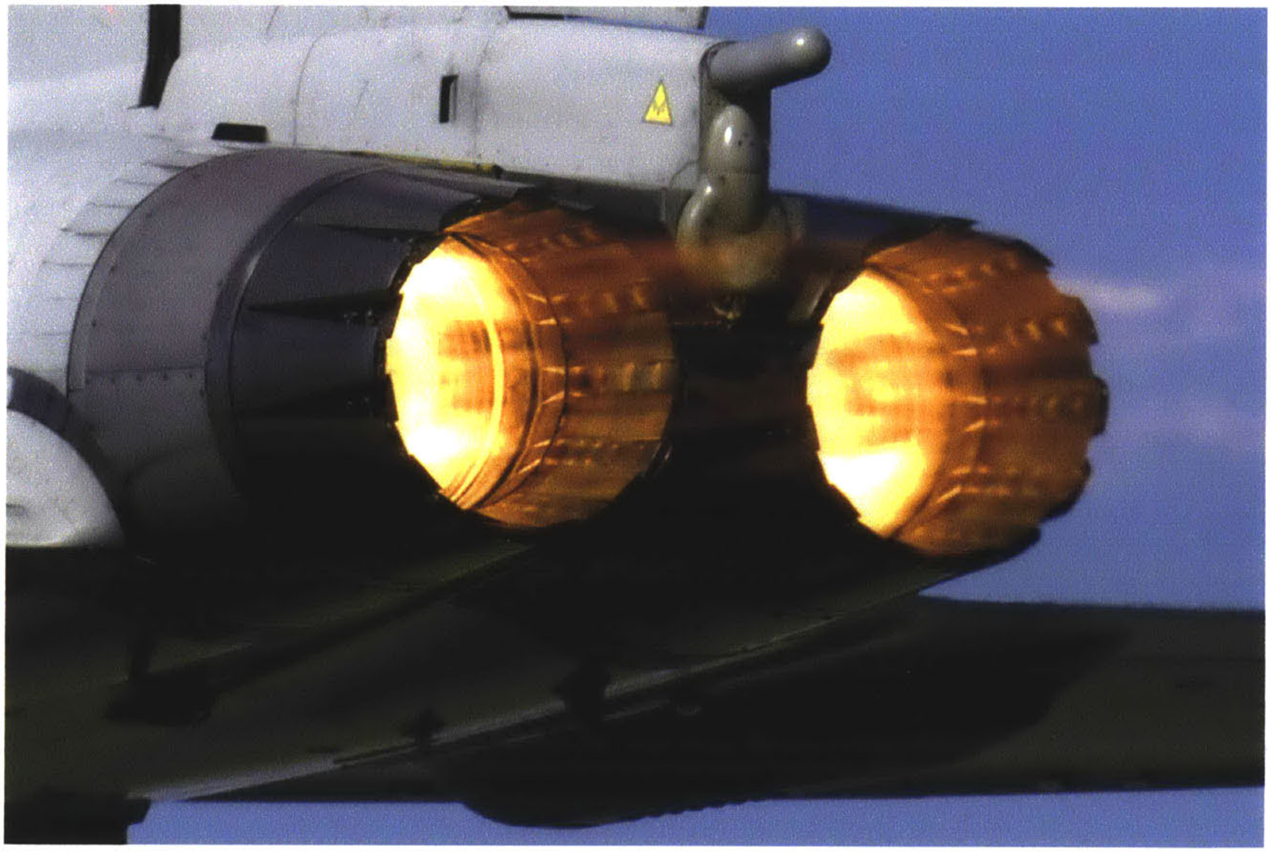
1.3.3 Increased Capacity

Composites' are constructed of molded panels, allowing for extremely complex geometries to be produced in a single panel. Considering that fasteners and assembly account for half of the total cost of a composite part the capacity to introduce the complexity within the part, reducing the number of fasteners and amount of assembly, could make composites more economical.

Traditionally structures made of wood or steel are broken down. They are then cut into individual parts and assembled, either by welding, gluing or connecting with fasteners. Even in constructing the simplest building, thousands of parts are required and a single joint may consist of hundreds of individual components. When it comes to composites and plastics, extremely complex joints or assemblies can be made at one time. This consolidation simplifies the assembly process and allows the potential for an entire house to be constructed with only a handful of essential parts.

We have always been bound by the limits and capacity of our materials. Due to material limitations, traditional dwellings range from two to three stories in height. Whereas with composite materials the same limitations do not apply. Wood joists have a certain span in which they are efficient, and plywood has a certain distance upon which deflection is negligible. However with composites, these spans are greatly increased. A 12" wood joist and an 8" inch thick concrete slab can be replaced by a 4" thick composite.

The Composites Exhaust of a Fighter Jet Airplane



http://upload.wikimedia.org/wikipedia/commons/2/26/A_Typhoon_F2_fighter_ignites_its_afterburners_whilst_taking_off_from_RAF_Coningsby_MOD_45147957.jpg

1.4 /// Composite Stigmas

Many limitations that have prevented composites from becoming a viable building material stem from the numerous misconceptions that have been harbored through decades of previously unsolved problems. In the past, composites were stereotyped and stigmatized by early concerns originating from high toxicity, consistent off gassing, and poor UV ray resistance. However, in recent years composites have evolved quickly and through consistent use and research, many of the previous downfalls have become obsolete. New and innovative solutions are constantly being developed today to address composites' shortcomings, such as the use of low VOC resins, UV resistant resins as well as fire rated resins.

Because the materials involved in composites are critical to many industries outside of architecture such as the aerospace, automotive, and marine industries , many large international organizations and companies are quite invested in the success and performance of these materials. NASA, Boeing, Airbus, and BMW, just to name a few, all have 'Research and Development' departments aiming to extend the capacities of composite materials and resolve any shortcomings. The innovations and findings developed by these satellite industries, in particular with fiber and matrix systems, can be utilized and perhaps even further developed, in the field of architecture.

Of particular interest is the ongoing research on methods and alternatives for more environmentally friendly materials. There has, for instance, been significant development in the utilization of natural fibers such as flax, rather than synthetic fibers like glass fiber. In addition to this, matrices have evolved from using thermosets to thermoplastics, which can be recycled to emerging natural bio resins. In the next five to ten years the possibility to produce natural composites will be readily available as they will not only be easier and safer to build with, but they will also become cheaper as synthetic, petro fibers become more and more expensive.

BOEING

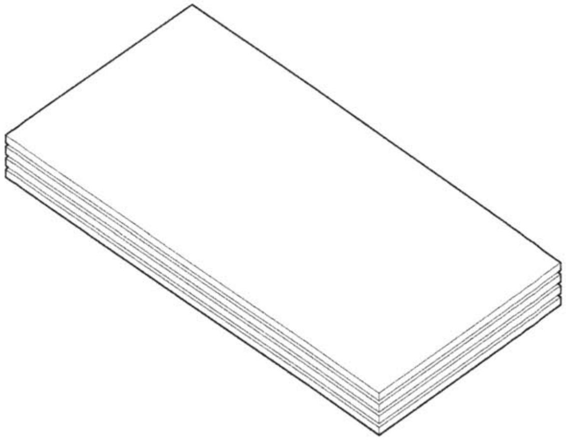
BMW

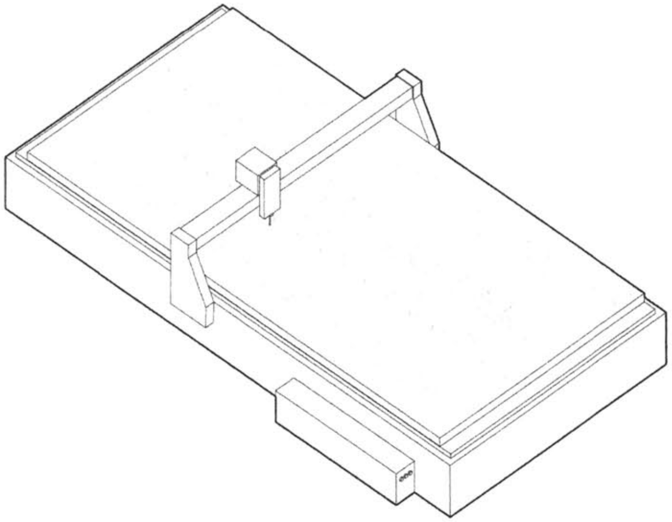
SIEMENS

America's Cup

NASA

CNC Fabricated Composite Mold



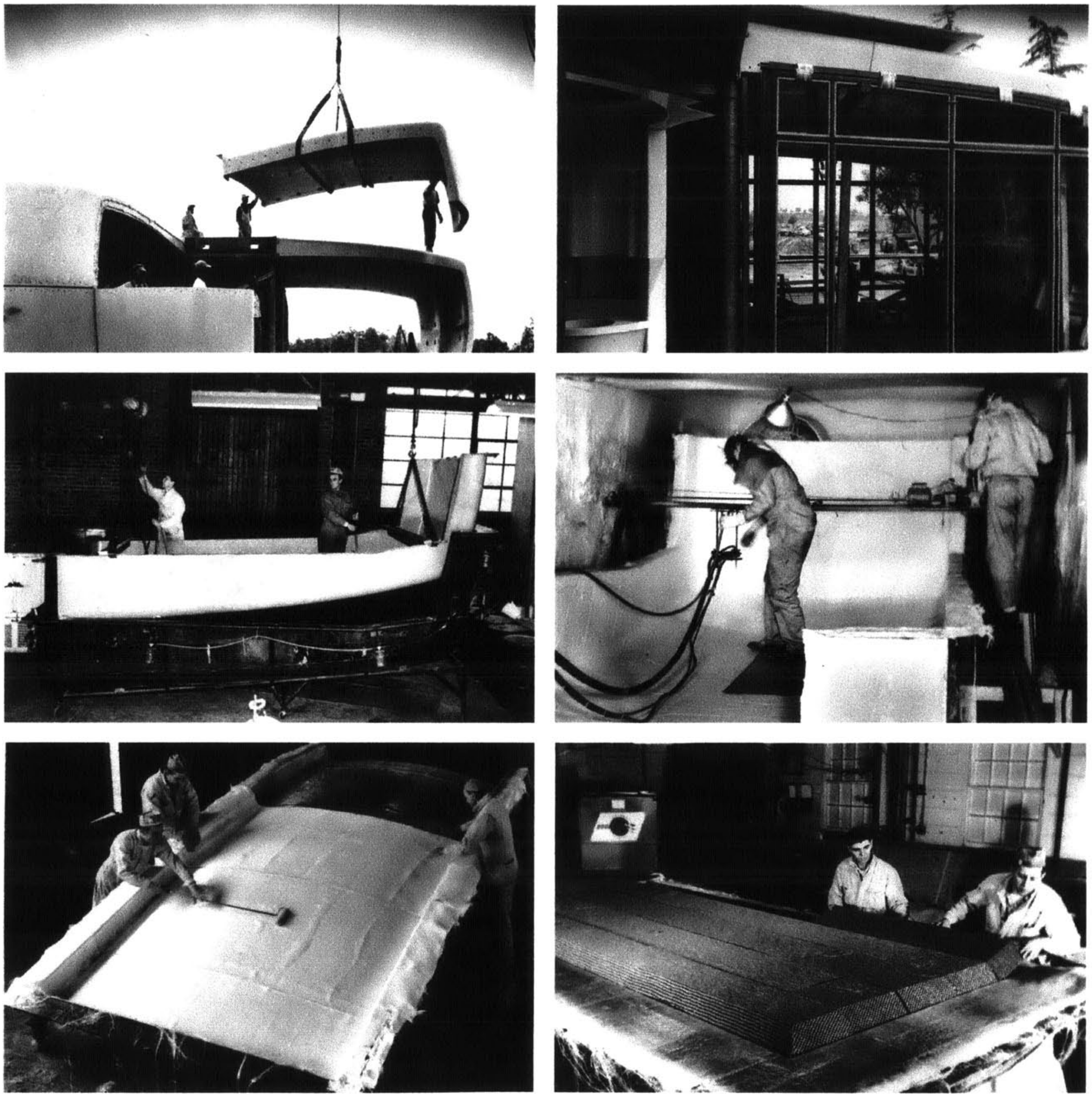


1.5 /// Composite Limitations

1.5.1 Mold Scalability & Customization

Architecture presents an interesting challenge in that nearly every built project is unique. When we discuss automotives like the BMW i3 or Aerospace's Boeing 787 dreamliner, an economy of scale exists. Every BMW i3 chassis is exactly the same just as every Boeing 787 dreamliner is exactly the same. In architecture, a building must resolve the requirements of a specific site, specific program, and specific client, resulting in a custom product.Thus far, molds have been a large inhibitor to the integration and deployment of composites in architecture, particularly at a large scale, due to high costs and slow production times. However, as a result of digital manufacturing, molds are increasingly becoming cheaper and faster to produce. Innovation in mold production will be the deciding force on whether composites can become mainstream within architecture.

Traditional Construction of Monsanto House of the Future



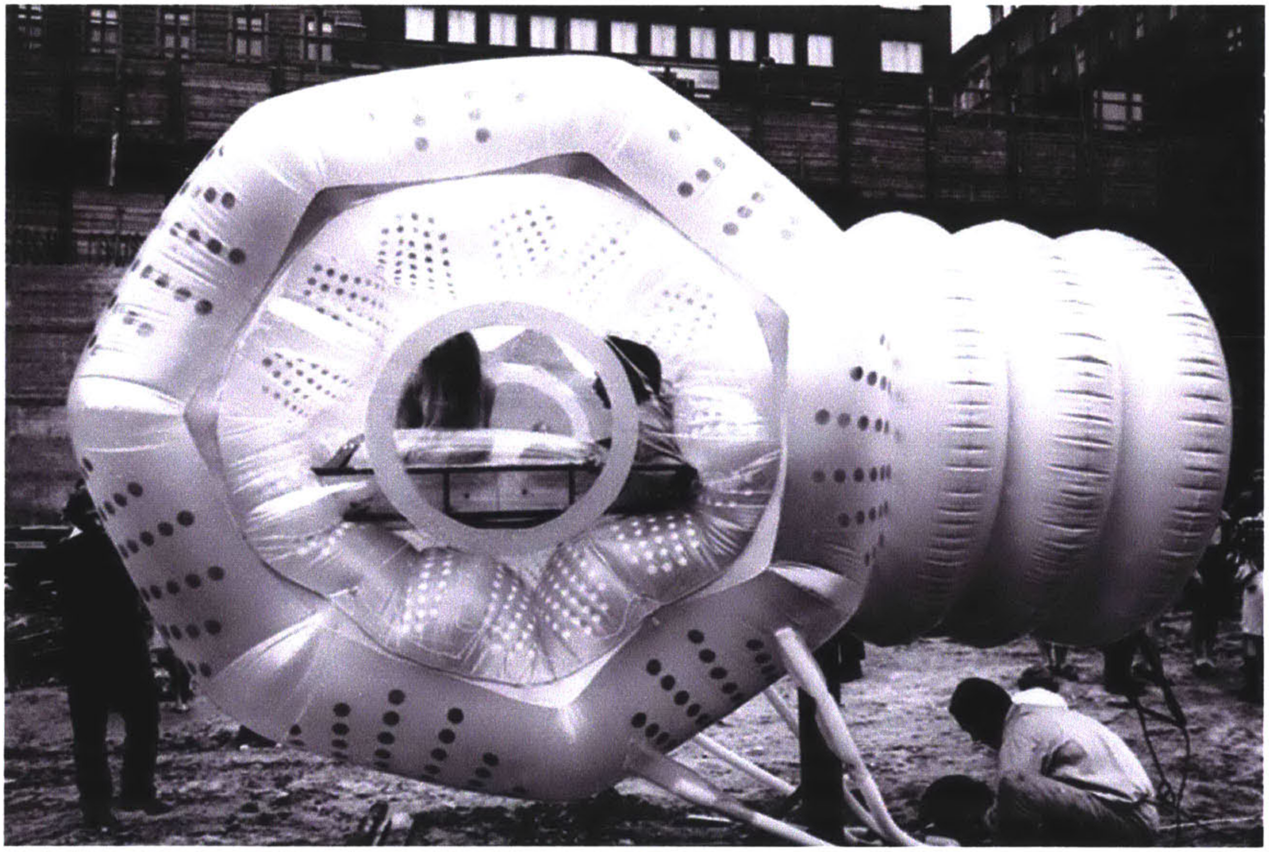
Whittier, R. P. *Engineering Analysis and Structural Design of the Monsanto House of the Future*. Springfield, MA: Monsanto Chemical, 1957. Print.

1.5 /// Composite Limitations

1.5.2 Traditional Manufacturing

A typical composite part begins with the production of a mold. The geometry of the part is usually CNC milled out of a large sheet of foam. The many foam parts are then assembled and coated with a gel coat that seals the foam and provides a high surface quality for the part. The completed mold typically is used in one of three main processes: hand or wet layup, wet layup compression molding, vacuum bagging wet layup. These processes require the manual wetting out and collation of plys driving up cost and production time. This is even more pronounced as the scale of the part increases. Small parts on the order of a few square feet can be achieved with these manually intensive processes. As the parts begin to expand into the realm of automobiles, turbine blades, and eventually in architecture, the discrepancy of time and cost between manual and automated manufacturing increases exponentially.

Yellow Heart by Archigram 1968

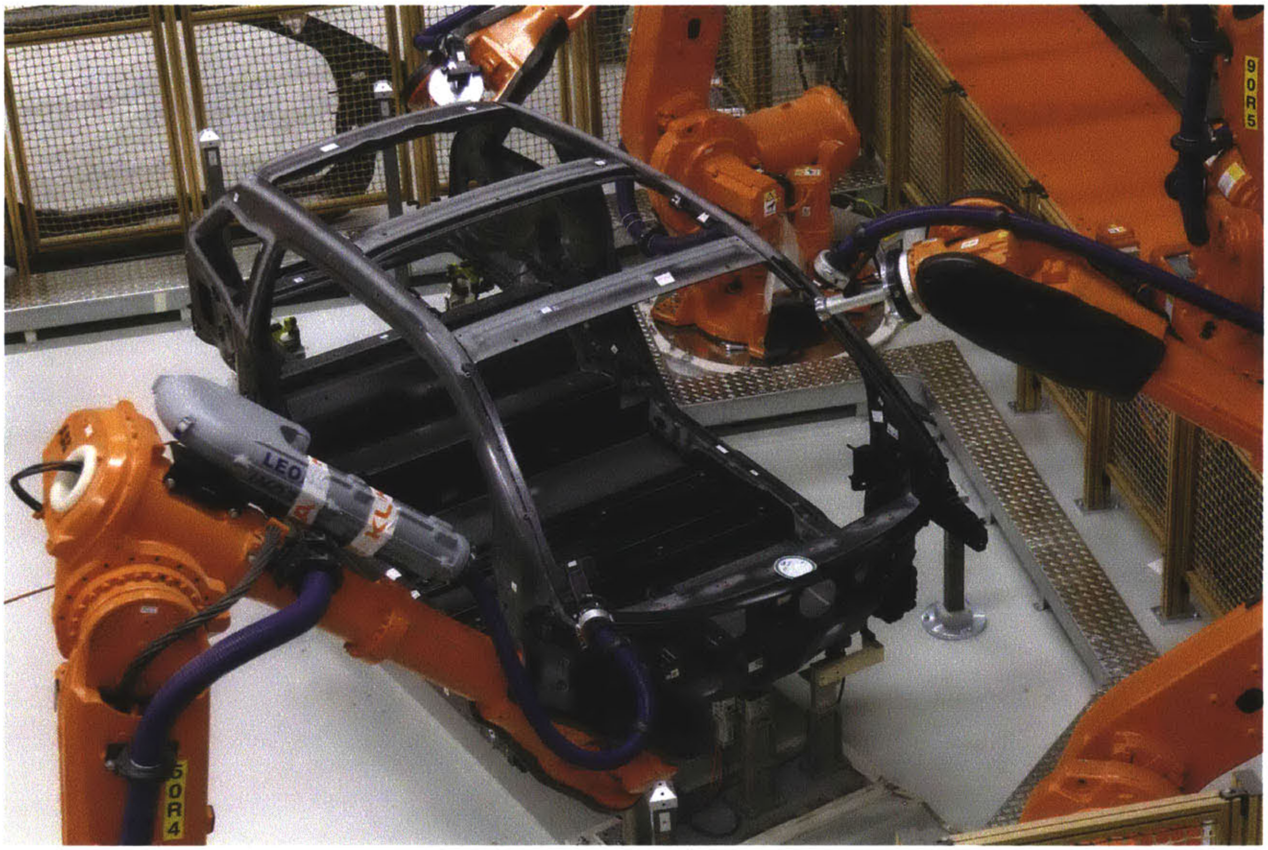


http://loves.domusweb.it/wp-content/uploads/2014/07/gelbes_herz_61.jpg

1.6 /// Proposed Solution

1.6.1 Pneumatic Molds

Pneumatic structures have a long history in proto-architecture offering the promise of inexpensive transportation and rapid deployment and scalability. By capitalizing on the simple use of air and pressure, with minimum effort and materials, inflated bladders can produce spaces of an architectural scale. Typically, pneumatic structures require constant pressure but the use of inflated bladders such as molds in a composites workflow capitalizes on the advantages of pneumatic structures while coupling it with the rigidity and structural capacity of composite materials.



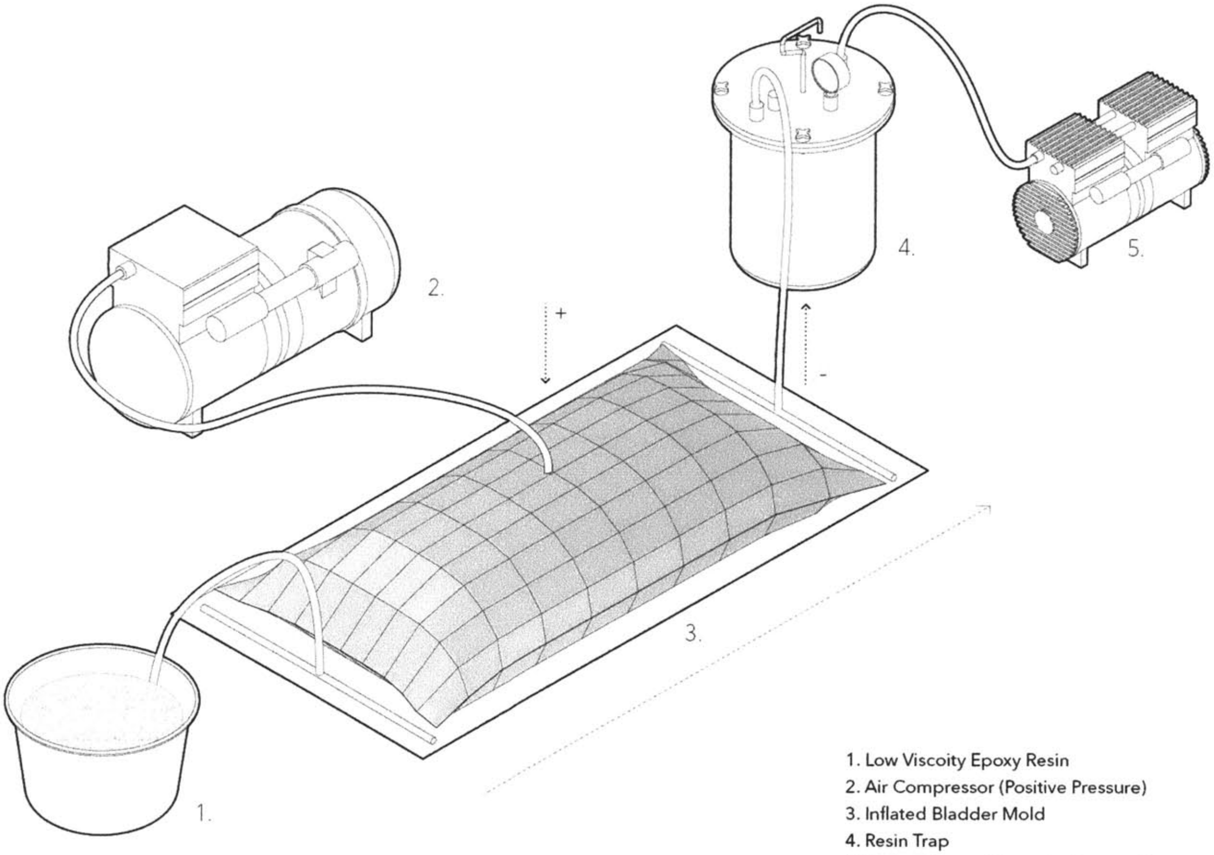
http://designapplause.com/wp-content/xG58hlz9/2013/09/bmw13-i3-81.png

1.6 /// Proposed Solution

1.6.2 Advanced Manufacturing

The possibility of a composite architecture has only become feasible within the past five years as digital manufacturing and ideas of mass customization have become integrated into everyday practice. For example, automated tape placement has allowed for the first fully composite fuselage, eliminating the more typical, manually intensive processes. The benefit of this transition from manual to automated is clearly demonstrated by automobile assembly lines, which are continuously becoming more autonomous. The digital manufacturing paradigm has allowed the efficiency and accuracy of robotics to accelerate production in many fields, and will similarly allow composites to become active participants within the field of architecture.

Vacuum Assisted Resin Transfer Molding with Inflated Mold



1. Low Viscoity Epoxy Resin
2. Air Compressor (Positive Pressure)
3. Inflated Bladder Mold
4. Resin Trap
5. Vacuum Pump (Negative Pressure)

1.7 /// The Approach

The research combines bio-composites and pneumatic molds with the process of VARTM (vacuum assisted resin transfer molding) in order to reduce production costs, increase efficiency, and produce functional variance.

1.7.1 Bio-Composite

The research utilizes burlap fabric as a natural fiber for reinforcement in the composite. As an economical and safe material, it was ideal for prototyping geometries and methods. As the matrix for the composite I used a high bio content, low viscosity epoxy resin.

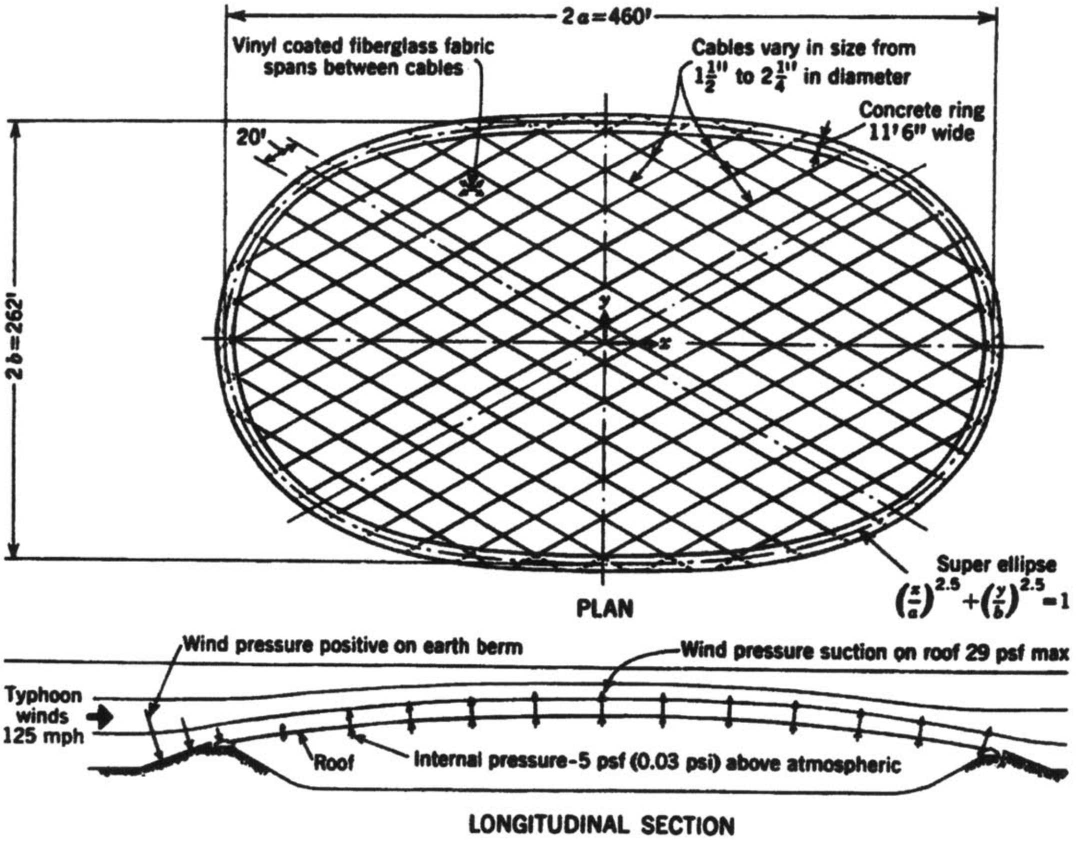
1.7.2 Pneumatic Molds

Pneumatic molds can produce architectural scale spaces using minimal amounts of material with the simple use of air and pressure. In the research I use chemically welded vinyl coated polyester fabric to make the bladder, or the pneumatic mold, which is internalized in the composite preform. Once inflated the bladder takes on a taught rigid surface on which the composite can be compressed.

1.7.3 VARTM

Vacuum assisted resin transfer molding is a process which already exists in the composites manufacturing industry. It has started to take root over the last five years as a possible replacement and alternative to the long standing autoclave compaction cure, by promising equally robust parts at a fraction of the cost. VARTM greatly reduces the time and cost by utilizing the nylon vacuum bag, typically used to compact a hand wet layup, and infusing the the the dry fibers by pulling the resin through and across the fibers using the vacuum needed for compaction. This process, in which resin is pulled through the fibers, greatly reduces the amount of air voids in the part, significantly increasing its strength. The most promising aspect of VARTM is the potential to scale up from 3 meter boats to 200 meter turbine blades.

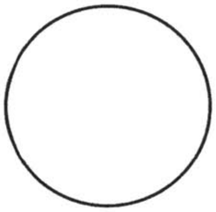
02 // PNEUMATIC STRUCTURES

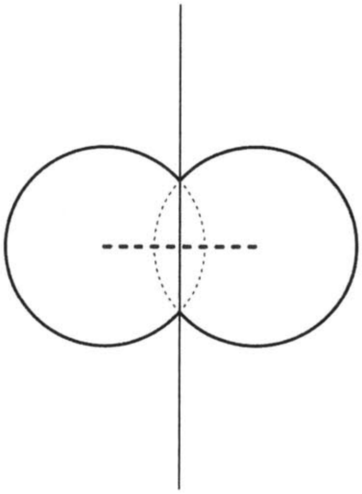

2a=460'
Vinyl coated fiberglass fabric spans between cables
Cables vary in size from 1½" to 2¼" in diameter
Concrete ring 11'6" wide
20'
2b=262'
y
x
PLAN
Super ellipse $\left(\frac{x}{a}\right)^{2.5}+\left(\frac{y}{b}\right)^{2.5}=1$
Wind pressure positive on earth berm
Wind pressure suction on roof 29 psf max
Typhoon winds 125 mph
Roof
Internal pressure-5 psf (0.03 psi) above atmospheric
LONGITUDINAL SECTION

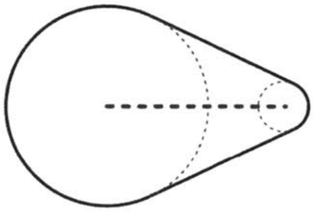
2.1 /// History of Pneumatics

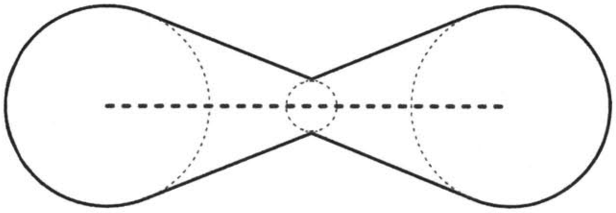
Pneumatics have a long history in proto-architecture. They emerged in the the mid 20th century alongside the development of petroleum based plastic products that allowed for the relatively effective and economical encapsulation of air. Pneumatics were used throughout World War II as decoy tanks and ships but were not popularized in architecture until the late 60's as demonstrated in the speculative work of Archigram in 1968. Pneumatics were not widely considered as a viable construction technique until the US pavilion at the 1970's world expo in Osaka, Japan.

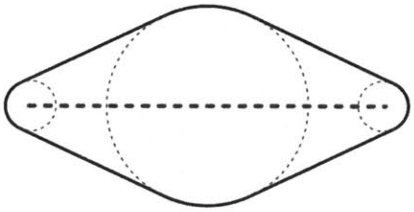
Opposite Page:
http://www.arch.mcgill.ca/prof/sijpkes/Downloads/United-States-Pavilion-1970-World-Exposition-Osaka-Japan-4.jpg











2.2 /// Equal Pressure Geometries

It is imperative to understand the geometries dictating pneumatic shapes in order to design with them.

Equal pressure geometries can be defined as a sphere or the result of a series of swept spheres of any size. If you take a sphere and divide it uniformly into 100 quadrilateral shapes and apply the same amount of pressure normal to the surface of each of the 100 quadrilateral shapes the resulting geometry would still be a sphere. This cannot be said for any other shape. If the same experiment were conducted with a cube or a cone, the large planar surfaces would billow out and the rigid edges of the cube or cone would begin to cave in. The billowing out of the planar surfaces is an attempt to approximate an equal pressure shape ie. the sphere. For example, though a cone is not an equal pressure geometry, a cone with a spherical base is an equal pressure geometry. This shape can also be described as a sphere that decreases in diameter along a rail infinitely.

Inflatable Dam In Downtown Tempe, Arizona

http://archive.azcentral.com/i/E/5/F/PHP4D715350DFF5E.jpg

2.3 /// Adavantages of Pneumatics

Pneumatic structures offer the promise of inexpensive transportation, rapid deployment and scalability while remaining materially and economically sensible. Its applications have included deployable rafts to hydro-infrastructure such as the inflatable dam in downtown Tempe, Arizona. Typically, pneumatic structures are constructed from a thermoplastic film or infused fabric for more intensive applications. The use of thermoplastics allows for the reheating necessary to weld the airtight seams.

Inflatable Dam In Downtown Tempe, Arizona.

http://www.digitaljournal.com/img/2/2/5/9/9/9/i/7/4/6/o/Dam_Burst.jpg

2.4 Disadvantages of Pneumatics

In spite of the the many advantages, pneumatic structures have a few key disadvantages. First, they require constant pressure; meaning they leak and require continuous inflation to maintain their geometry. This necessity for constant inflation has plagued pneumatics and has prevented them from becoming permanent structures. Part of this temporal nature can be attributed to its material fragility. Most often, pneumatics are made from less than a millimeter of plastic film, which has the tendency to develop small leaks. As result, they have been more effective as temporary and episodic structures rather than durable and permanent ones.

03 // COMPOSITE FIBERS

3.1 /// Fiber Materials

3.1.1 Glass

Fiberglass is known for its low cost, high tensile strength (4000 MPa or 500 KSi) and good chemical resistance. Fiberglass is made primarily from silica sand and limestone with a small amount of other ingredients depending on the material properties. The materials are mixed dry and melted in a high temperature refractory furnace. The fiber is then drawn out from the molten glass. Because of the fragility of the individual fiber, the fibers are typically combined into rovings to make them easier to work with. If the roving is going to be used to weave a fabric, the roving is then twisted to form a yarn.

3.1.2 Kevlar

Kevlar is positioned between glass and carbon in regards to cost and material properties such as stiffness, strength and weight. Kevlar fibers are organic fibers made by reacting paraphenylene diamine with terephthaloyl chloride. Kevlar is most known for its impact resistance and fire resistance, used in ballistics and for bulletproof vests and hard hats. But because the fibers are organic, Kevlar fabric will deteriorate as it absorbs surrounding moisture.

3.1.3 Carbon

Carbon fibers have the highest tensile strength, stiffness and toughness while maintaining an extremely lightweightedness. Carbon fiber is made from PAN or poly-acrylo-nitrile or petroleum-based-pitch. Carbon fibers come in untwisted bundles called tows. Tow sizes can start as small a 1000 fibers per tow designated as 1k to 200,000 fibers per tow (200k).

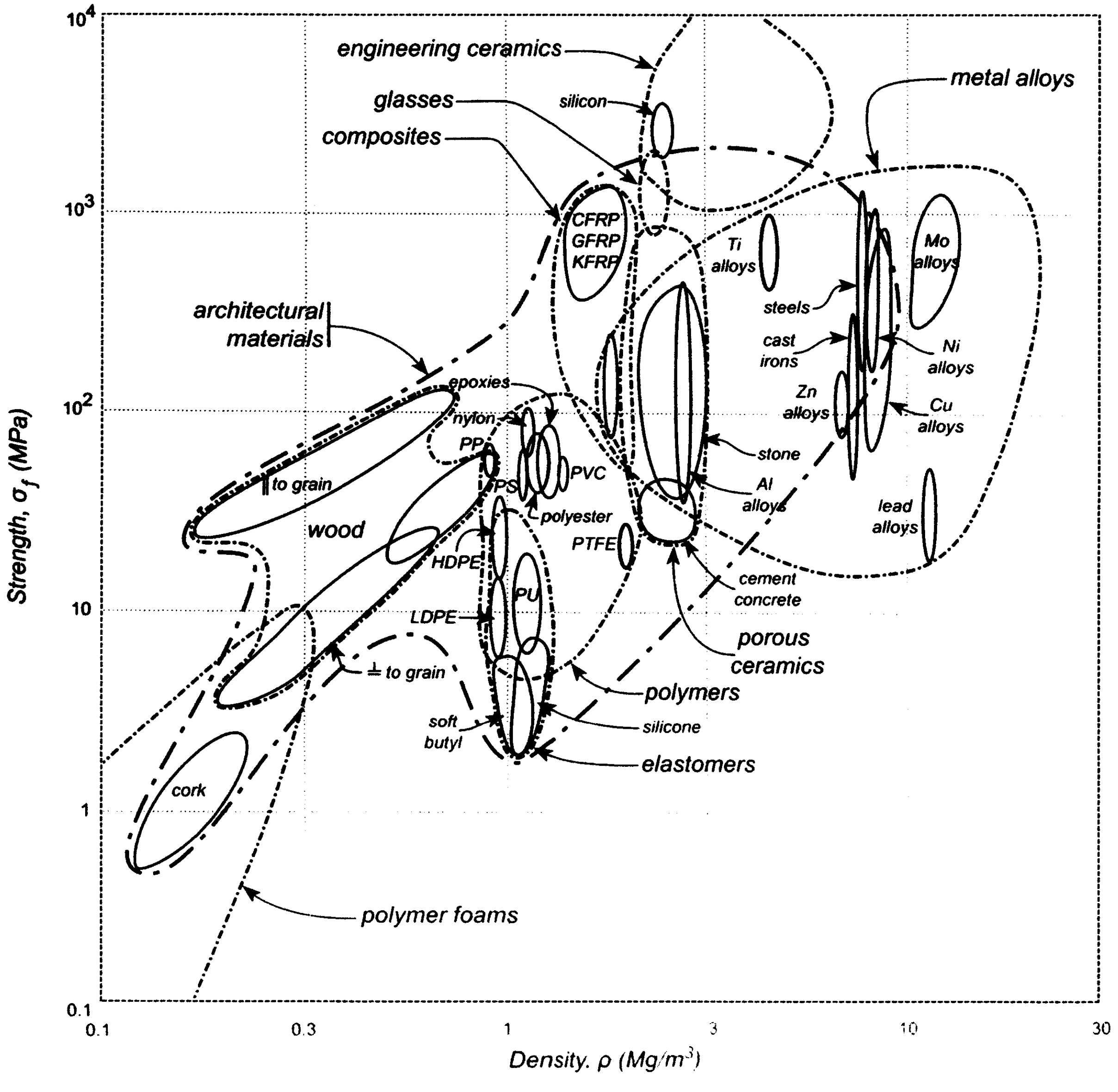
3.1.4 Natural

Natural fibers are emerging as potential replacements for synthetic fibers such as carbon or glass. Natural fibers alone are a fraction of the tensile strength of glass or carbon but offer a natural, economical material that is easier and safer to work with. Automobile manufacturers in France are beginning to use Flax fibers in non critical interior components.

Though natural fibers only offer a fraction of the tensile strength of synthetic fibers, in relation to their cost, they could be used in instances such as architecture where the weight vs cost benefit is slightly different. In architecture the metrics by which we judge success is different than automotive or aerospace. For example in high end yachts, boat builders are willing to spend millions of dollars laying each fiber along a load path in order to reduce the weight. Architecture cannot afford this luxury, materials like natural fibers that can drastically reduce cost while still providing structure, even if at fraction of the strength to weight ratio, must be considered.

Opposite Page:
Natural Burlap Fabric

Graph Mapping Strength vs Density of Various Materials



Fernandez, John. Material architecture : *emergent materials for innovative buildings and ecological construction*. Boston: Architectural Press, 2006. Print.

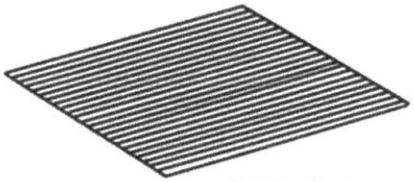
3.2 /// Tensile Strengths

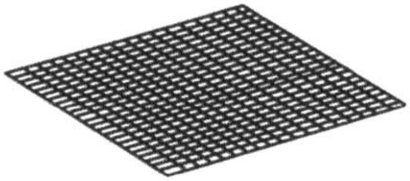
Tensile strength is the maximum stress that a material can withstand when put into tension before breaking. The unit of measurement for tensile strength is MPa (megapascal (1 MPa = 1,000,000 Pa)),also measured in KSI or Kips per square inch. It is a measure of perpendicular force per unit area. ie. Mild steel 800 MPa Fiberglass 4000 MPA Carbon fiber 6200 MPa.

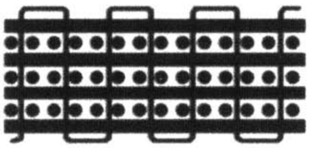
MATERIAL`	**ULTIMATE STRENGTH (MPa)**
Structural Steel	0400-0550
Mild Steel	841
Steel Stainless	860
Aluminum Alloy 2014	483
Aluminum Alloy 6061	300
Cast Iron	200
Copper	220
Tungsten	1510
Titanium	1040
Brass	550
Concrete	3
Marble	15
Wood, Pine (parallel to grain)	40
Bamboo	0350-0500
Polypropylene	0019.7-80
High-Density Polyethylene	37
Clear Acrylic Cast Sheet	114
Nylon	75
Human hair	380
E-Glass	3450 for fibers alone
S-Glass	4710
Aramid Kevlar	3757
Carbon Fiber	6370 fiber alone
Spider Silk	1000

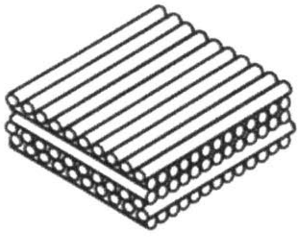
Fiber Form Factors

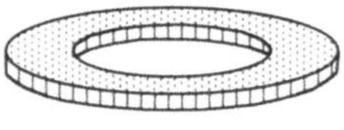

Roving


Unidirectional


2-D Woven Cloth

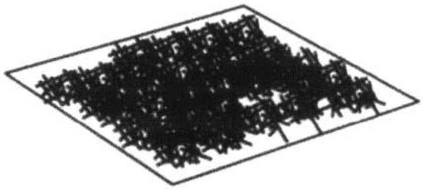

Stitched Fabric

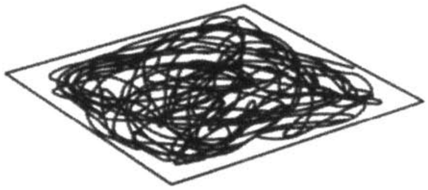

Hybrid

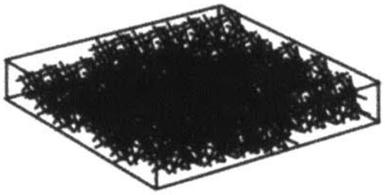

Shaped Preform


Chopped Fiber


Injection Molding Pellets


Chopped Fiber Mat


Continuous Strand Mat


Sheet Molding Compound


Bulk molding compound

Campbell, F. C. *Manufacturing processes for advanced composites*. New York: Elsevier, 2004. Print. PG 13

3.3 /// Fiber Form factors

Fiber = L/Diameter > 100

Strand = Bundle of glass filaments

Tow = Bundle of carbon filaments (K = 1000 fibers) (larger = cheaper but higher void probability)

Roving = Bundle of strands (glass) or (tows) without twisting

Yarn = Twisted Rowing (Easier to work with)

Band = Several tows, rovings or yarns (used for filament winding)

Tape = Unidirectional parallel filaments held to gether with a binder / epoxy

Woven Cloth = Textile made by weaving tows or yarn. various widths, 2k, 12k, 25k in various 2d patterns (Plain weave, Twill Weave, Satin Weave, Basket Weave. etc.

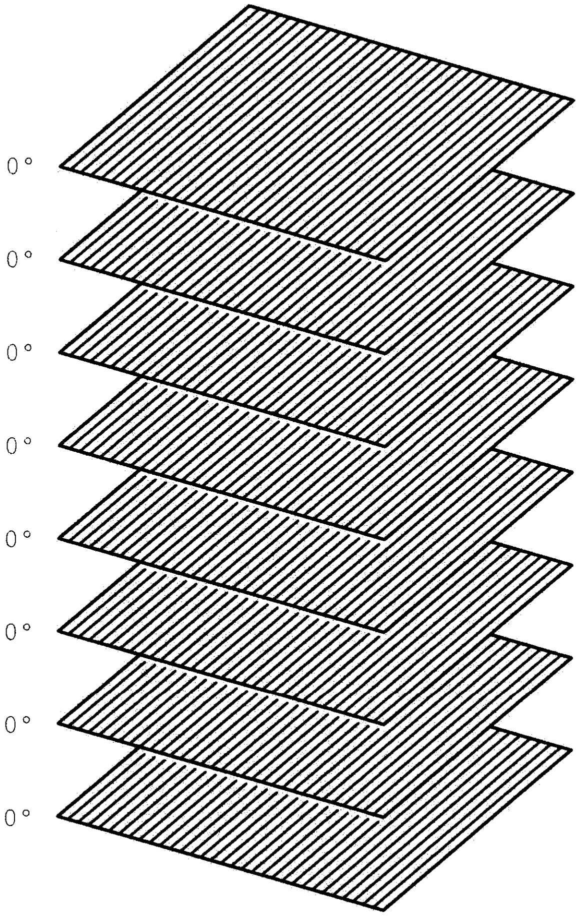
Prepreg = Woven cloth pre impregnated with resin

3D Fabrics or Stitched Fibers = Woven cloth in 3 axis where rovings / tows are stitched into a thickened 3d fabric

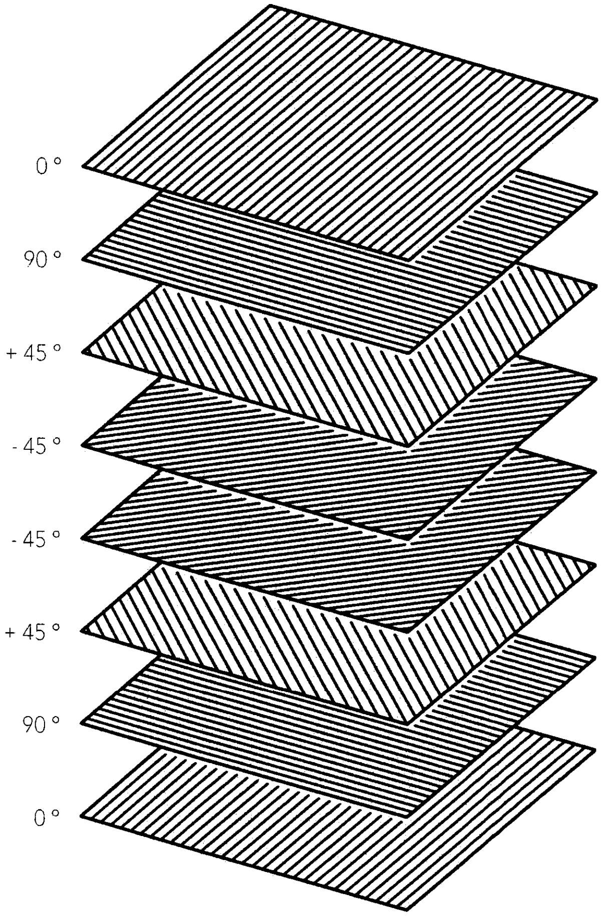
Reinforced Mats = Chopped strand or continuous strands (not very structural)

Performs = Rovings stitched together with geometric specificity and fiber orientation

Unidirectional and Quasi-Isotropic Fiber Orientation



Unidirectional Lay Up



Quasi Isotropic Lay Up

3.4 /// Fiber Orientation

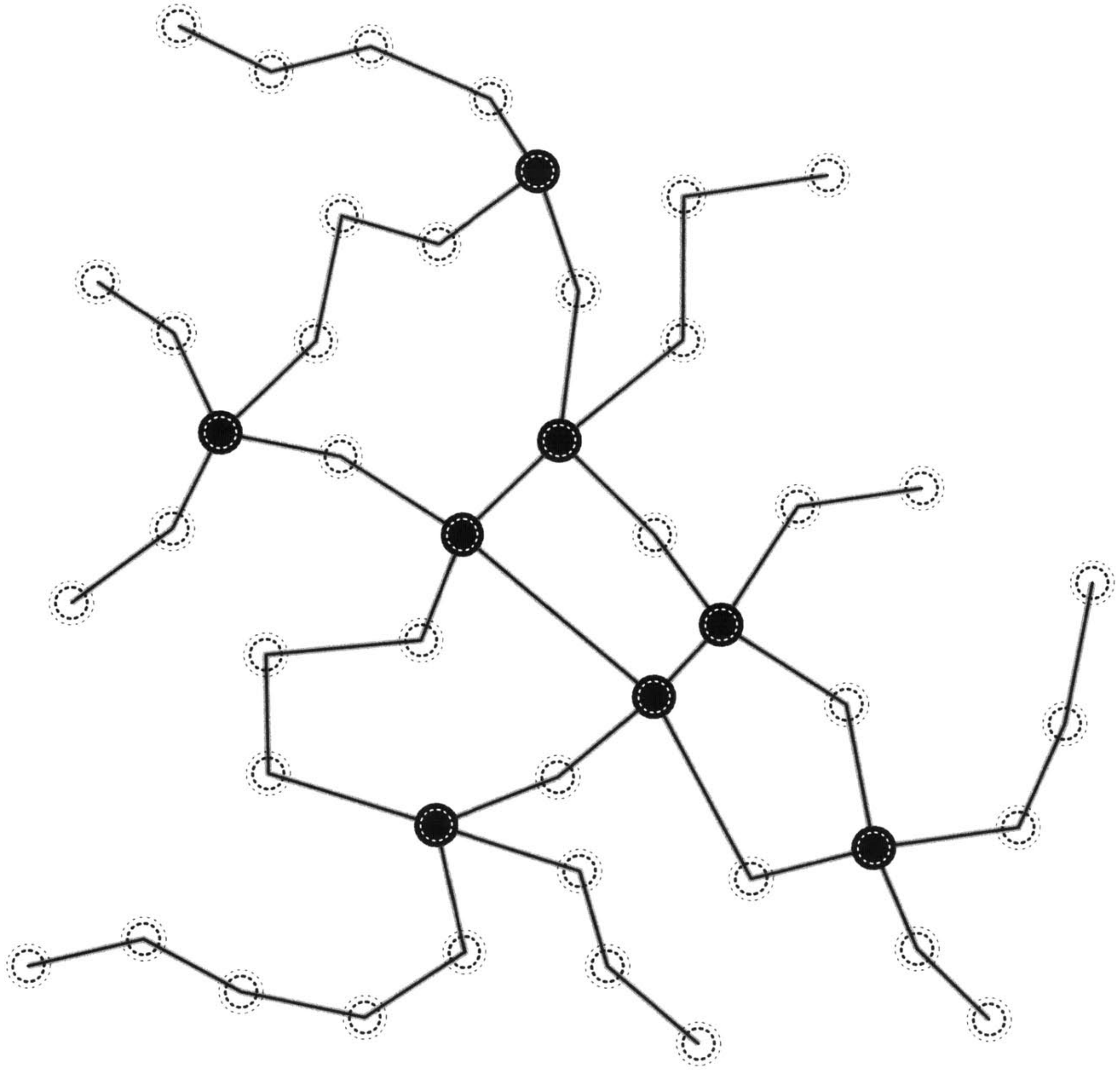
Warp is the lengthwise fiber in a textile roll, while weft (fill) is the transverse thread. The warp orientation of fabric is traditionally much stronger in that it is continuous and remains in tension on the loom. A roll of fabric is typically manufactured in widths of one to two yards and over one hundred yards in length. The warp fiber is continuous through the one hundred yards whereas the weft fiber weaves back and forth across the warp fiber and is only ever as long as the width of the fabric roll. This process of textile production orients the fabric.

During the design and finite element simulation of a composite part, the orientation of the textile in relation to a part is extremely critical. The fibers in the composite transfer loads across their length and because composite fabric is structurally biased in the warp direction, the placement and orientation of the fabric on the part must be engineered. For certain geometries the load paths are clear and the orientation of the fabric is parallel to the load path, known as a unidirectional lay up. To deal with complex load paths, parts can be discretized into clear structural orientations, such is done with the load paths of vertical columns and horizontal beams which can then be laid up unidirectionally. More commonly the load path is infinitely complex and the source of the loads are extremely varied. For example a house may experience downward loads from snow or gravity as well as seismic loads from the earth and shear loads from wind, necessitating multi-axial reinforcement known as a quasi-isotropic layup, where the fabric is oriented in the order of 0,90,+45,-45,-45,+45,90,0.

Isotropic (Identical properties in all directions)
Quasi Isotropic (Balanced Composite. Equal number of plies for loads in all directions.)
Anisotropic (is the property of being directionally dependent)
Orthotropic (Material properties depend on the axis. 3 distinct orientations)
Unidirectional (Material properties in only 1 direction)

04 // COMPOSITE MATRICES

Thermoset Molecular Chain



4.1 Thermoset Resin

Composite matrices primary task is to transfer compressive forces between fibers along a load path. In a composite assembly the matrix also protects the fibers from abrasion, holds the fibers in position and provides shear strength between plys. Matrices can also be chemically engineered to have specific material properties such as chemical or fire resistance.

4.1 Thermoset

Thermoset plastics are composed of two parts, a resin and a curing agent or hardener. When mixed, the liquid begins its curing cycle. Thermosets can cure exothermically through their own heat or through externally applied heat. When cured the molecular chains of a thermoset are crosslinked and can not be reprocessed or reformed.

4.1.1 Epoxy Resin

Epoxy resins are the most commonly used matrix for advanced composite parts. Epoxies are extremely versatile and strong, while providing unsurpassed adhesion. Epoxies can be engineered to cure exothermically or to not cure until an external high temperature heat source is applied to the part.

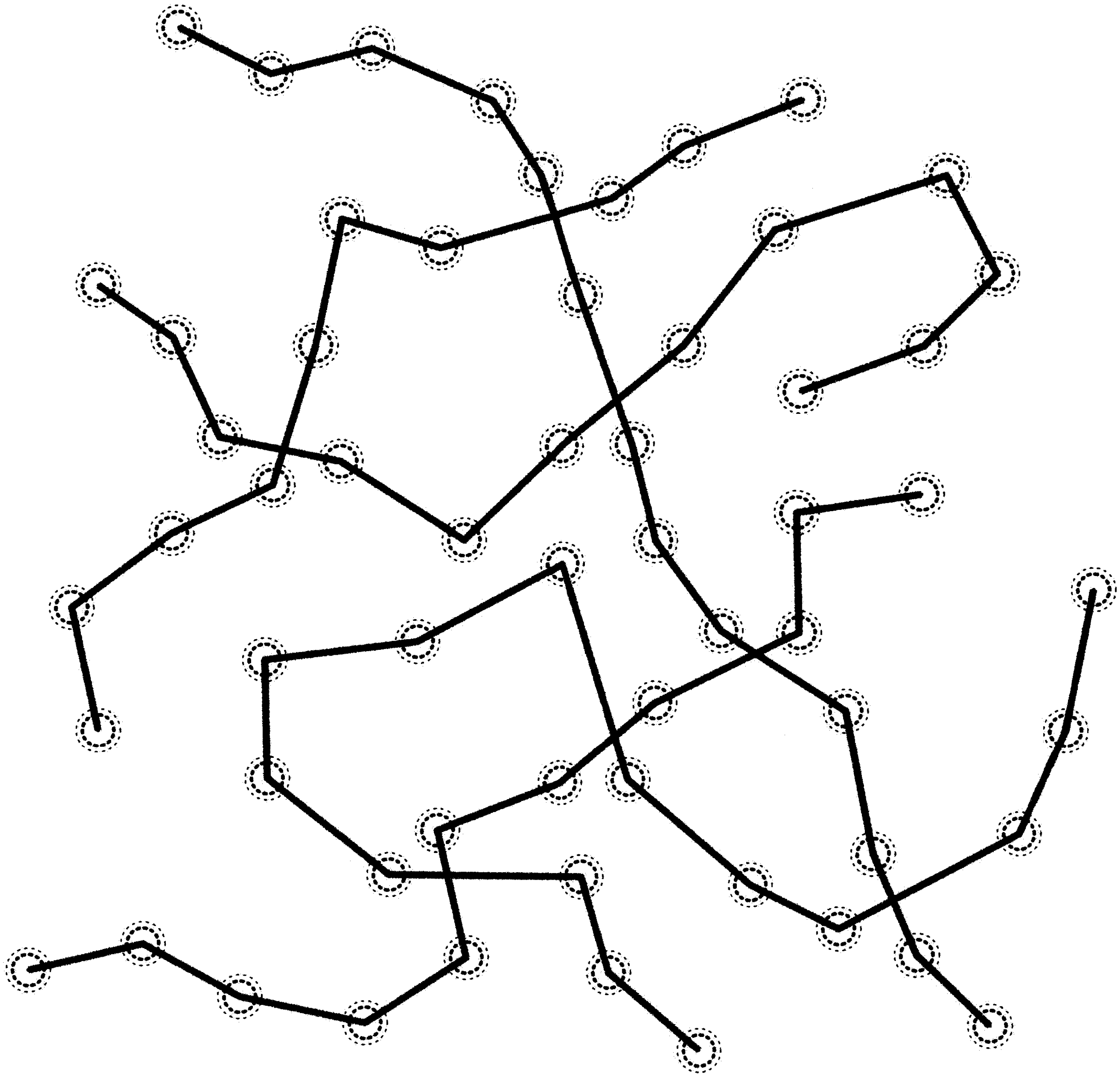
4.1.2 Polyester Resin

Polyester resins are extensively used throughout the composites industry but due to their lower mechanical properties, they are not used for advanced composite parts. In addition, polyester resins are inferior for exterior applications and are prone to shrink during the cure cycle. Like epoxies, polyester resins can be engineered to cure exothermically or to not cure until an external high temperature heat source is applied to the part.

4.1.3 Eco High-Bio Resin

High Bio content epoxies are emerging as possible alternatives to traditional epoxy resin. High Bio epoxies have a lower environmental impact and are now competitive economically in relation to the rising cost of petroleum based epoxy resins. High Bio epoxies substitute a large portion of the petroleum based resin with corn based resin.

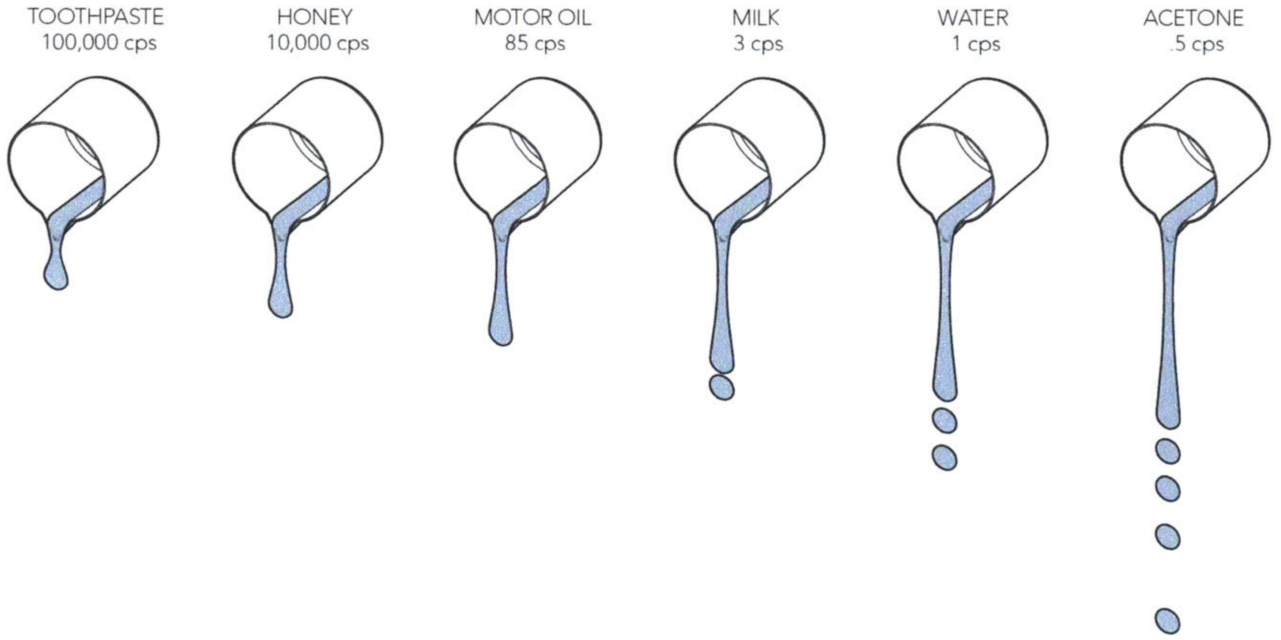
Thermoplastic Molecular Chain



4.2 Thermoplastic

Thermoplastics are polymers that have already reacted and are linked together in a stable state within a specific temperature range. Above the glass transition temperature the woven (not linked) molecular chains soften becoming pliable, and allowing for reforming. Thermoplastics are largely unused in advanced composite assemblies but offer the possibility to recycle composite parts. By heating the part, the matrix can be removed from the fiber, allowing for a second life of both the fiber and the matrix.

Viscosity Comparison /// Water = 1 cps



4.4 /// Viscosity

For a thermoset, once the resin and the curing agent are mixed, their resistance to flow is known as viscosity. Viscosity is measured in centipoises with water being the basic unit of measurement at 1 cP. The viscosity is critical in the process of wetting out of the fiber. This is evident more so in vacuum assisted resin infusion where the resin must be pulled through the fibers. The viscosity changes throughout the cure cycle reaching a gel state at 100,000 cP before curing.

4.3 /// Cure Cycles

4.4.1 Pot life

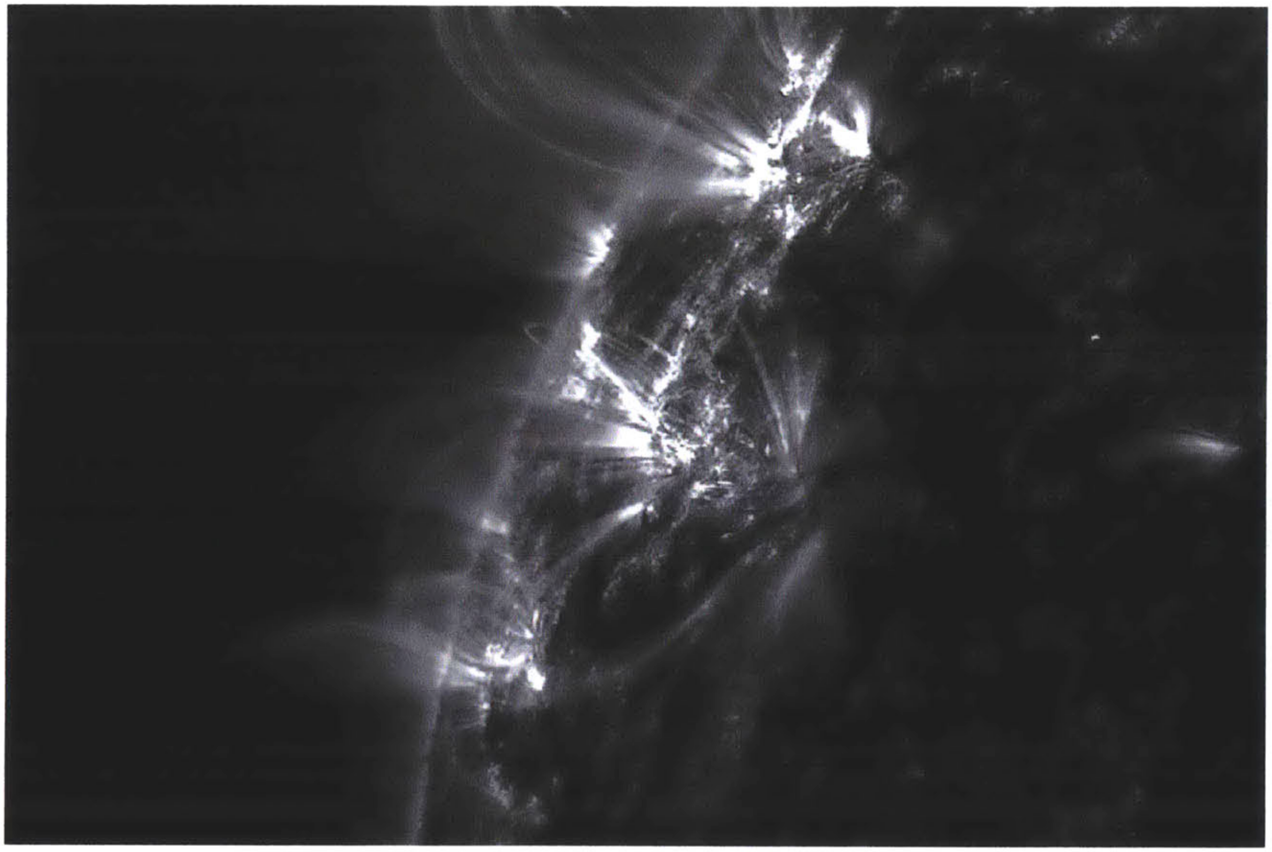
Pot life is a critical period in the cure cycle of a thermoset resin. Once the resin and the curing agent come into contact the pot life begins. For most thermoset resins this can range from 15 min to 1 hr. During the pot life and before the cure time the wetting out of the fibers and ply-collation must take place.

Thermoset pot life is largely determined by the processes by which the composite part is being manufactured as well as the size of the part. In comparison to vacuum assisted resin transfer molding, the manually intensive nature of hand wet layup necessitates a longer pot life. Longer pot lives are also needed when the scale of the composite part is too large to finish wetting out and ply-collation before the pot life expires.

4.4.2 Cure time

Thermosets can cure exothermically through their own heat or through externally applied heat. Either way the cure time happens in many stages. The initial cure time begins once the pot life has ended, once the cross linked molecular bonds have taken place. But the full cure time usually takes 12 hrs - 24 hrs to reach full strength. Exothermic cures are often accelerated with the use of additional heat.

Solar UV Flares as seen by NASA's SDO Spacecraft



http://www.nasa.gov/sites/default/files/files/Goddard_View_V10_I11.pdf

4.5 /// Custom Resins

4.5.1 Fire and UV

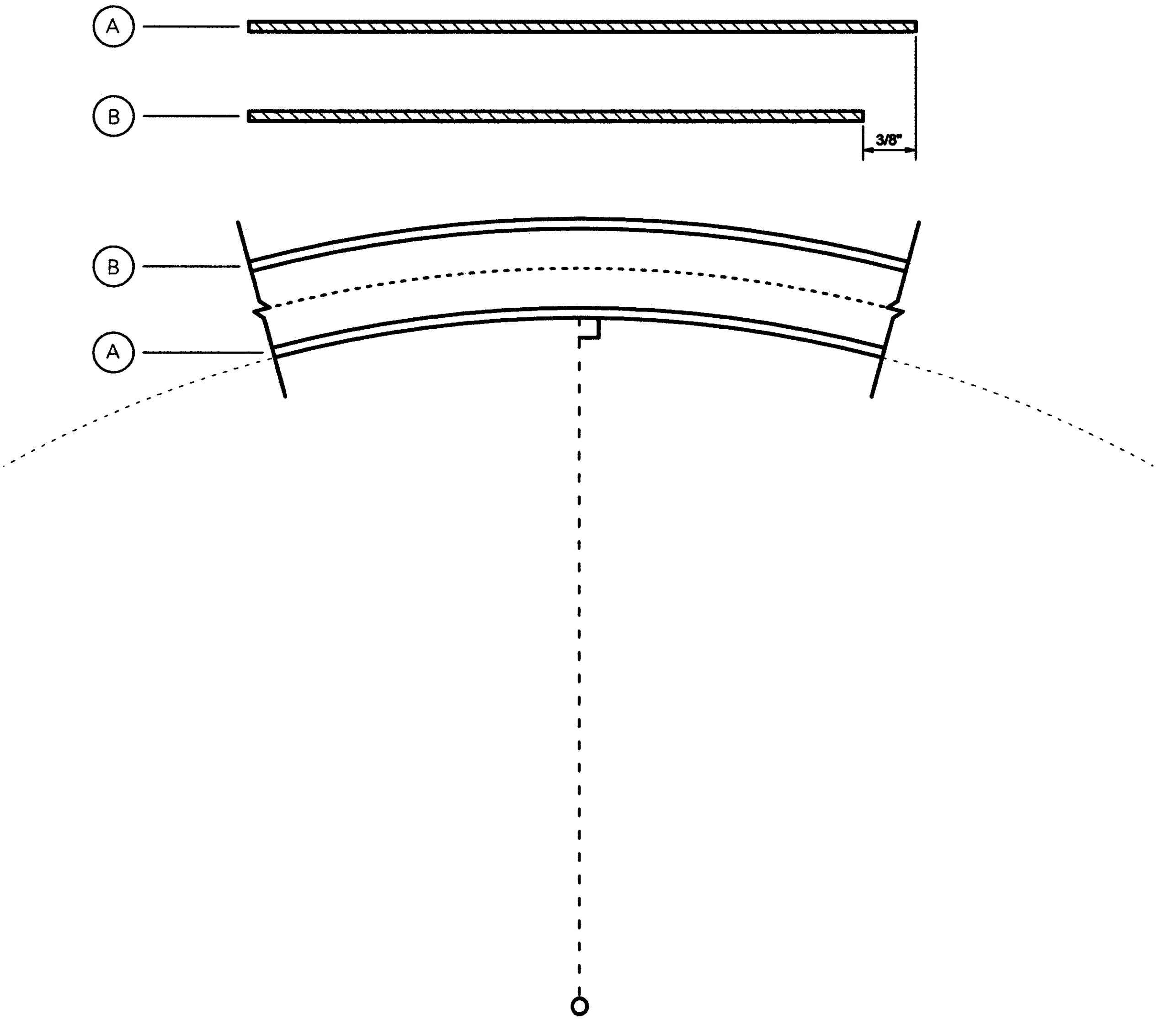
Fire and UV vulnerability are the most overstated critic for composites within architecture. As one of the early stigmas of composites and plastics, fire is an extremely important and relevant health and safety concern for any building material in architecture. Just as cementitious fireproofing spray is applied to structural steel, the composites industry, led by Boeing and AirBus, have developed UV and fire resistant matrices. The evolution of matrices and their capacity to be chemically engineered for specific material properties make composites the only material capable of resisting the 4000° f at the exhaust of a fighter jet airplane.

Buckminster Fuller Biosphere Montréal Expo 67 1976 Fire

http://ad009cdnb.archdaily.net/wp-content/uploads/2014/11/546b6cdce58ecea75a000118_ad-classics-montreal-biosphere-buckminster-fuller_x4fxgzf.jpg

05 // COMPOSITE CORES

The role of the core in a composite is to add strength by separating the inner skin from the outer skin producing a radius of curvature



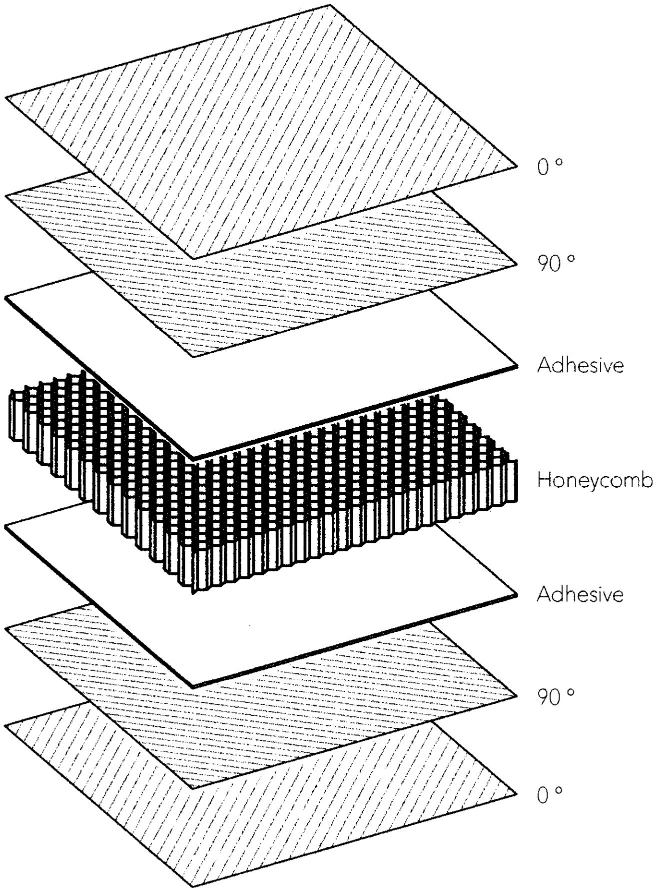
5.1 /// Role or the Core

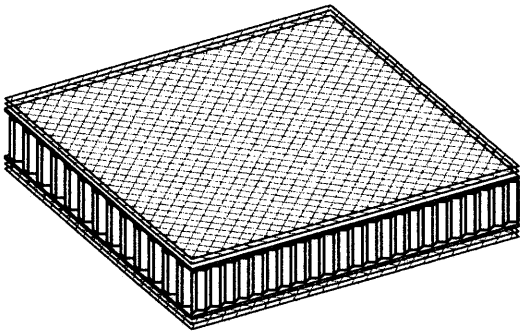
Forces in composite structures are transferred through a skin; typically the skin is separated by a core forming an interior skin, and an exterior skin. The core can be made of a number of materials; the most common types are light materials such as an aramid honeycomb, or a expanded polyurethane foam resulting in a sandwich structure. Sandwich construction is used broadly in high performance composites because it offers an extreme strength to weight ratio that grows exponentially as the thickness of the core grows linearly.

The strength of the composite is in direct relation to the thickness of the core. As the interior and exterior skin are held apart, the core works to transfer loads between the two skins. When the interior skin goes into compression, the exterior skin is put into tension. The matrix serves to transfer forces to the fibers, which are extremely strong in tension The core creates a radius of curvature between the two skins, the greater this offset, the stronger the composite.

In the context of architecture, the cavity created by the core, creates an exciting potential. This delamination of the interior and exterior allows for a thickening and thinning of the wall section and creates opportunities for apertures, storage and integrated joints.

Sandwich Panel Construction





Completed Sandwich Panel

5.2 Core Types

5.2.1 Honeycomb

Honeycomb cores are the most expensive and highest performing type of core. They can be made from various materials including aramid, fiberglass, thermoplastics and aluminum and are attached to the composite face sheets using structural film adhesive. Honeycomb cores can be engineered to the necessary material properties by varying the thickness and cell size.

5.2.2 Balsa Wood

Balsa is the oldest core material and was used in early aircraft construction because of its lightweight properties. To use balsa wood as a core material, it must be cut down and reoriented such that the wood grain runs across the thickness of the core to transfer loads between the exterior and interior face sheets. The small blocks that are made by cutting down the balsa wood are then glued back together to form the core material. The primary disadvantage of balsa wood cores is that as a natural material the wood absorbs moisture and can display variable properties across its surface.

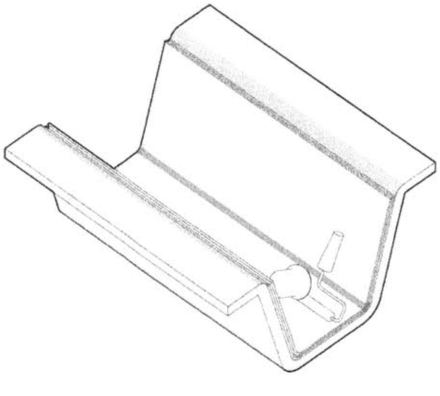
5.2.3 Foams

Foam cores are widely used as an economical yet structural alternative to honeycomb cores, but with only a fraction of the strength to weight ratio. Foam cores range broadly, consisting of polystyrene foam, polyurethane foam and pvc foam. Typically open-cell foam is weaker while closed-cell foam is stronger and more dense.

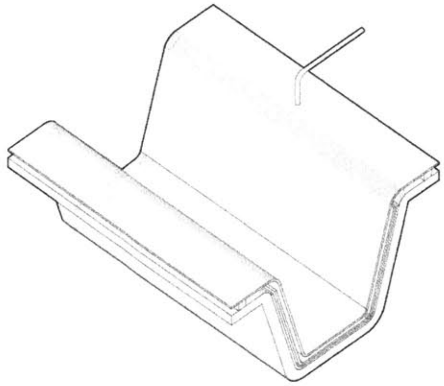
5.2.4 Infusion Cores

Infusion cores are used during vacuum assisted resin transfer molding as the flow media by which the resin is pulled through to wet out the fibers. Traditionally the flow media is an additional layer composed of an HDPE mesh that is laid on the outer skin of the composite then thrown away after the infusion. By integrating the infusion flow media into the core of the composite, the amount of waste is reduced and the distribution of the resin is more equally distributed. Most infusion cores are engineered from foam. The downside to integrating the infusion core to the composite part is that it adds a small amount of weight.

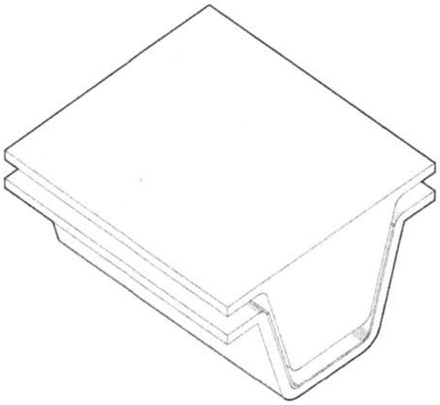
06 // COMPOSITE PROCESSES



HAND WET LAYUP



VACUUM BAGGING WET LAY UP

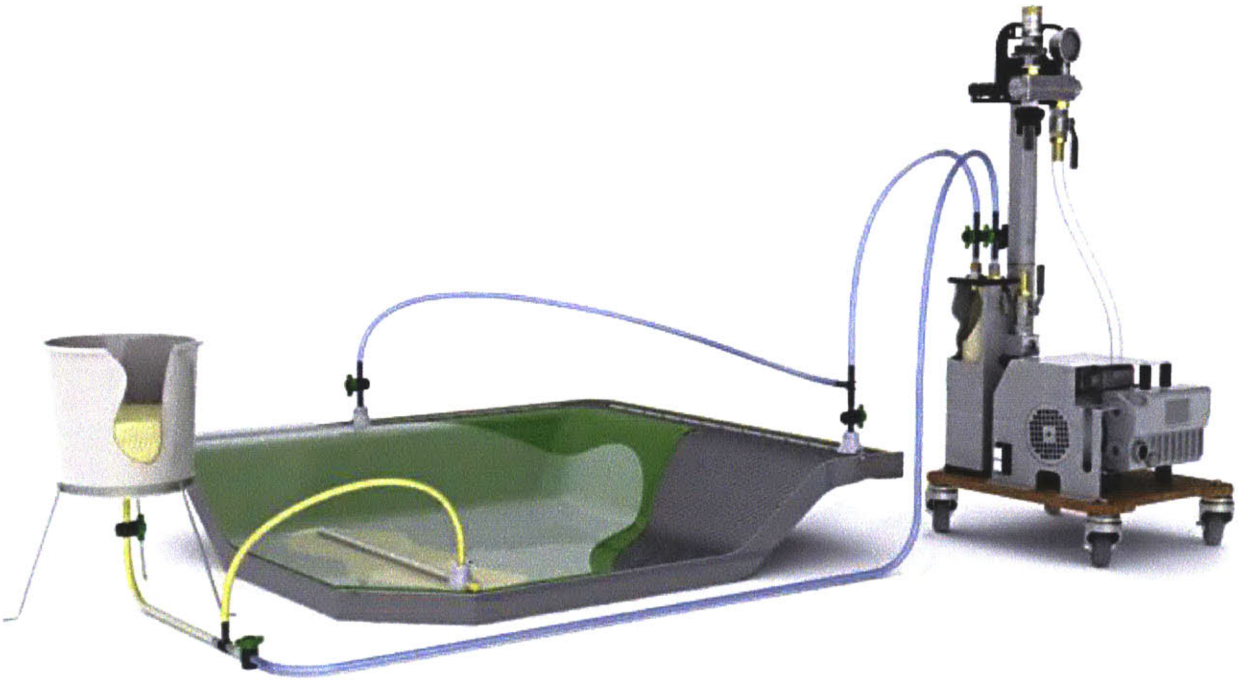


WET LAY UP COMPRESSION MOLDING

6.1 / Traditional Manufacturing

Hand wet layup is the most readily available and ubiquitous of the composite manufacturing techniques. It is an effective method for testing and producing low quantities of relatively small scale parts. Despite the manually intensive nature, the process is still used to build large and complex parts. The process begins by wetting out one ply at a time on a large flat table using a squeegee. This portion of the process is the most crude in that the amount of resin and the thoroughness of the wetting out is left up to the skill of the worker. These plys are then layered onto the mold one at a time. Traditional hand wet layup is rolled by hand in an attempt to compact the fibers and push out excess resin. Hand wet layup alone does not produce high performance structural composite parts.

Variation on the traditional hand wet layup process allow for slightly higher quality parts with lower void content. The two main variations on wet layup are hand wet layup compression molding and hand wet layup vacuum bagging. Both of which greatly increase the strength of the composite part by removing excess resin that weakens and adds weight and by removing air bubbles or voids that are encapsulated between the plys and in the resin.



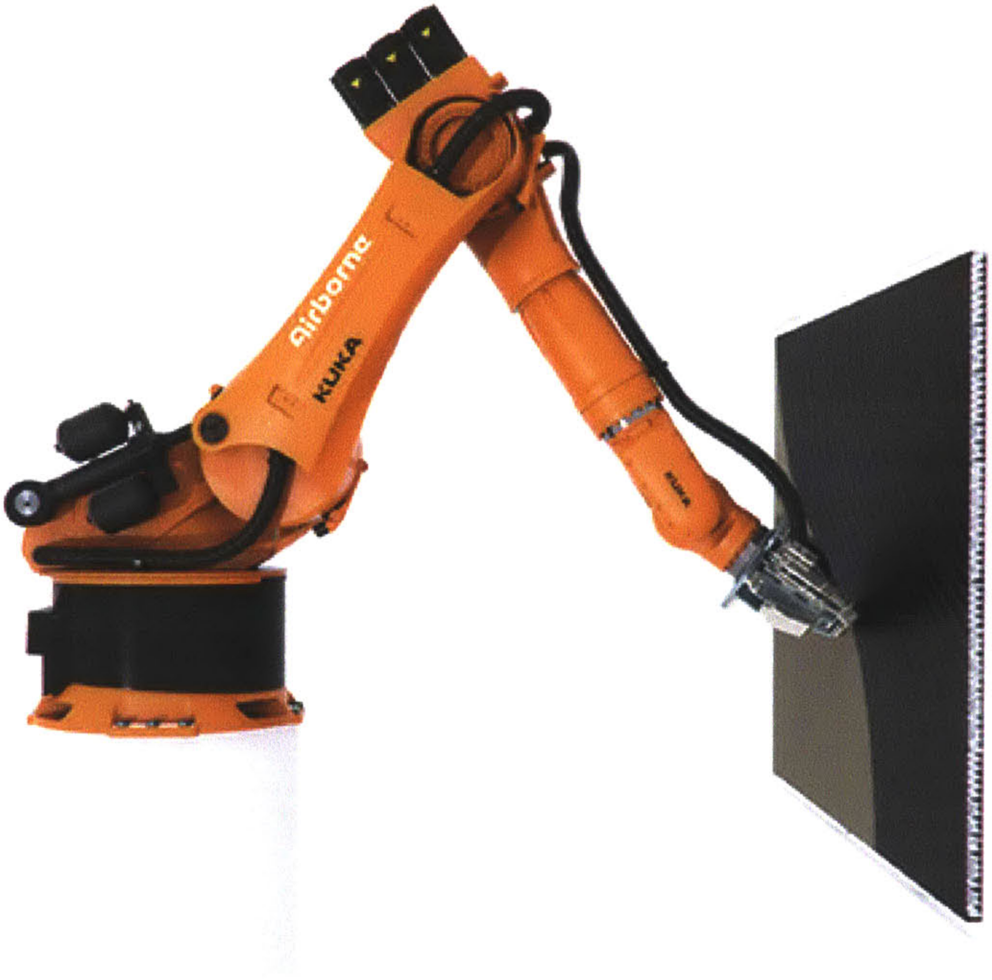
http://www.vacmobiles.com/site/vacmobiles/images/resin%20
infusion%20image%202.JPG

6.2 /// Advanced Manufacturing

6.2.1 Vacuum Assisted Resin Transfer Molding

Vacuum assisted resin transfer molding is a process which has already existed in the composites manufacturing industry. It has started to take root over the last five years as a possible replacement and alternative to the long standing autoclave compaction cure, by promising equally robust parts at a fraction of the cost. VARTM greatly reduces the time and cost by utilizing the nylon vacuum bag, typically used to compact a hand wet layup, and infusing the the the dry fibers by pulling the resin through and across the fibers using the vacuum needed for compaction. This process of infusing the fibers greatly reduces the void content in the part. The most promising aspect of VARTM is the potential to scale up. Because the process is automated the potential exists to produce something 10 times the size for only twice the effort

Automated Tape Laying 6 Axis Robot

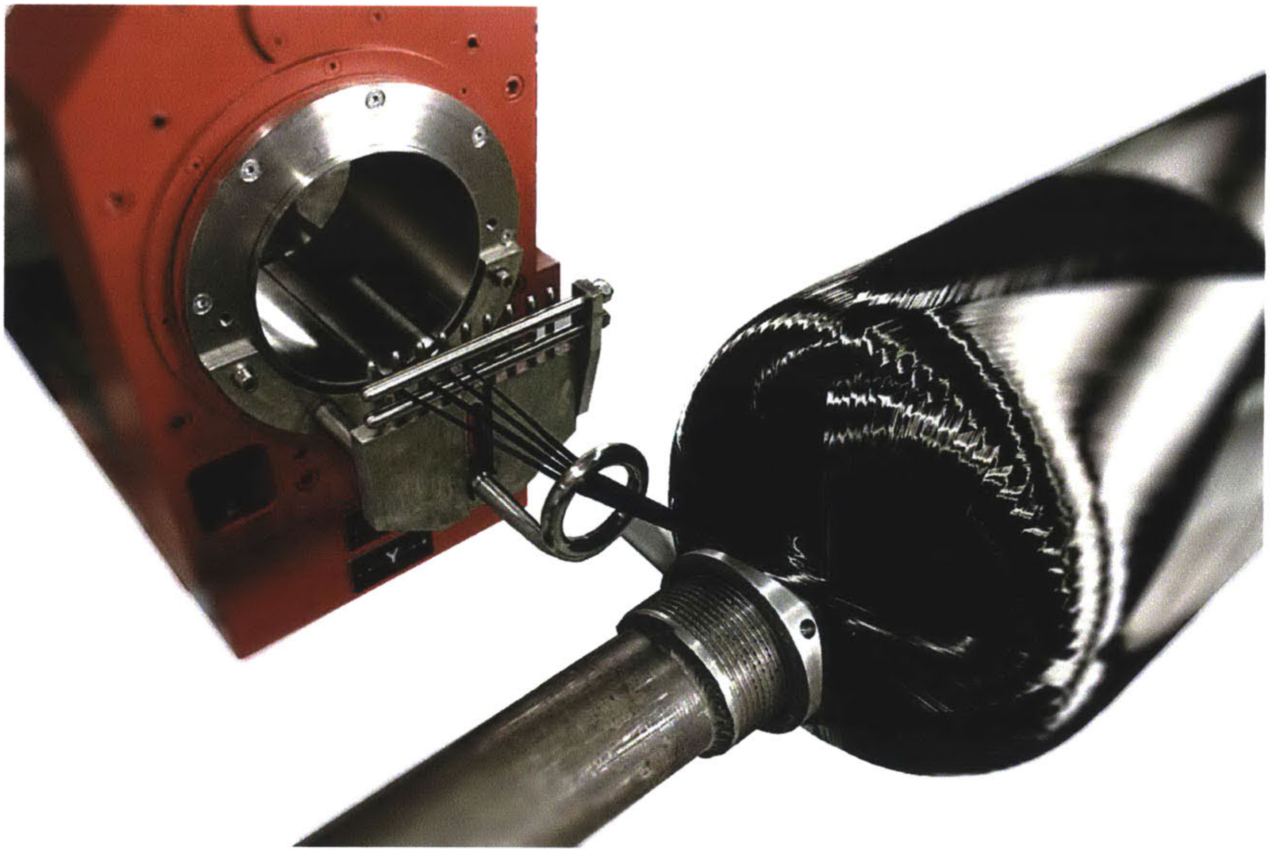


http://airborne-technologycentre.com/wp-content/uploads/sites/5/2013/05/fibre-steeringhead.jpg

6.2.2 Automated Tape Laying

Automated tape laying (ATL) is a process by which composite tape, a unidirectional bundle of filaments held together with a binder, is layered onto a mold's surface using a large gantry style machine that is capable of both heating and compacting the composite. Some ATL processes utilize a thermoplastic infused tape that only require re-heating while others use pre-impregnated thermoset tapes. Tapes typically come in 3, 6, or 12 inches in width. ATL is limited in geometry to slightly contoured surfaces with shallow angles.

Filament Winding Machine



http://www.moteam.com/images/Slides/filament3.jpg

6.2 /// Advanced Manufacturing

6.2.3 Filament Winding

Filament winding is a process by which dry rovings of fiberglass or carbon fiber are pulled through a bath of resin and wound around a rigid revolving mold known as a mandrel. It is critical that the mandrel be constructed of a material that can be used to compact the composite against but that can also collapse to allow for the removal of the part. Filament winding is limited in geometry to bodies of revolution in order for the fibers to have a constant surface to compact against.

Pultrusion Machine

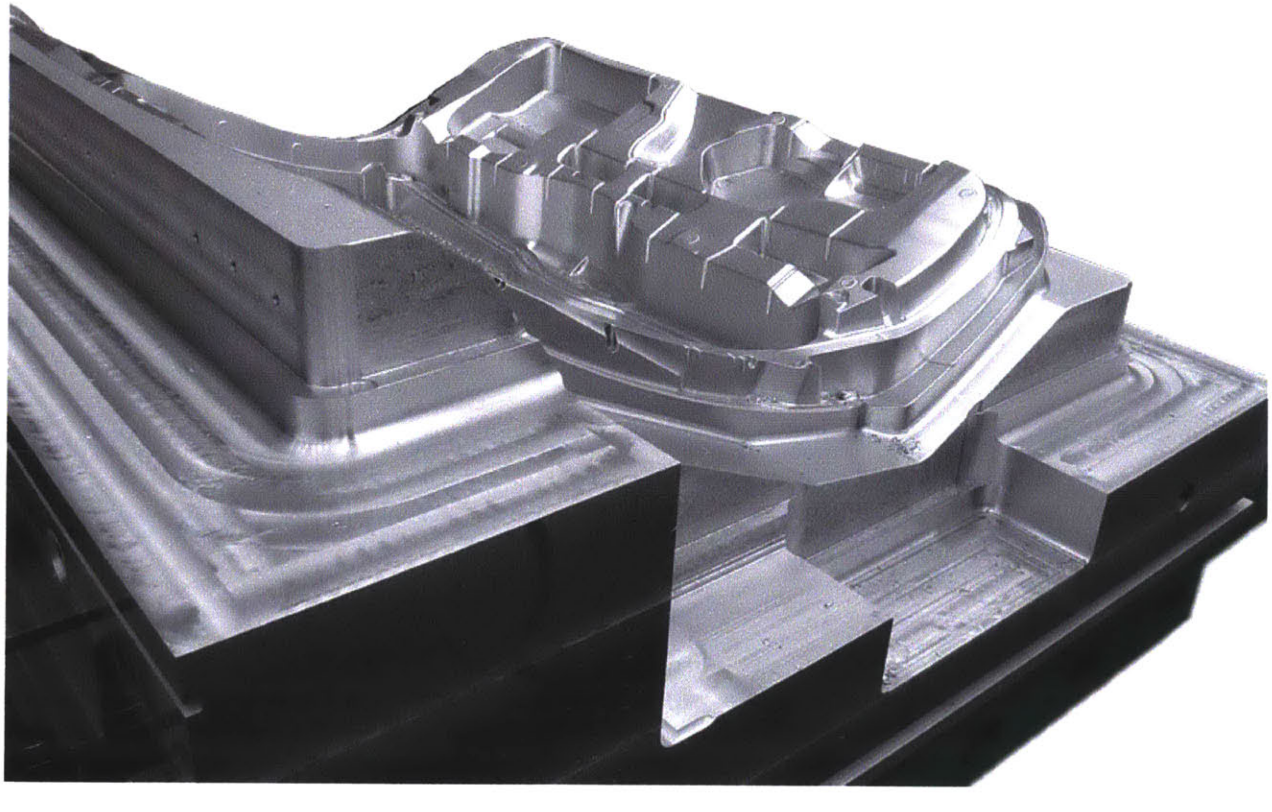
http://fibrolux.com/fileadmin/Bilder/pultrusion_process.png

6.2 /// Advanced Manufacturing

6.2.4 Pultrusion

Pultrusions are the composite equivalent to extruded plastic or metal parts. The process is extremely efficient and economical in producing parts with continuous sections at nearly any length. The manufacturing of pultruded parts begins with reels of rovings that are pulled through a resin bath followed by a performer and then a heated die and finally cut to length. Extruded metal parts can easily be substituted by their pultruded composite counterparts.

Two Part Compression Aluminum Mold



http://www.paragonde.com/wp-content/uploads/2012/03/compressionmoldAluminumTool-010.jpg

6.3 /// Tooling Design

Molds have been a large inhibitor to the integration and deployment of composites, particularly at a large scale, due to high costs and slow production times. However, as a result of digital manufacturing, molds are becoming cheaper and faster to produce. Innovation in mold production has been the deciding force on whether composites can become mainstream.

Mold fabrication is the leading upfront cost in manufacturing composite parts. A large tool can easily cost on the order of $500,000 to over 1 million dollars. These molds can be used to produce many parts using traditional processes, but as parts evolve and geometries change the need to modify or even build a new mold can quickly become an overwhelming prospect.

Mold materials vary considerably depending on the potential requirements needed for the composite part. The leading consideration for mold materials and design are: stable temperature working range, capacity to withstand compaction loads (up to 100 psi in autoclave), surface finish, transportability, etc. Typical mold making materials range from foam, which works well for low production run, to milled aluminum and steel. Steel is a fairly cheap yet durable mold material that allows for high temperature curing and autoclave compaction but does not allow for complex geometries that are needed for detailed parts.

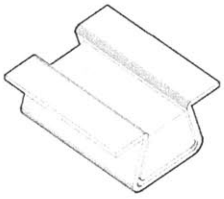
6.3.1 Pneumatics

Pneumatic molds occupy a narrow market in composite production, serving primarily as mandrels for fiber winding. Pneumatics utilize air and pressure to create large scale molds with very little material. Once inflated, pneumatic molds are essentially rigid surfaces capable of resin infusion and composite compaction. Pneumatic molds are cheap to produce, easy to transport and allow for large scale composite parts.

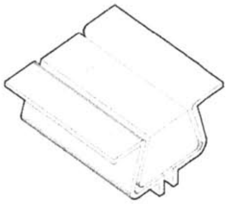
6.3.2 Reconfigurable

Reconfigurable molds are emerging and offering the possibility to produce different composite parts from the same mold. Though still in their infancy, they present the alternative of programing rather than milling variation. A yacht sail manufacturer in Nevada, North Sails, is producing custom sails from the same reconfigurable mold. In high end yacht sailing the geometry and the fiber placement of each sail is custom to the racing yacht: all sails are very similar in geometry and size but still vary in dimensions and depth.

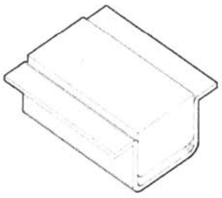
UNDERCUT MOLD



2 PART MOLD

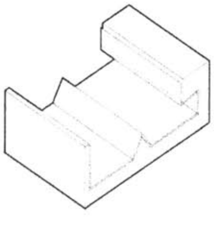


90 DEGREE MOLD

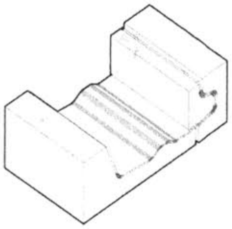


10 DEGREE MOLD

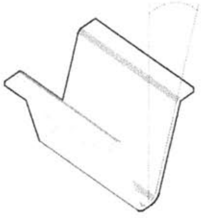
BAD MOLD



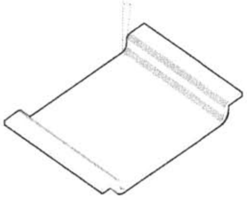
GOOD MOLD



15 DEGREE DRAFT ANGLE

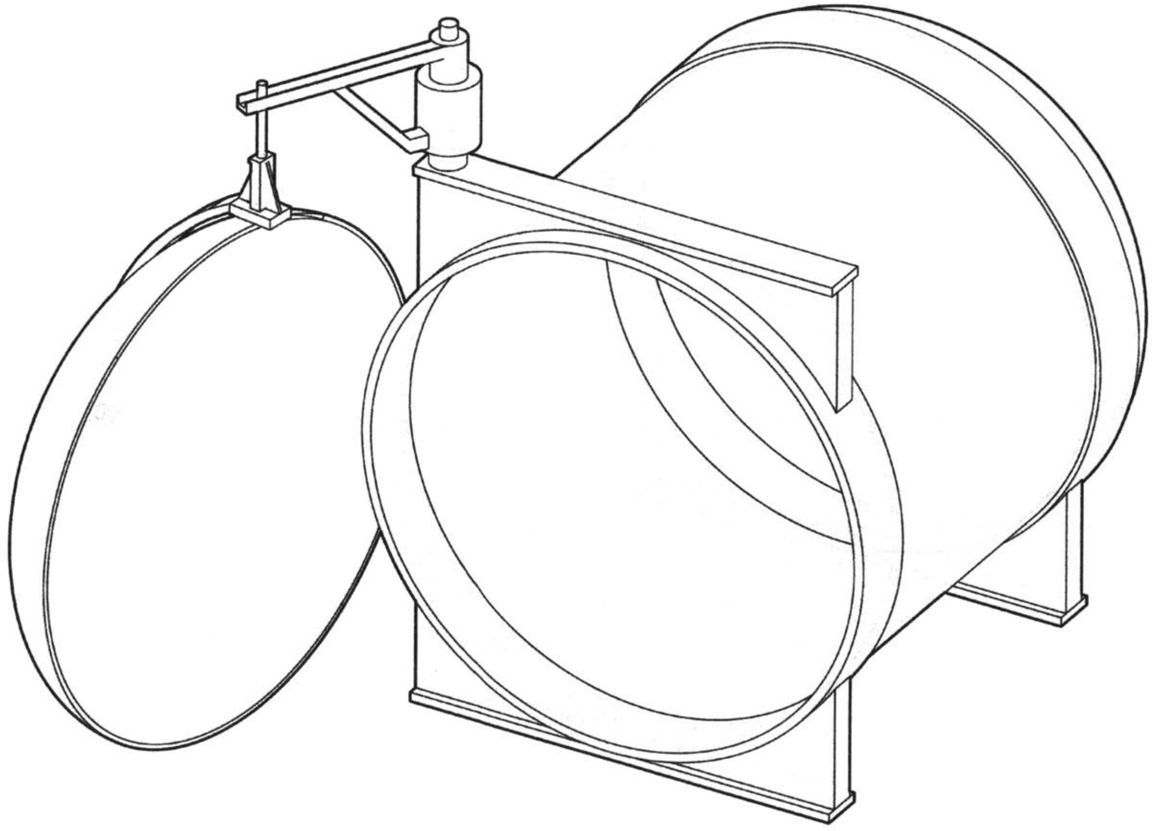


SHALLOW PART 5 DEGREE DRAFT ANGLE



6.4 /// Tooling Constraints

Guidelines must be considered when designing molds in order to allow for the successful production and demolding of the part. Draft angles must be proportional to the part depth. For example, with shallow parts, a 1° - 5° draft angle should be sufficient but with deep and narrow parts, a draft angle may range between 5° - 15°. In addition to draft angles, undercuts and sharp corners must be avoided. Sharp corners establish a weak point in a composite part that can be avoided with even a slight radius. If undercuts are critical to the composite part, the mold may be required to come apart in order to demold.



6.5 /// Compaction

After wetting out the fibers and ply collation, the plys and resin must be compacted to form a structural composite part. In traditional hand wet layup the fibers are compressed with a hand roller in an attempt to compact the fibers and push out excess resin. This is known as atmospheric compaction, though far cheaper and faster to produce it does not result in a high performance structural composite part.

To achieve higher quality parts with lower void content, fibers and resin can be compacted using two part compression molding or vacuum bagging, depending on the geometry of the part. Two part compression compaction relies on both a male and female mold that are compressed to remove voids and compact the plys. Two part compression molding is limited to geometries where the part is shallow or flat. Because the male and female molds are compressed in a hydraulic press, axially up and down, minimal amounts of pressure can be applied to side surfaces. In this case vacuum bagging is a viable alternative.

In vacuum bagging, the process is simplified by eliminating one side of the male-female mold. The remaining side is coupled with a vacuum bag, greatly reducing the material and cost needed to produce the composite part. Once a full vacuum pressure is attained, 26 - 29 inches of mercury, the excess resin is expelled and any air bubbles or voids that are encapsulated between the plys and in the resin are drawn out.

The last and most often used method of compaction for high performance structural composite parts is autoclave compaction. Because an autoclaves compaction is applied isostatically (state in which pressures from every side are equal) almost any shape part can be compacted and cured in an autoclave. Autoclaves are large steel chambers that can be pressurized up to 100 psi. Autoclaves are extremely effective means of compaction but come at a high cost, limiting the type and quantities of parts that can be produced. In addition, autoclaves are available only in fixed sizes, such as 8 ft diameter and 20 ft long or 12 ft diameter and 40 ft long. With limited dimensions, the autoclave may not be able to accommodate large scale parts, as is the case with wind turbines that must be vacuum bagged.

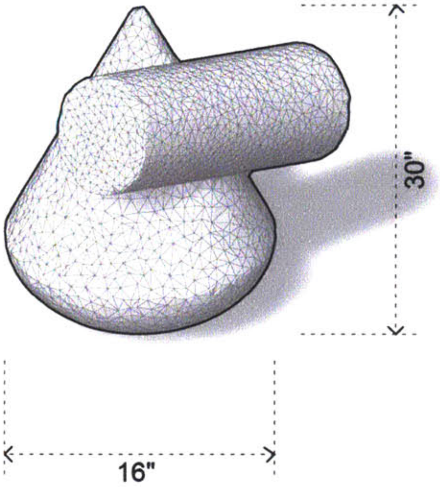
07 // PROTOYPES

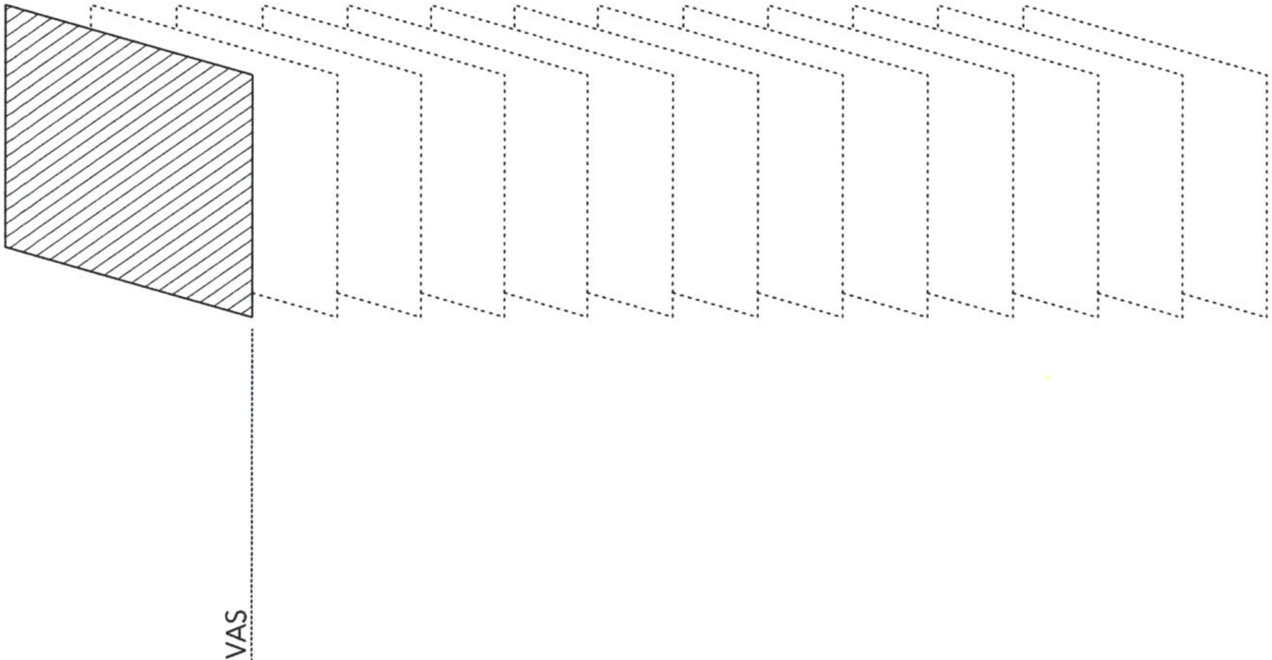
07 /// PROTOTYPE

The 16 prototypes presented here, were constructed over two years of research. Through the physical experimentation the final workflow emerged. Many challenges existed initially, such as the production of an inflated mold that could withstand the pressure of vacuum bagging. In this instance, many materials were tested and after a number of mockups, stitching and the process of heat sealing the edge were established as a high pressure seal. Other materials that were tested through the prototypes were the infusion flow media and the natural fiber. In addition to materiality, the prototypes also allowed for the testing of the infusion strategy in order to understand the resin flow through the fibers and therefore, where to locate the resin inlets and the vacuum outlets.

07 /// PROTOTYPE 01

SEPTEMBER /// 2014





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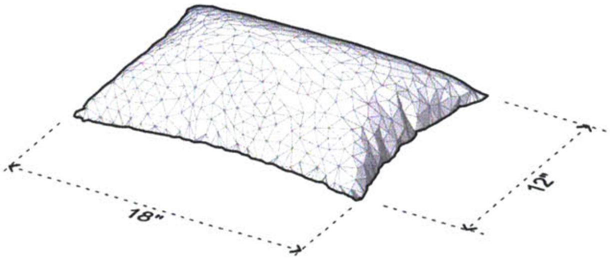

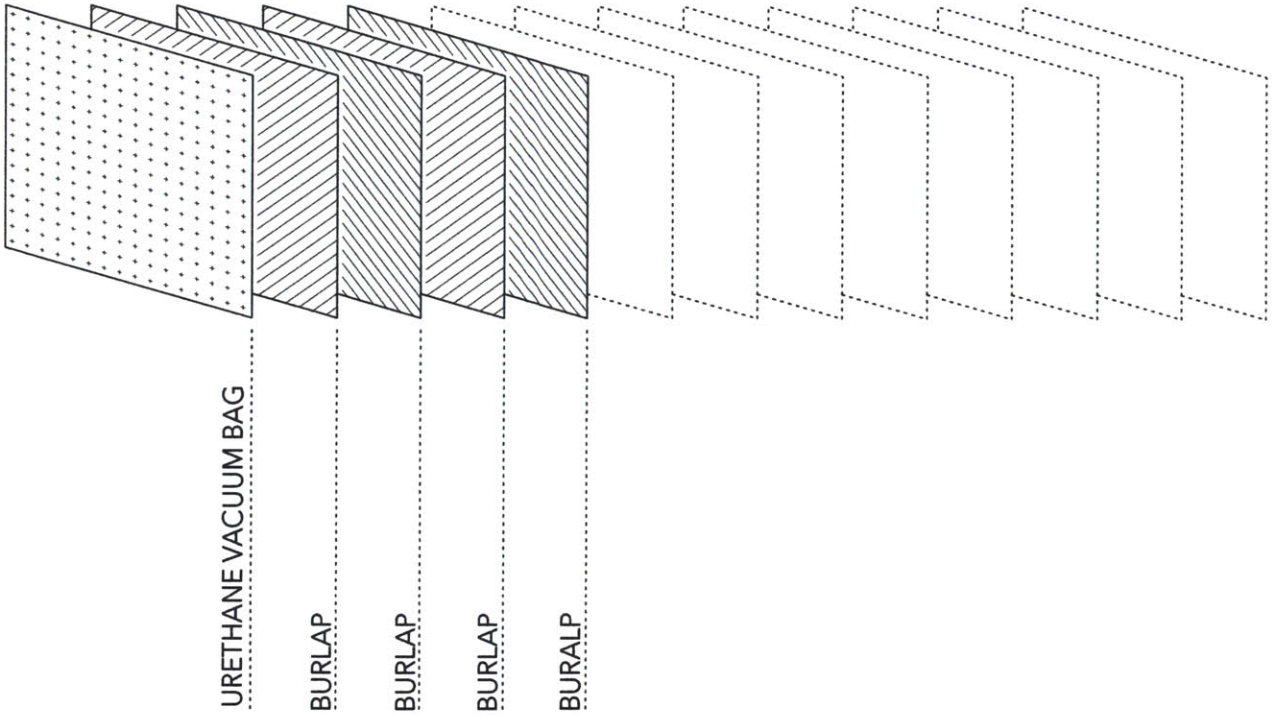

07 /// PROTOTYPE 03

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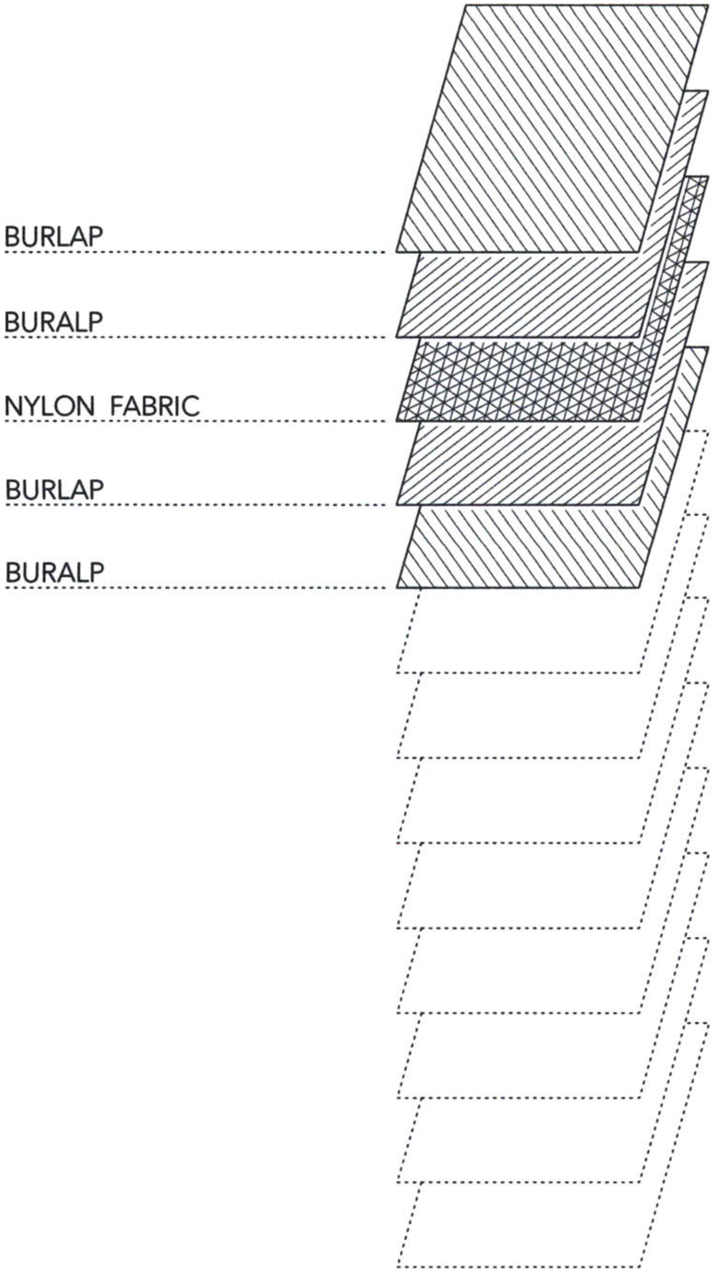

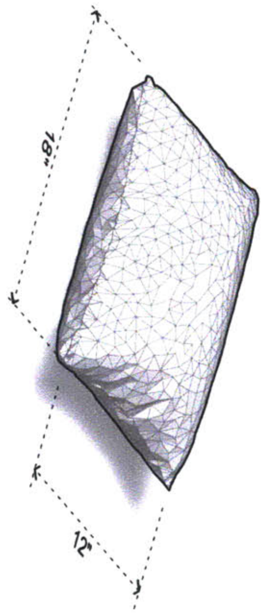

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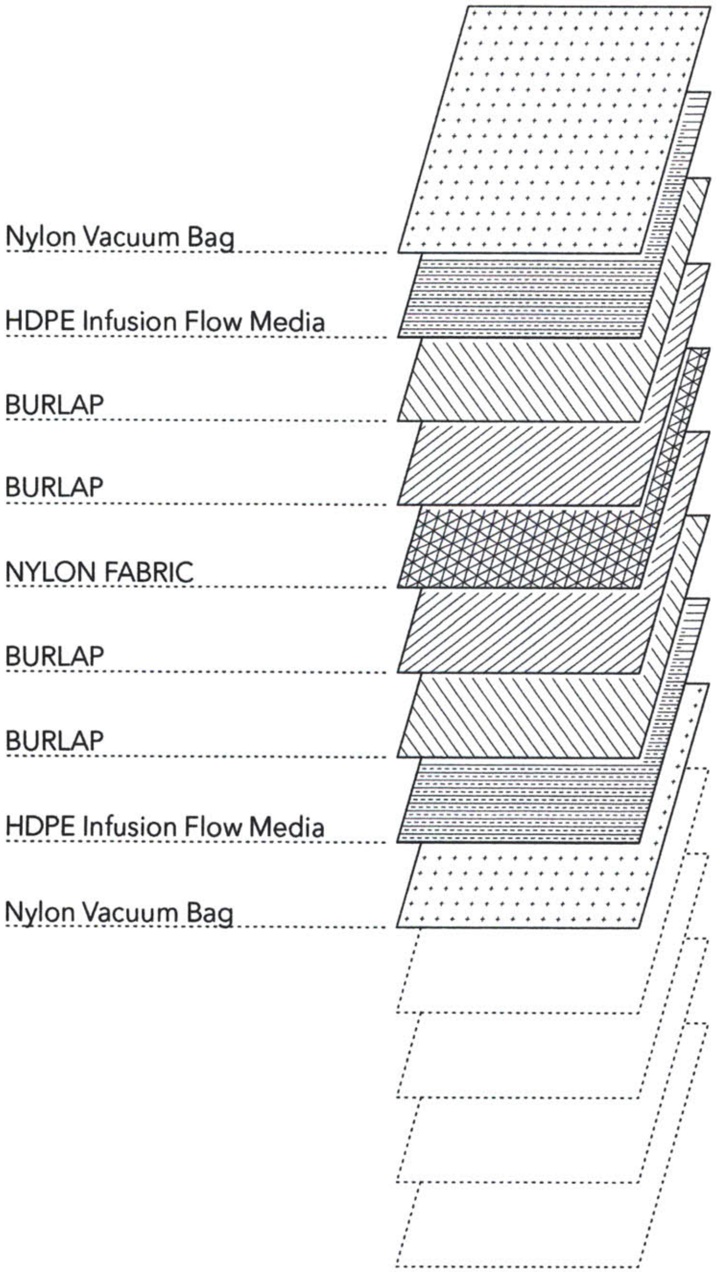

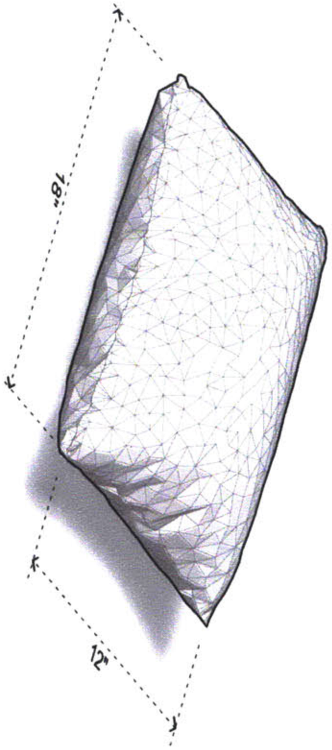

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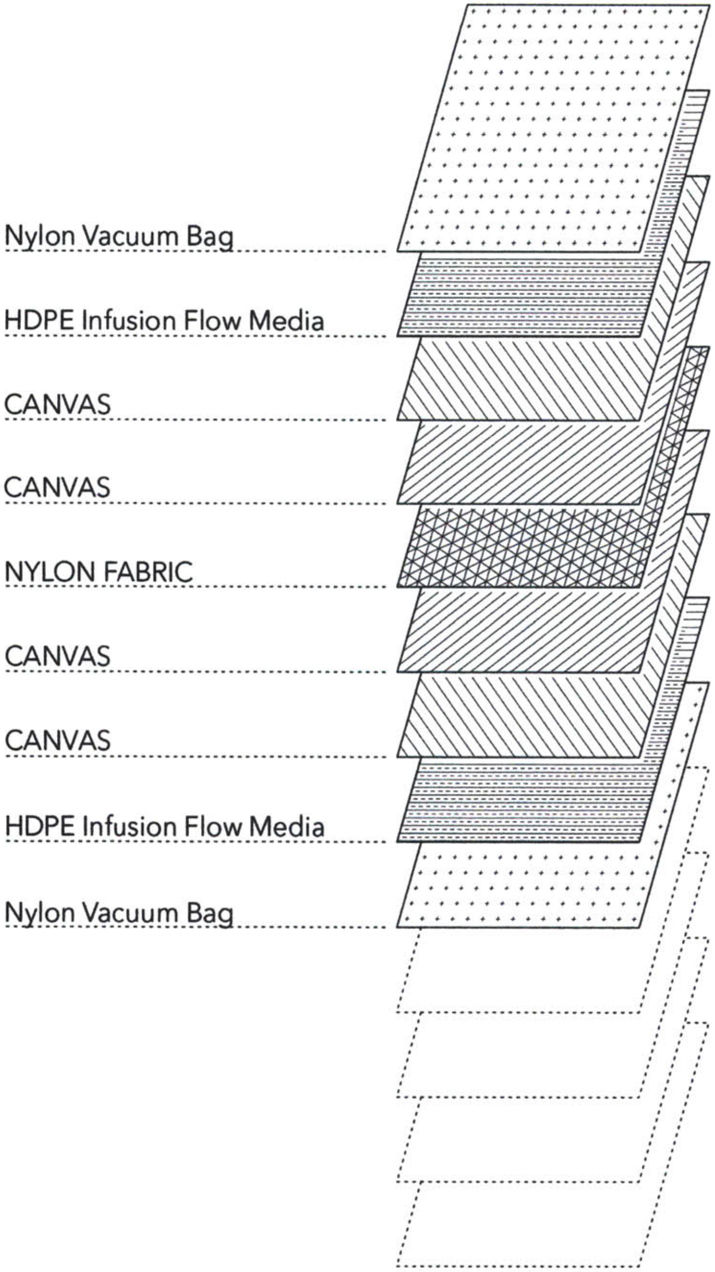

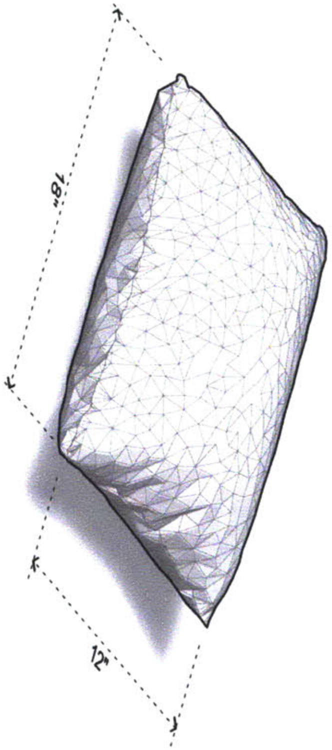

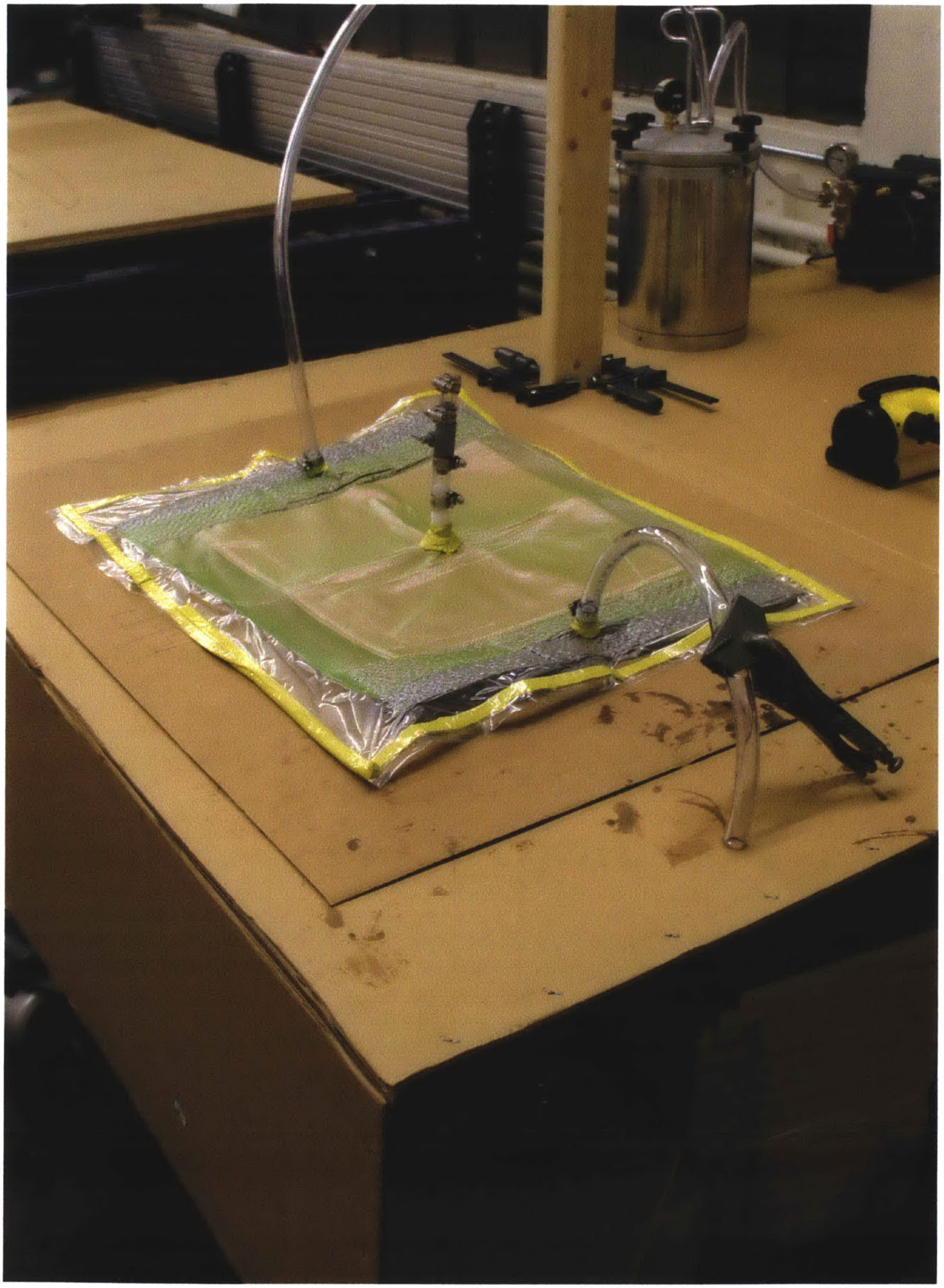

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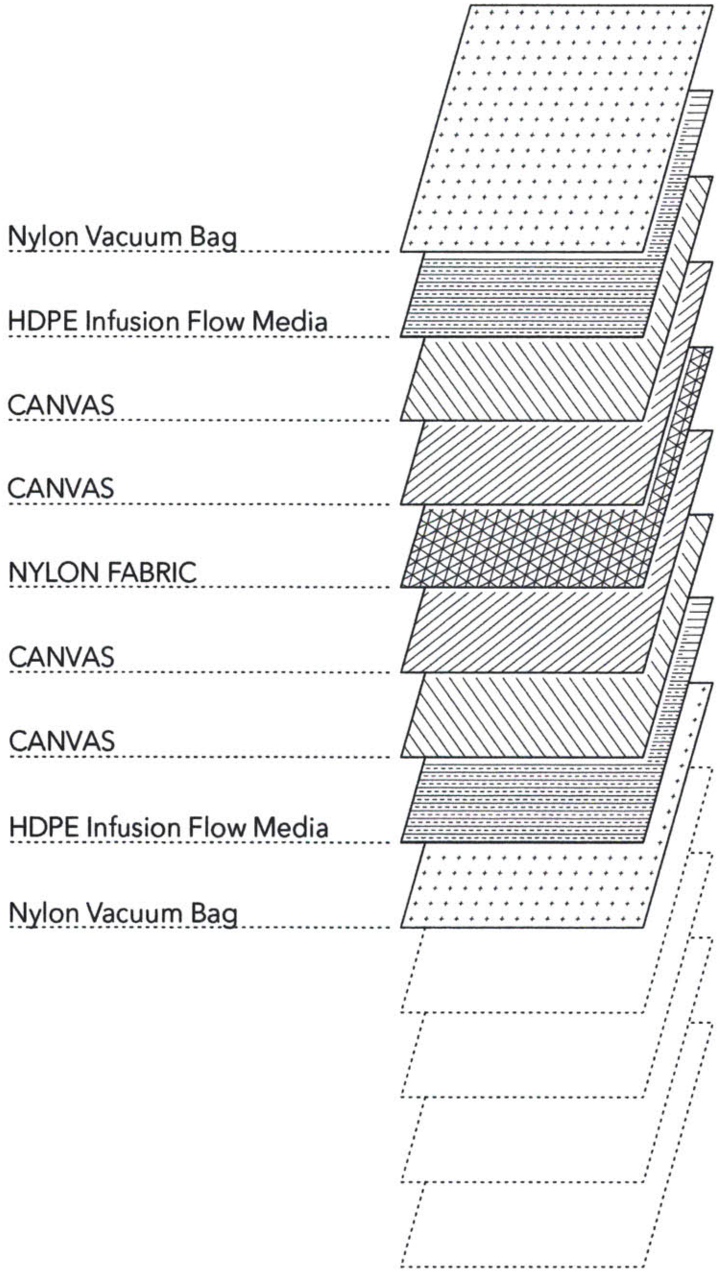

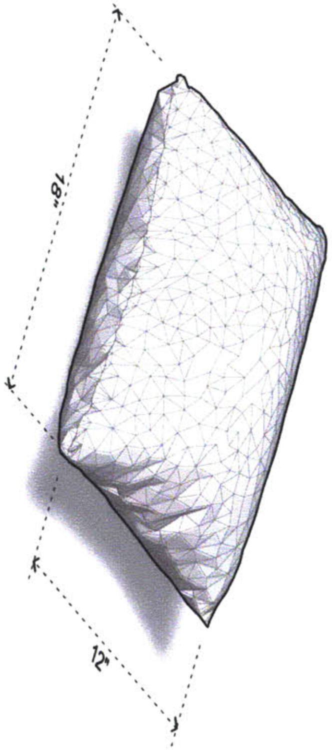

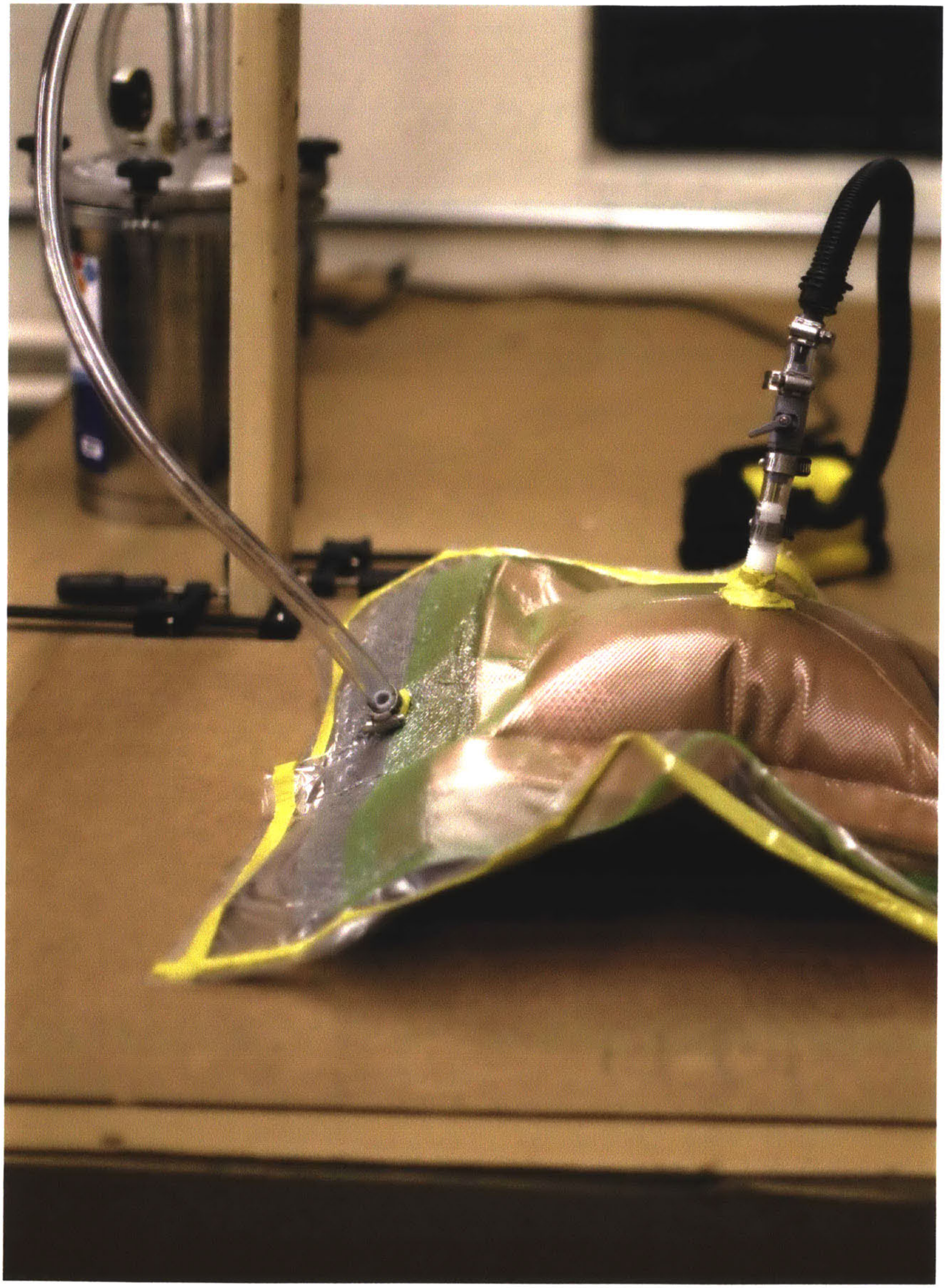

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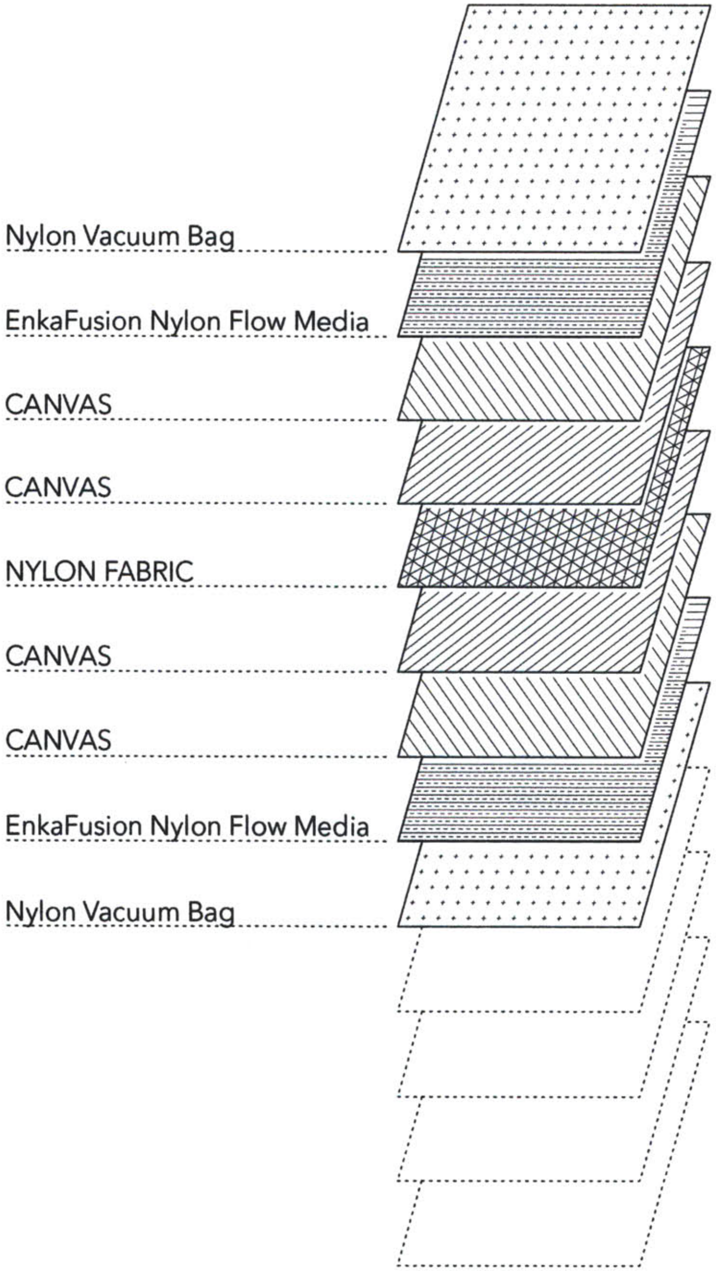

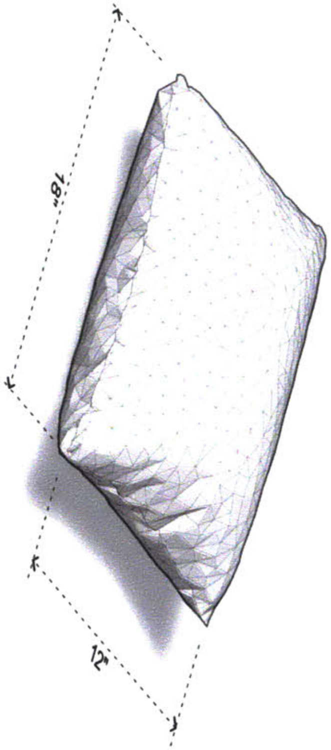

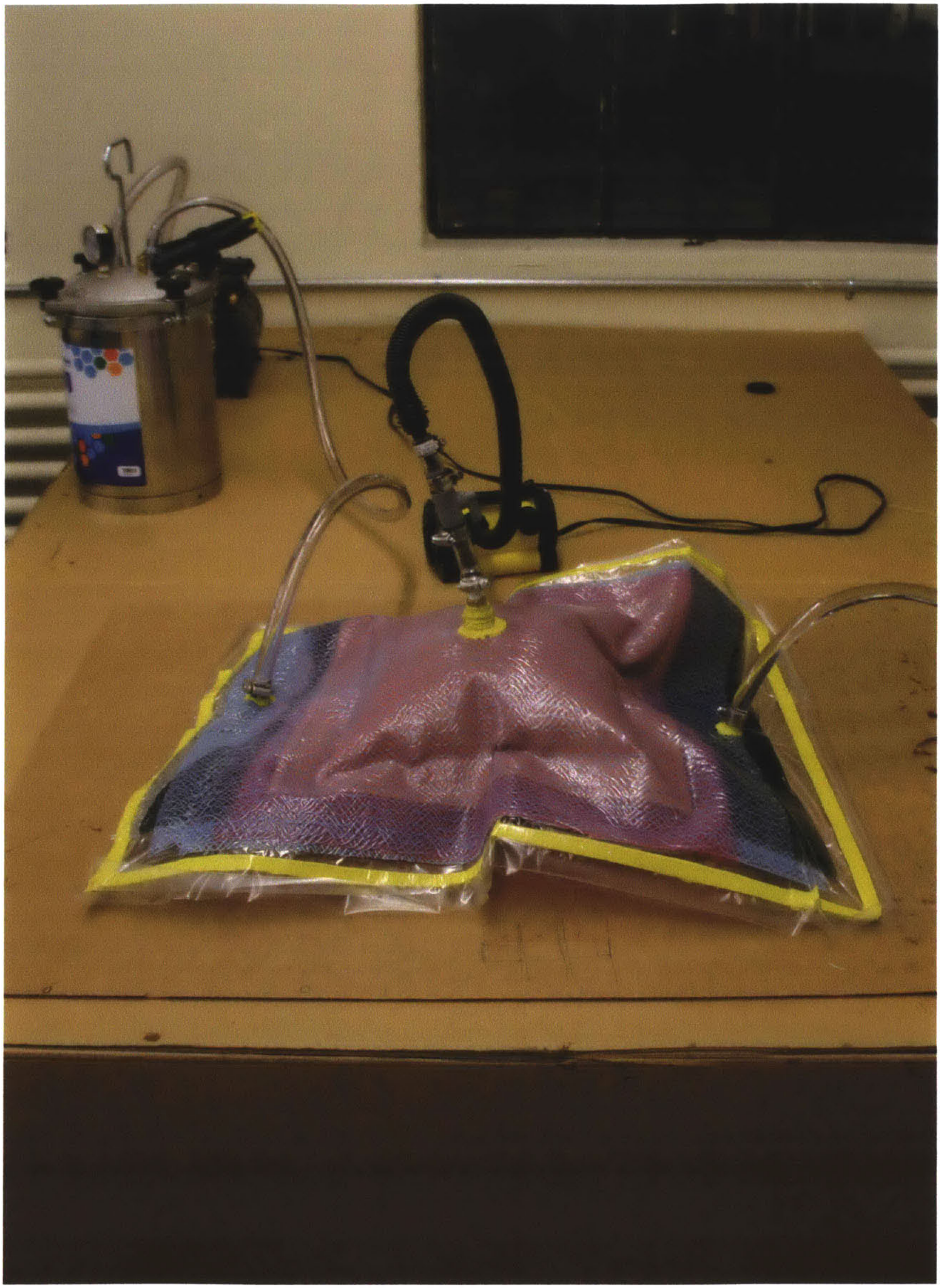

07 /// PROTOTYPE 08

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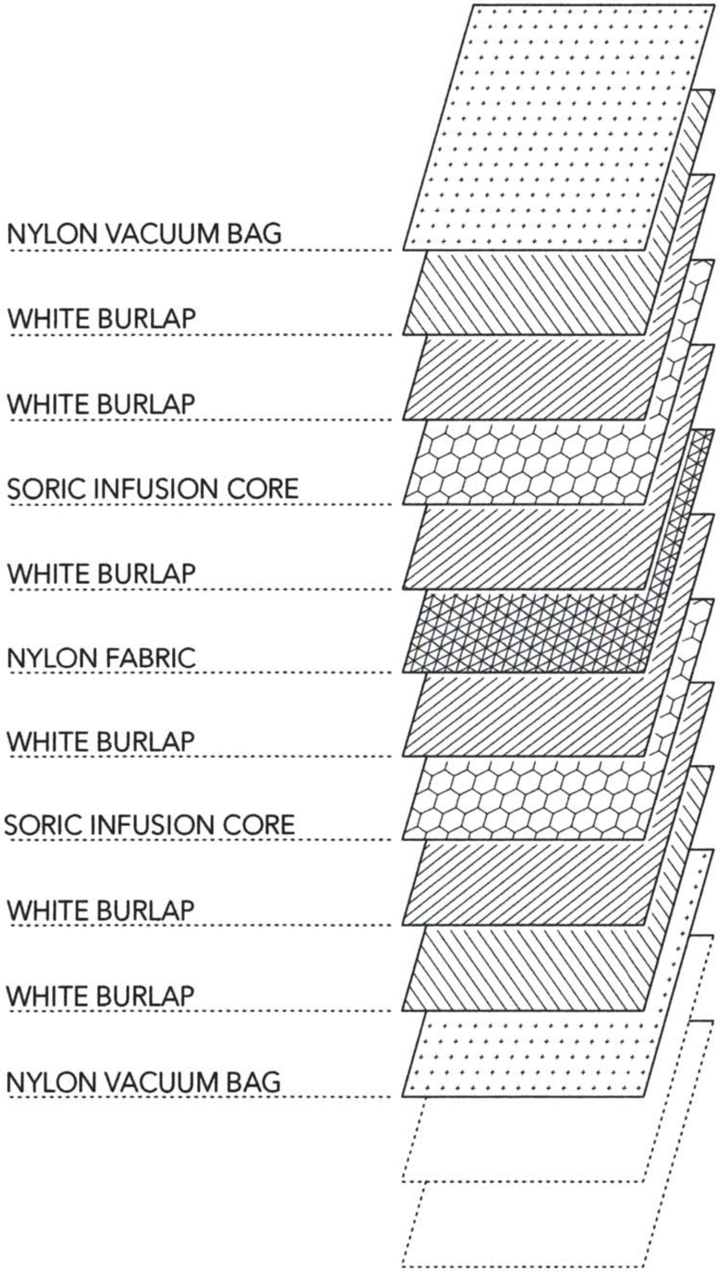

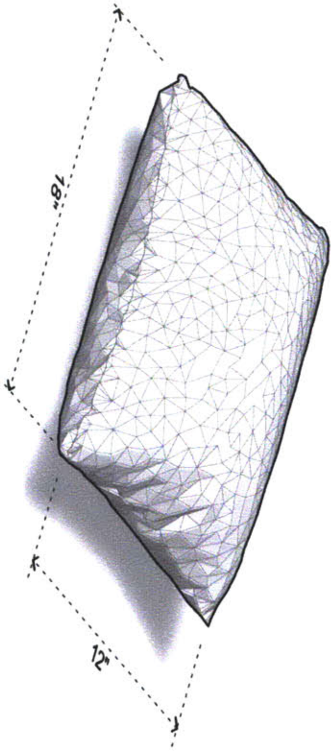

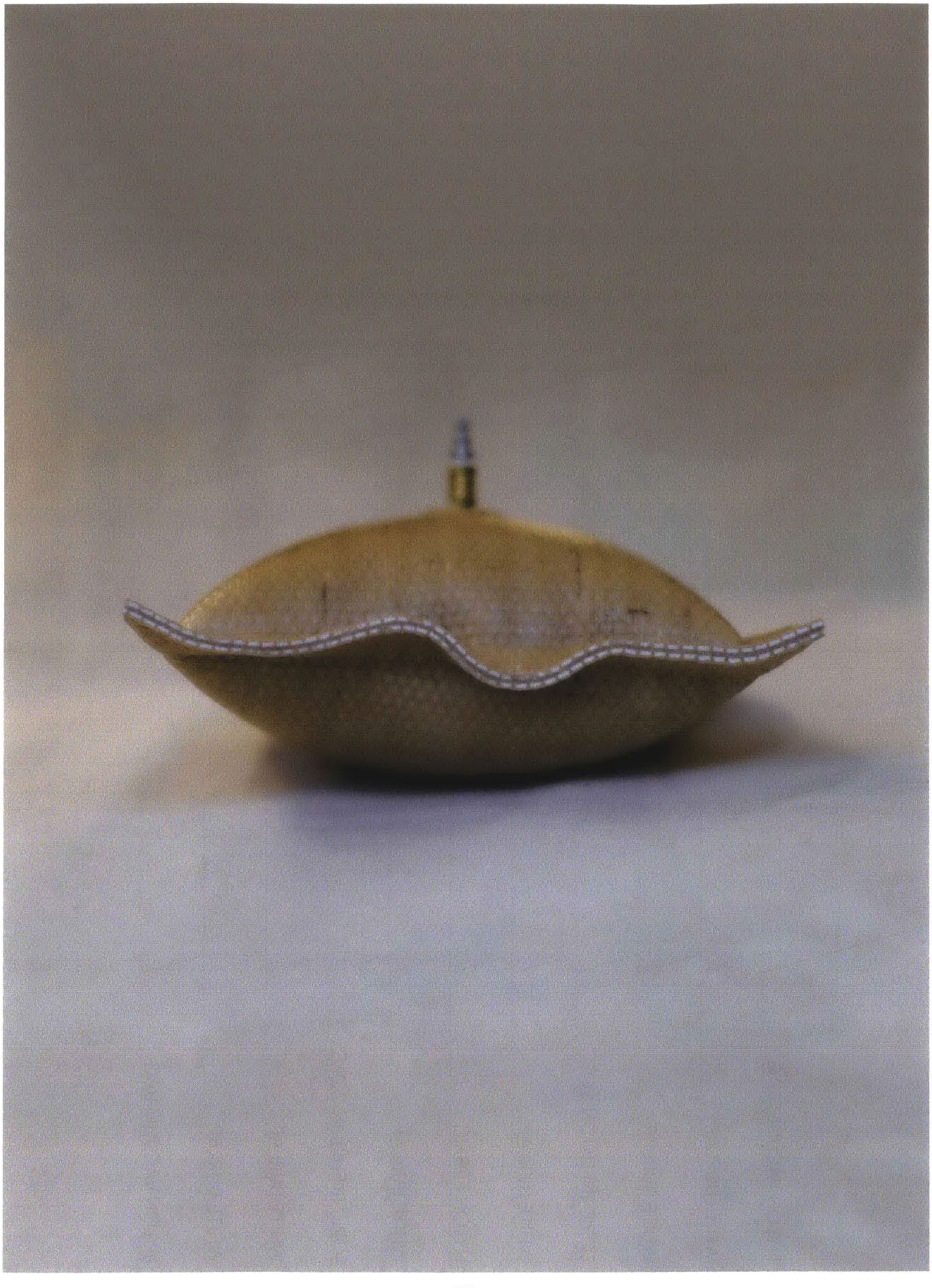

07 /// PROTOTYPE 09

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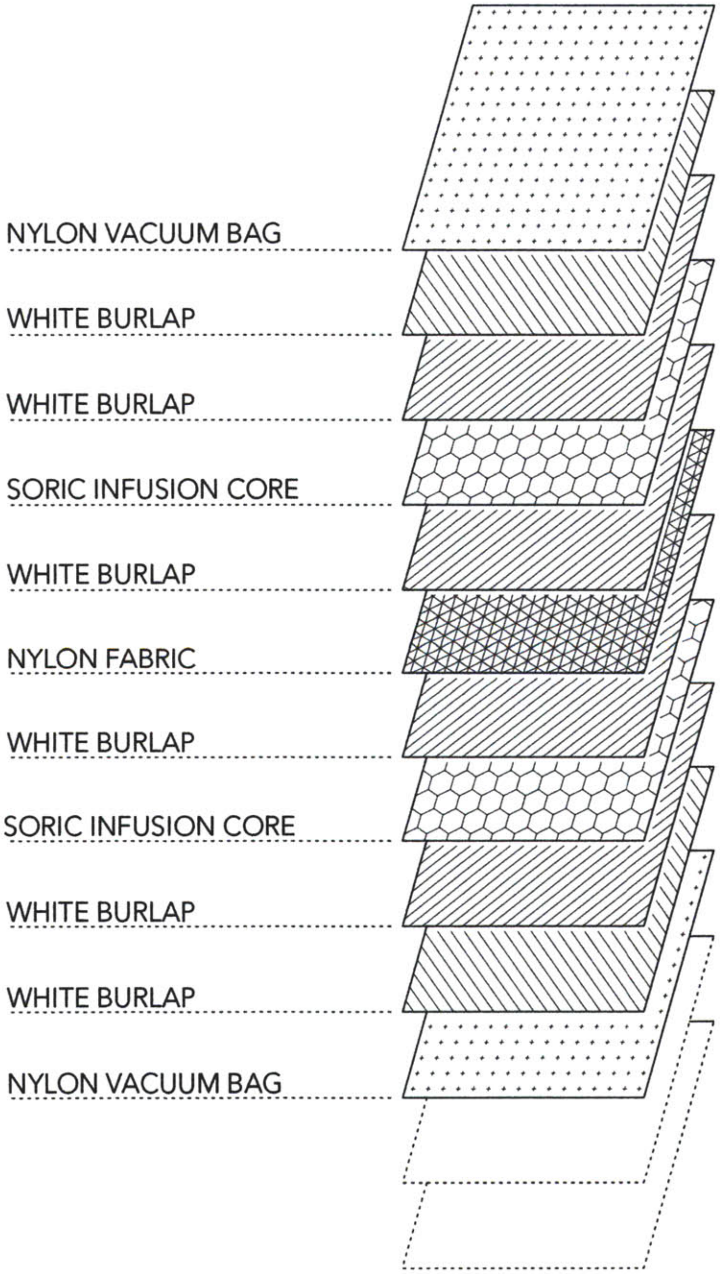

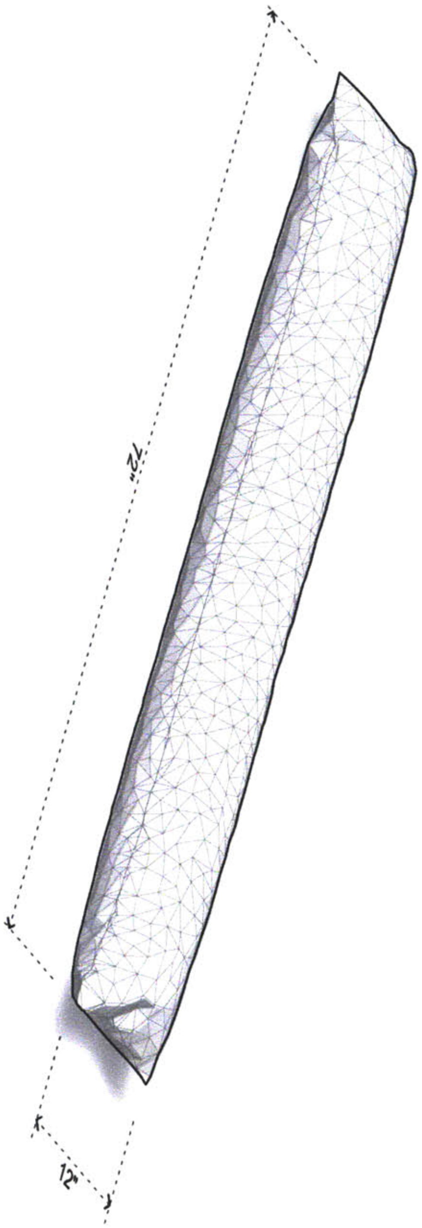

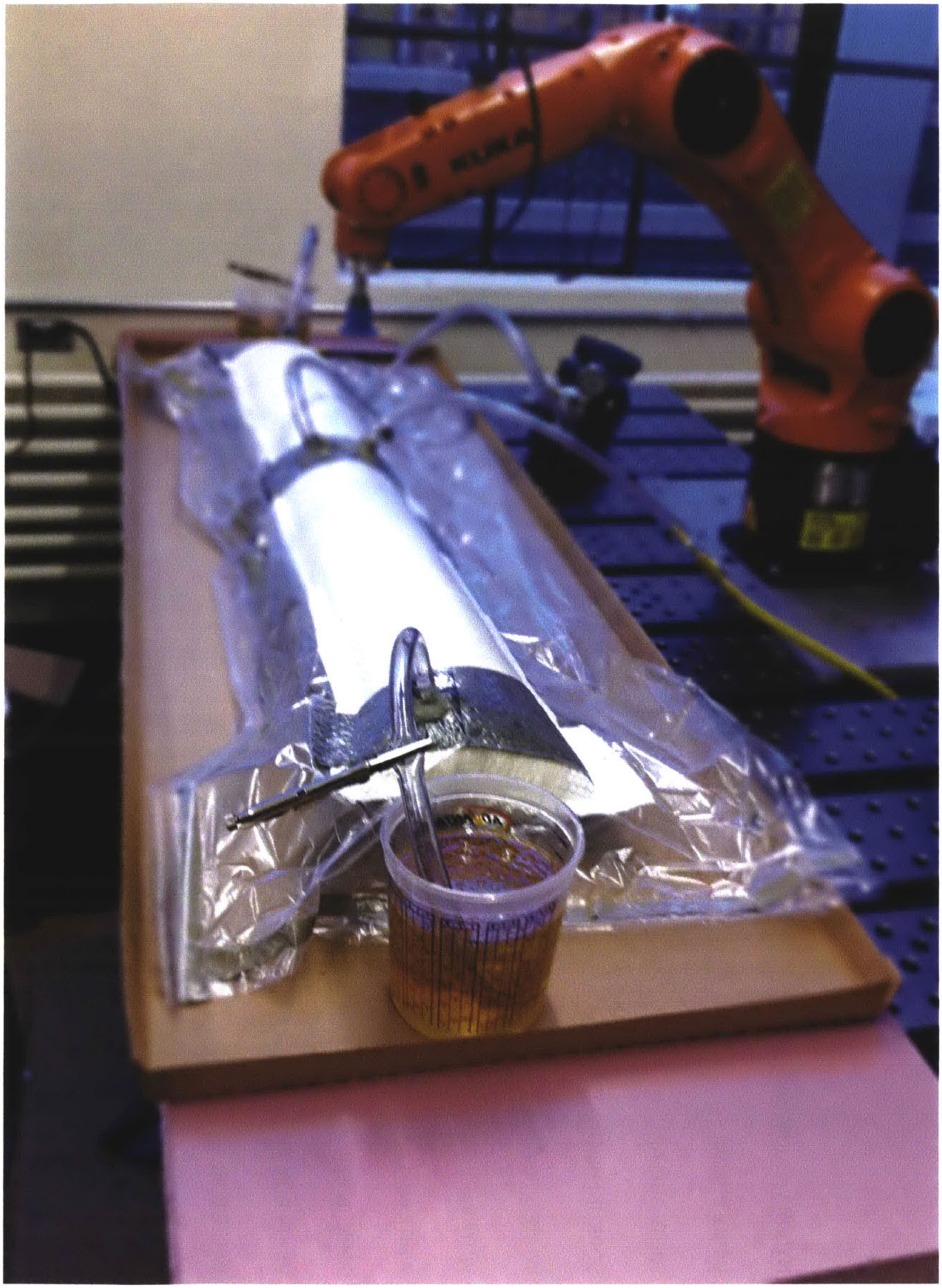

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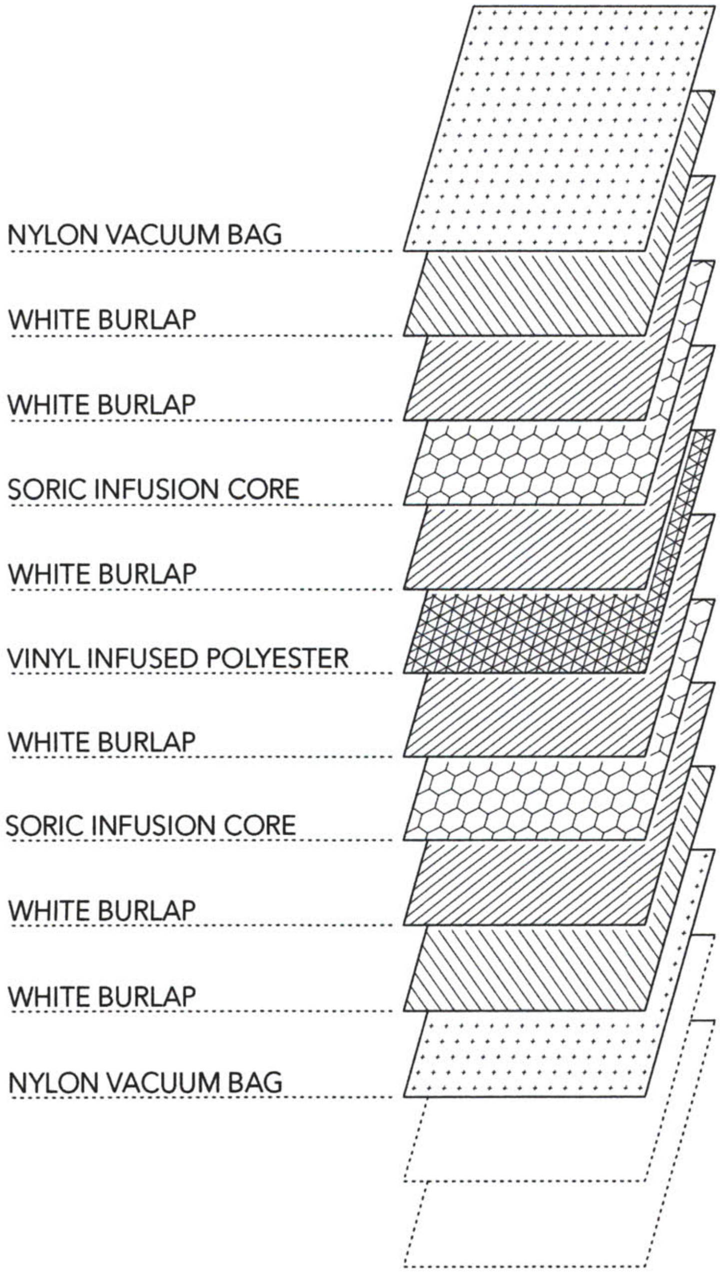

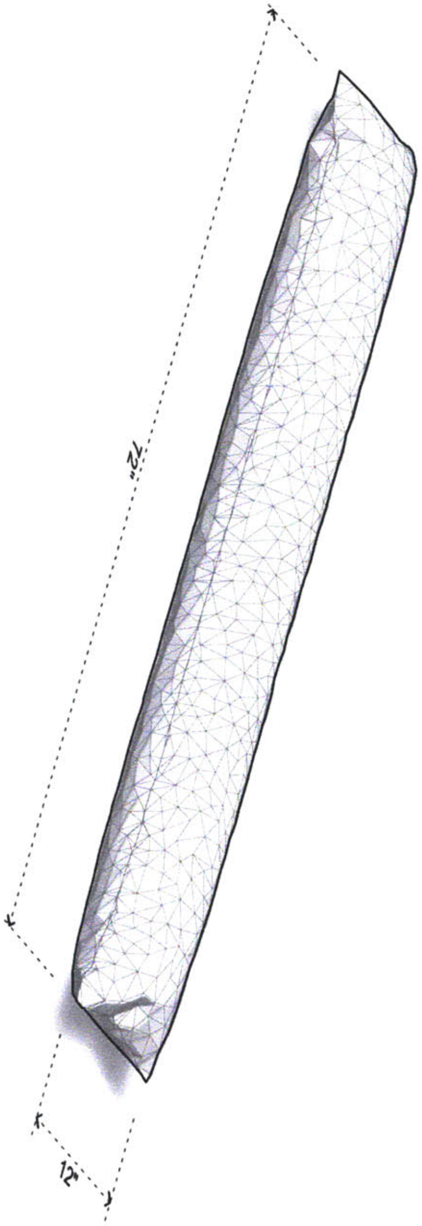

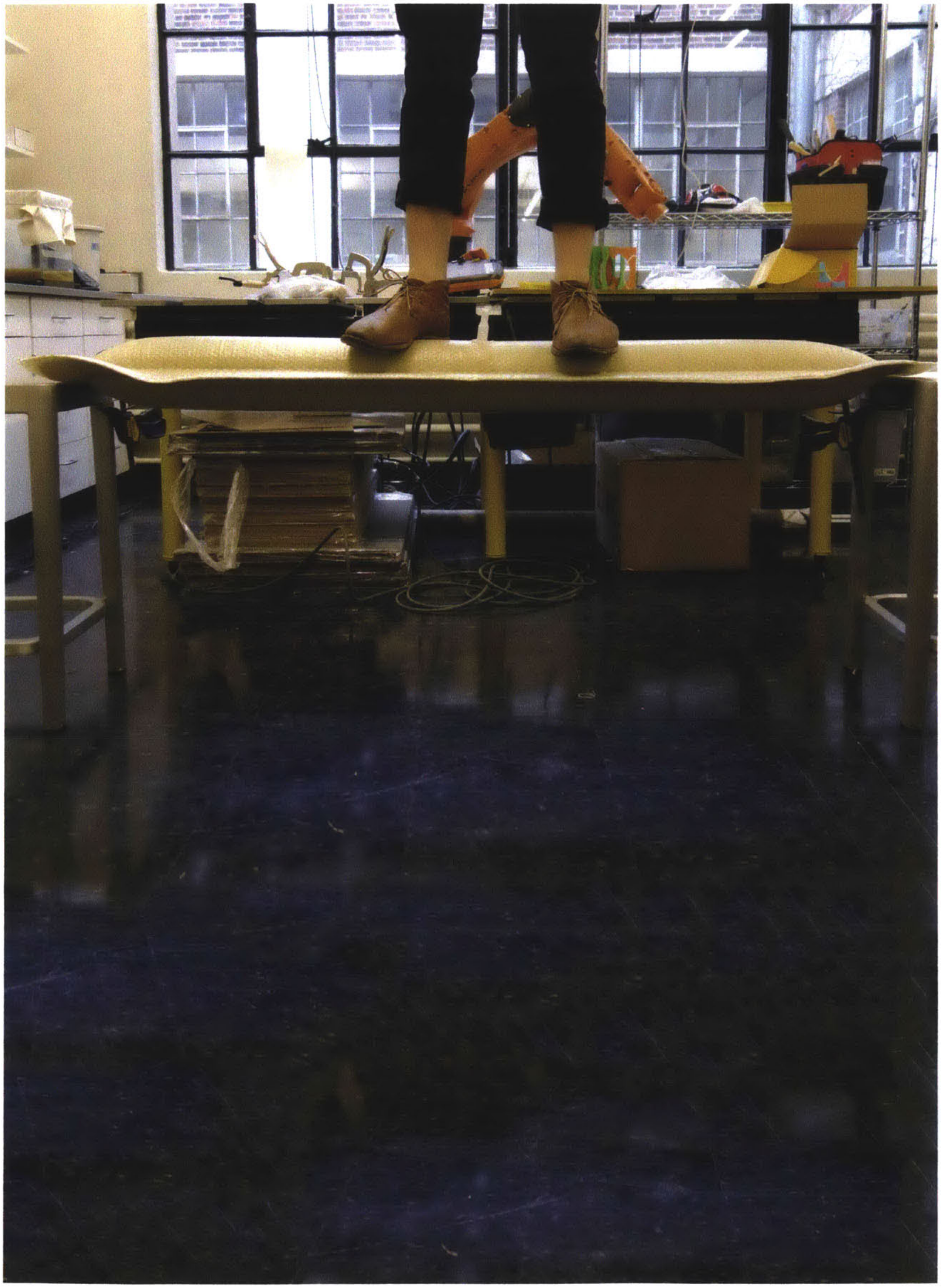

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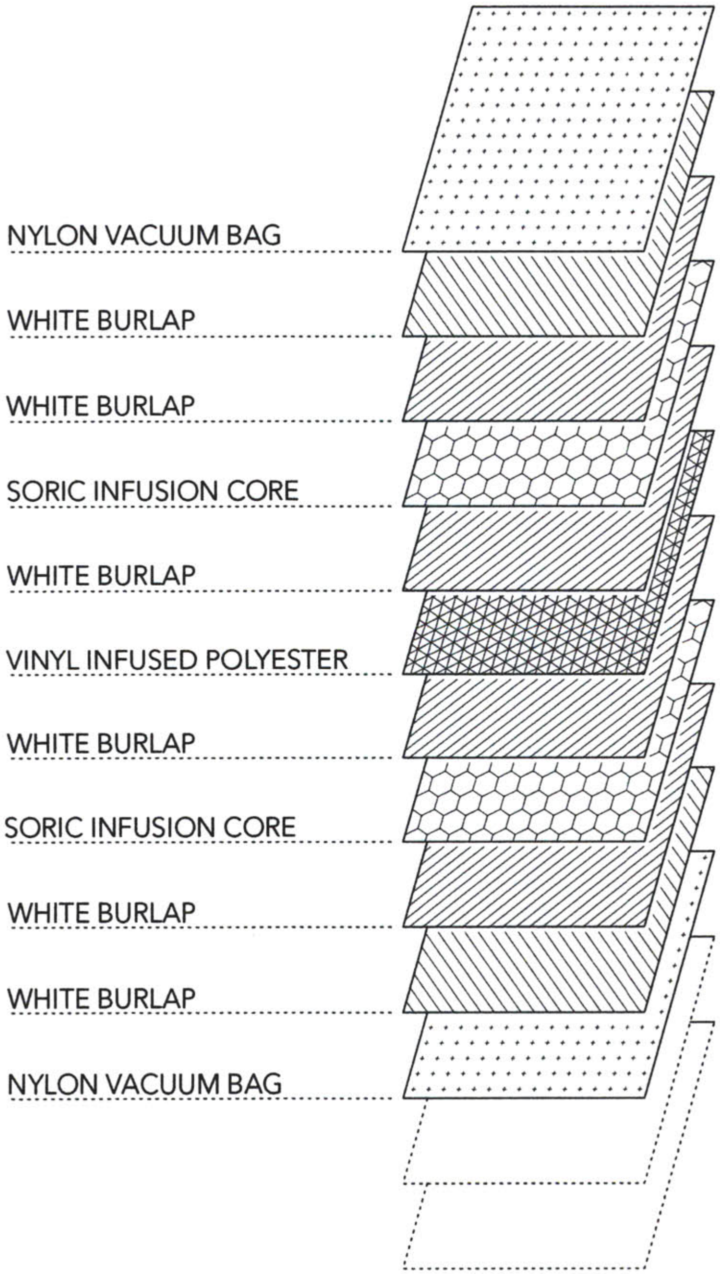

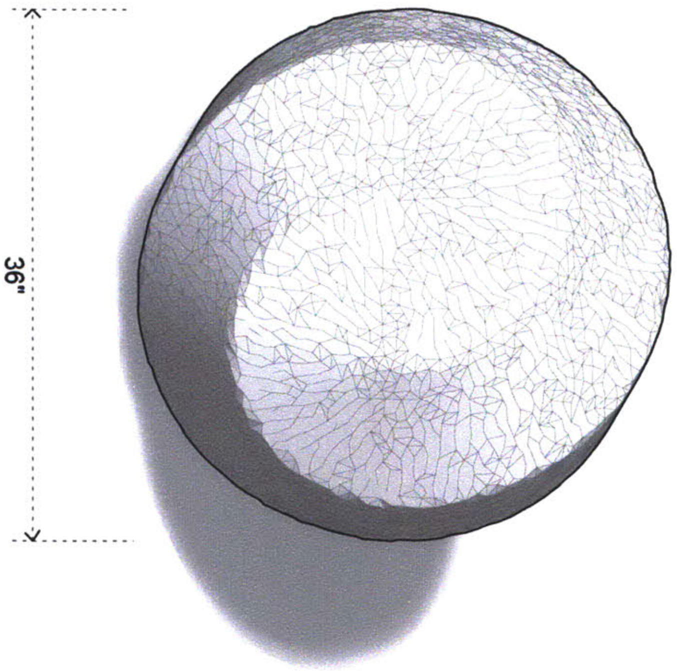

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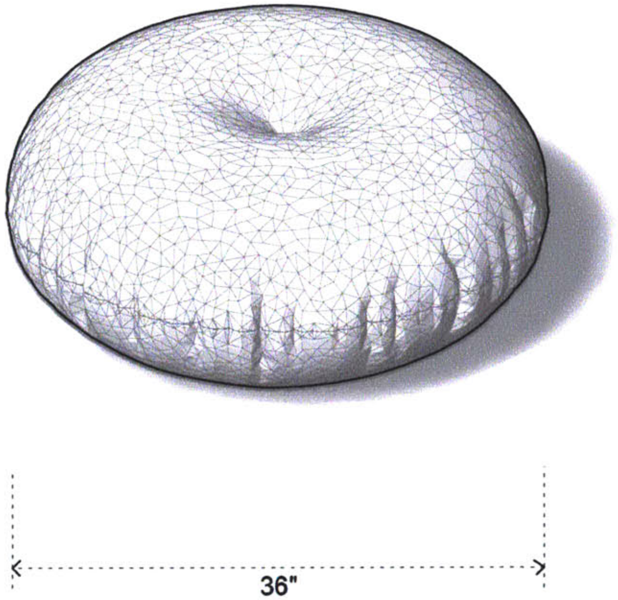

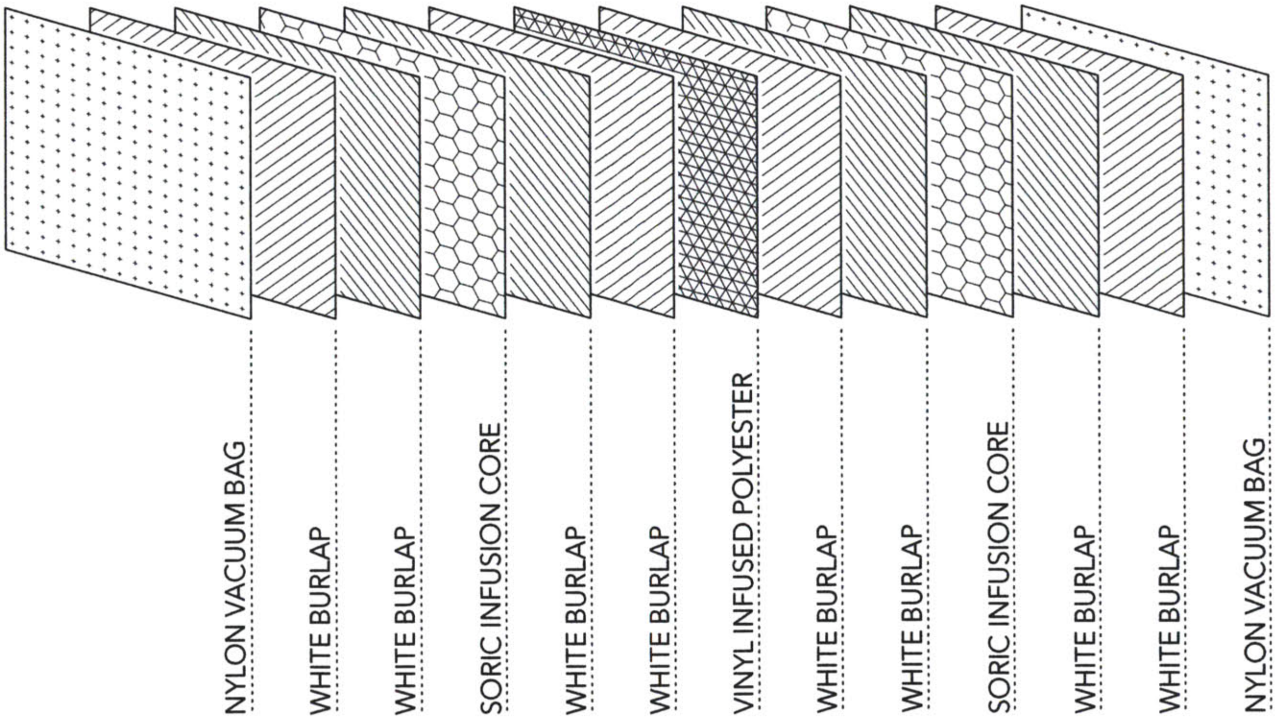

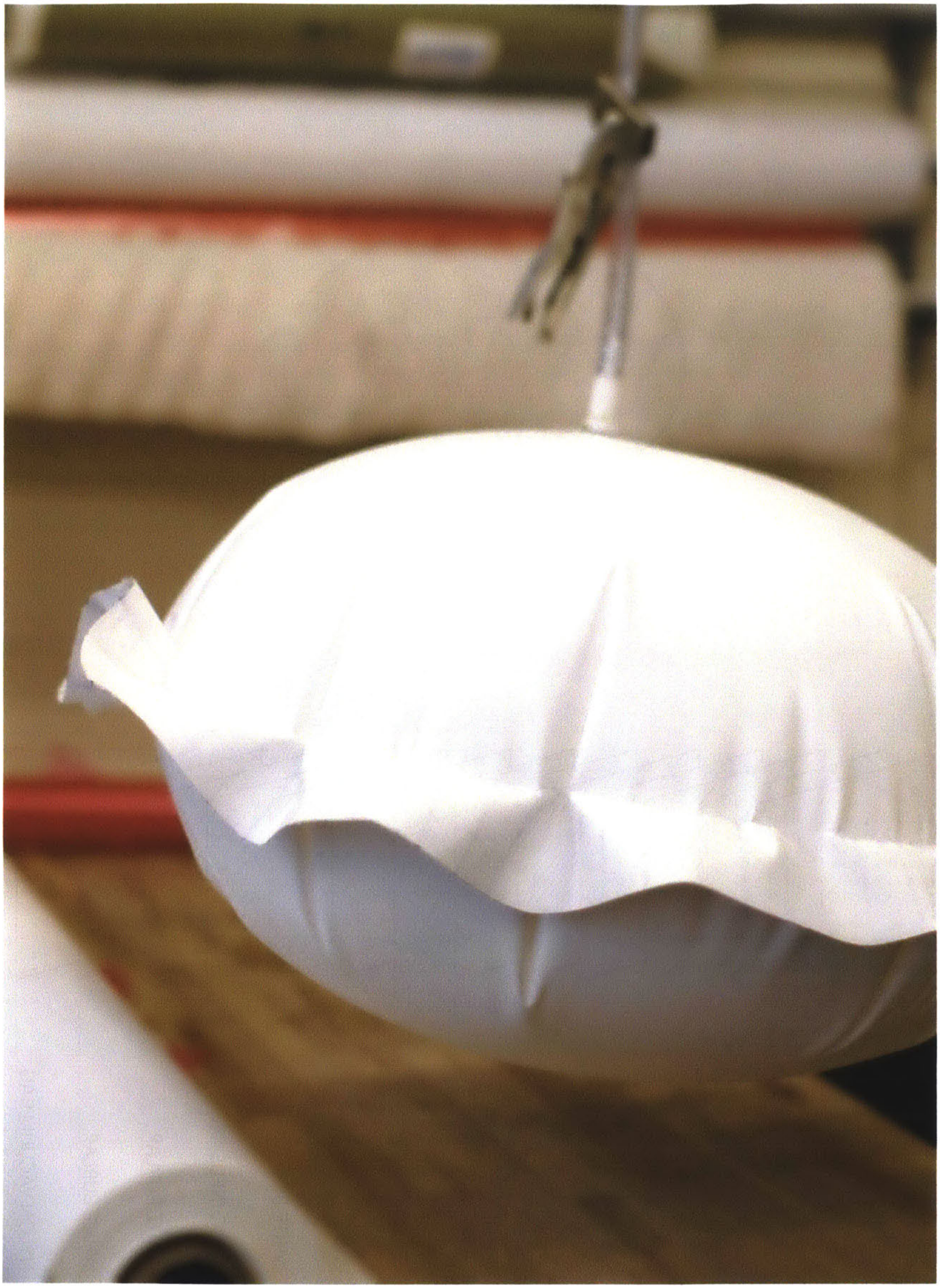

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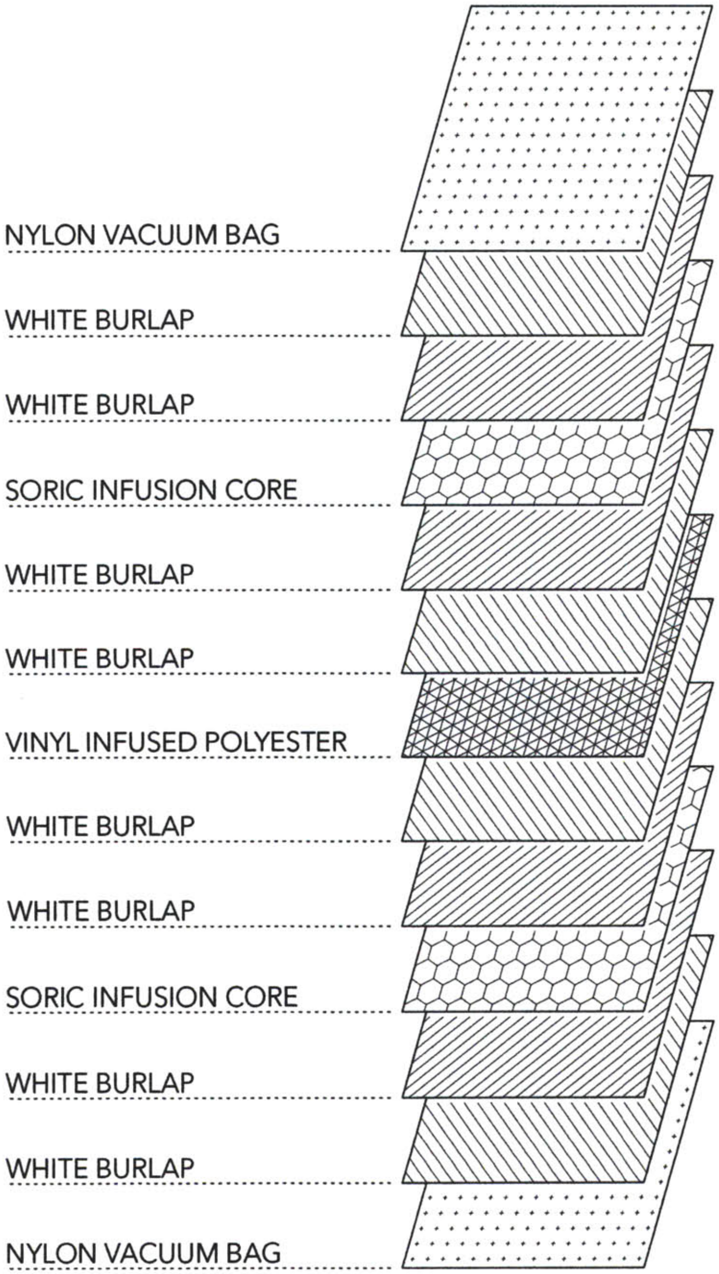

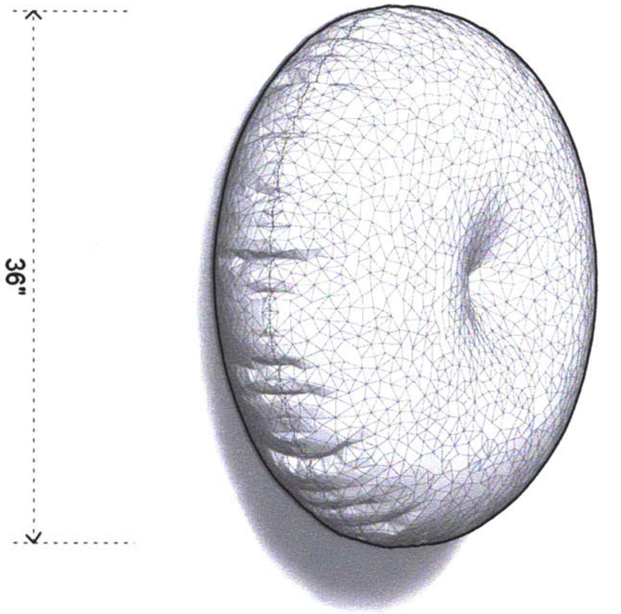

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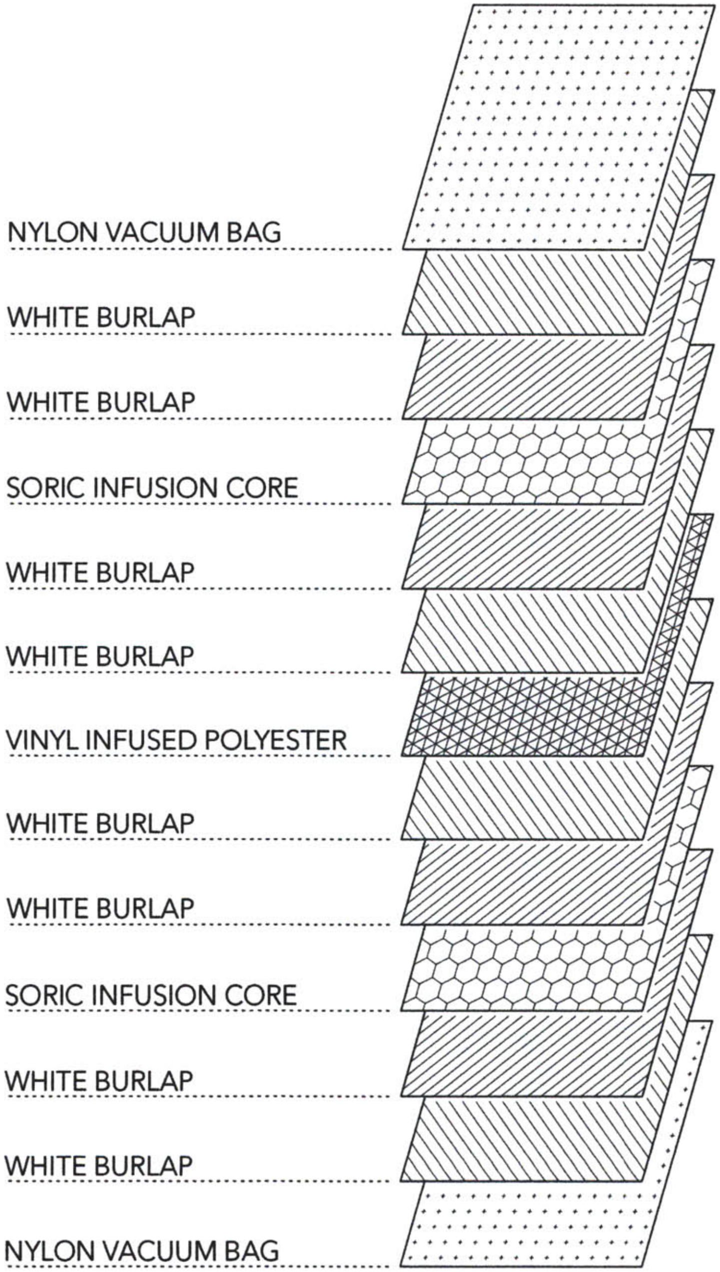

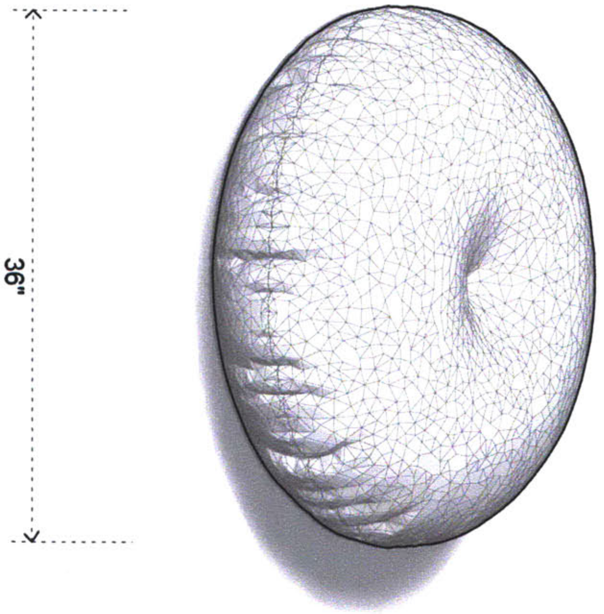

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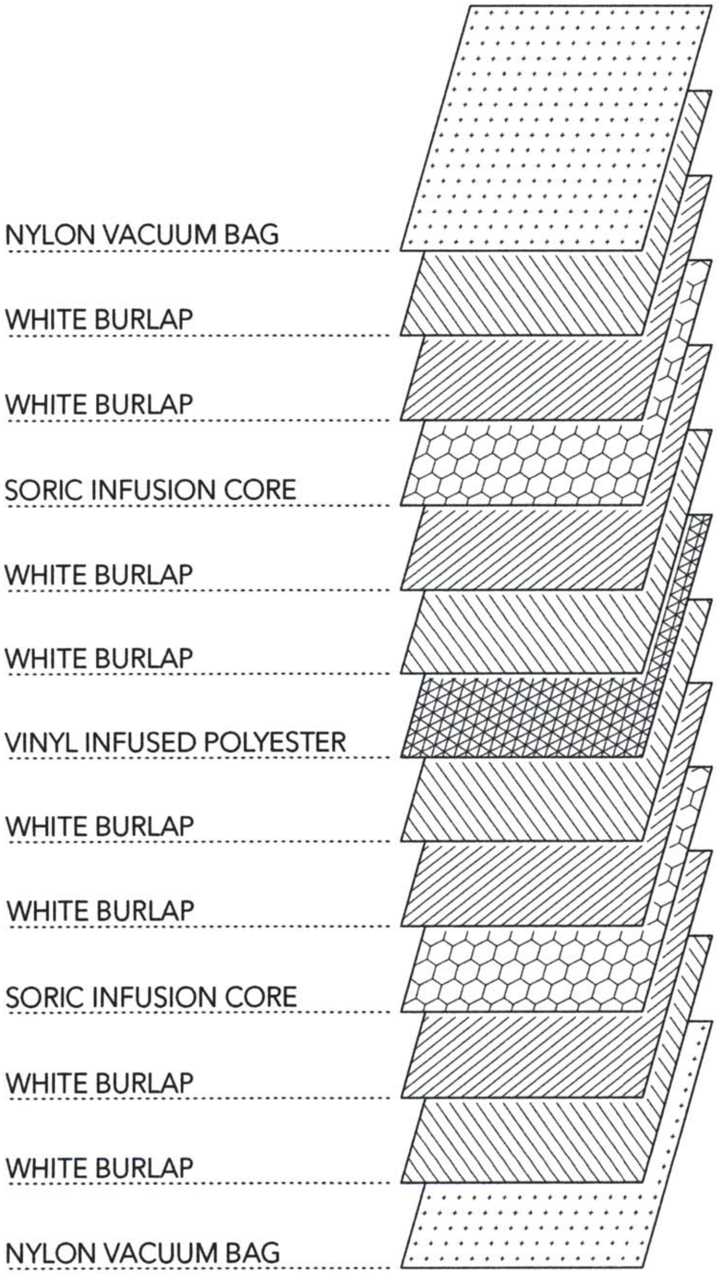

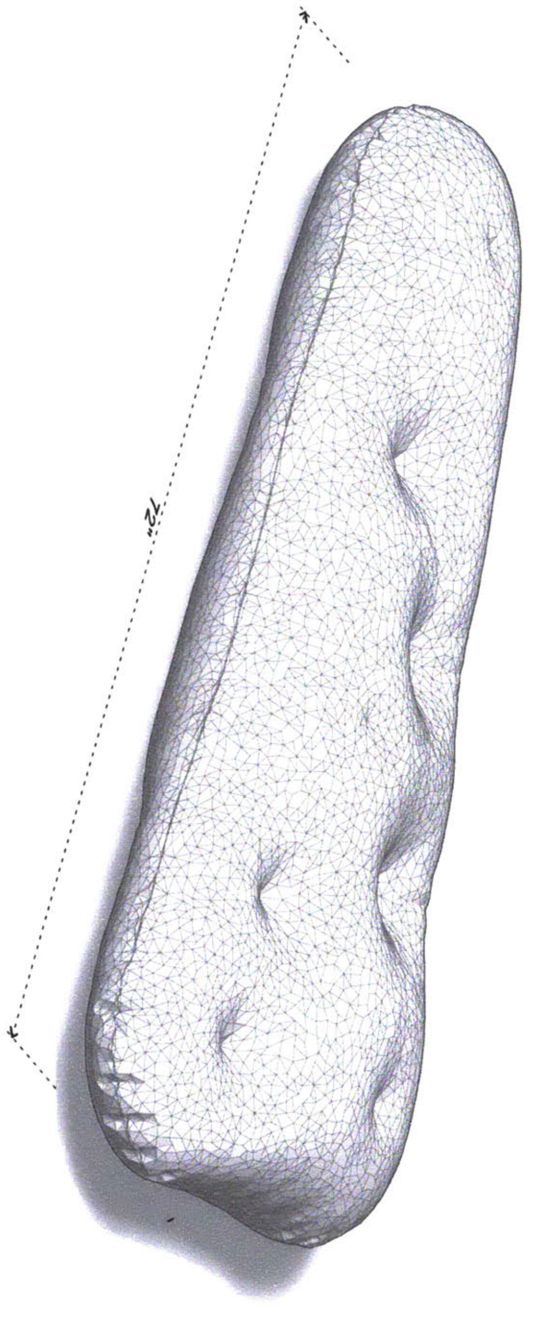

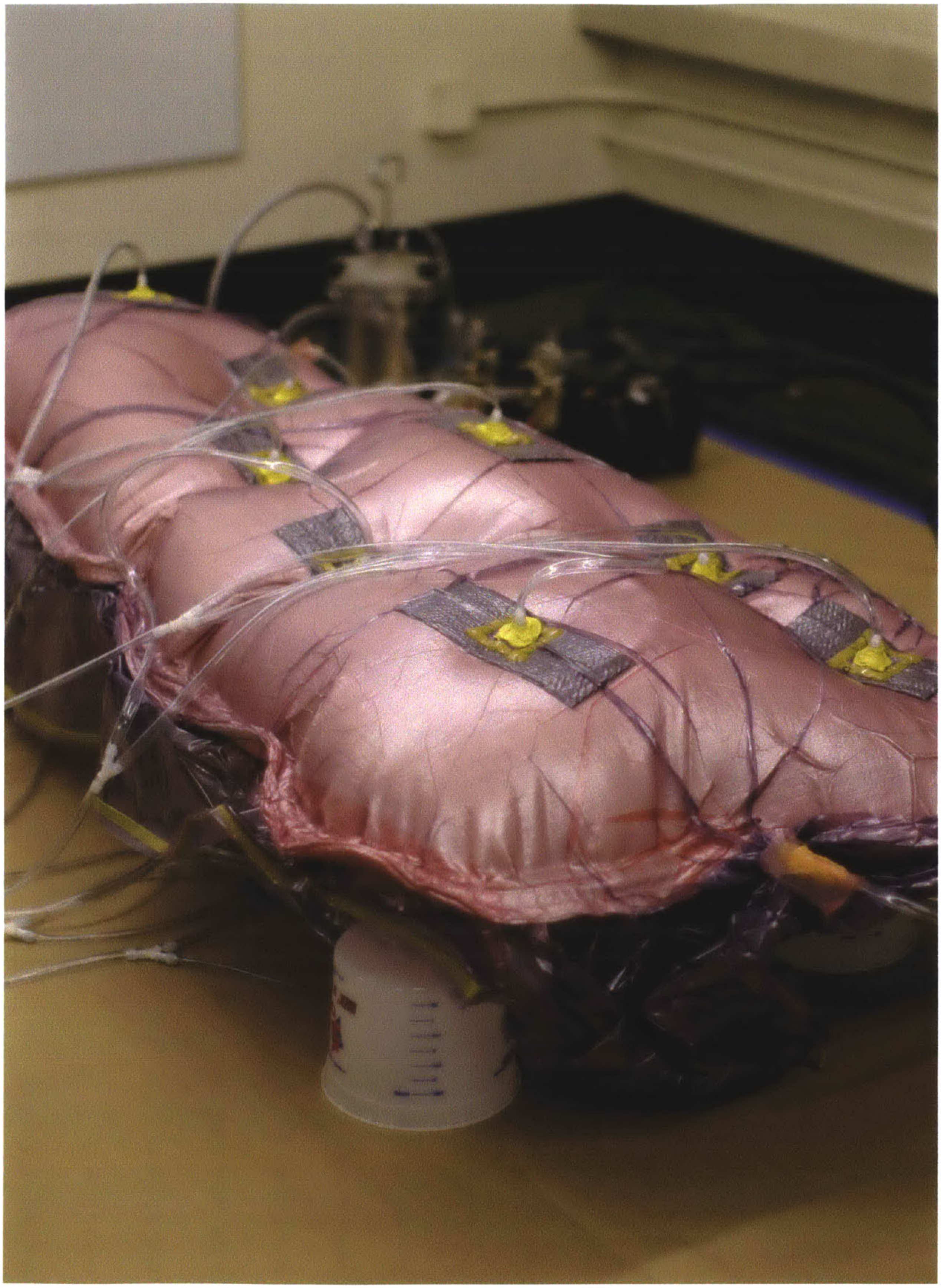

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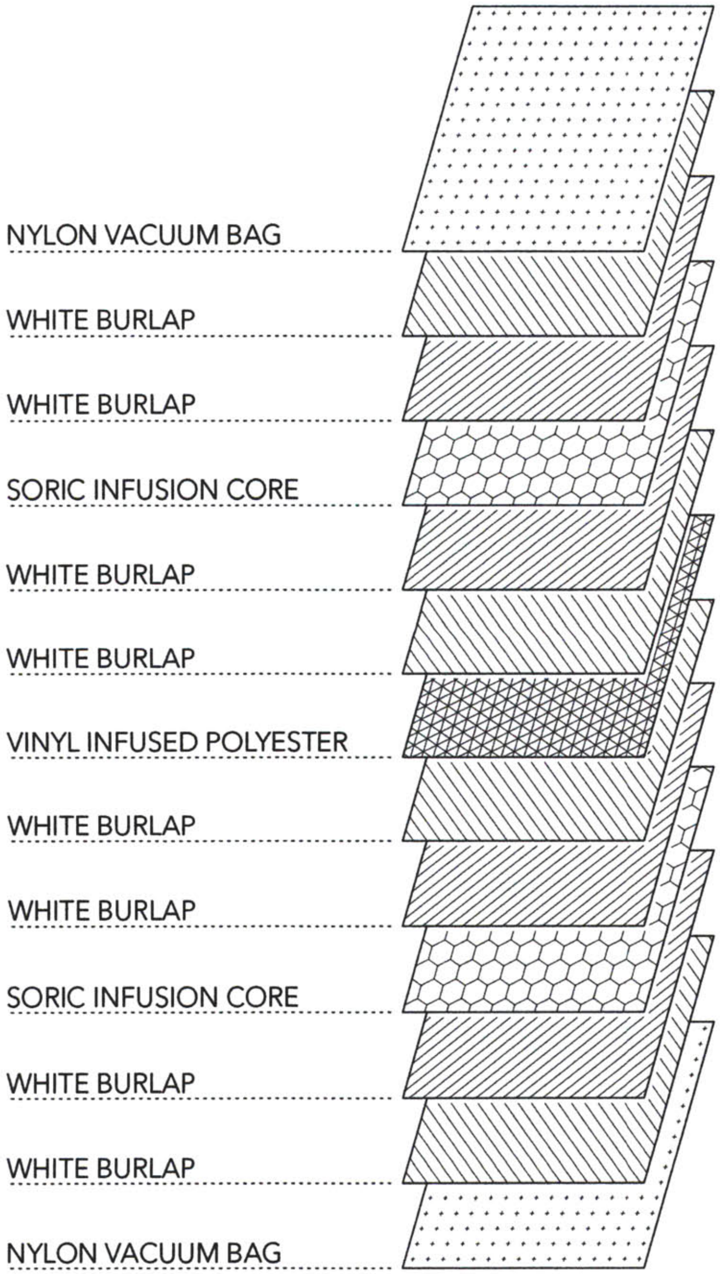
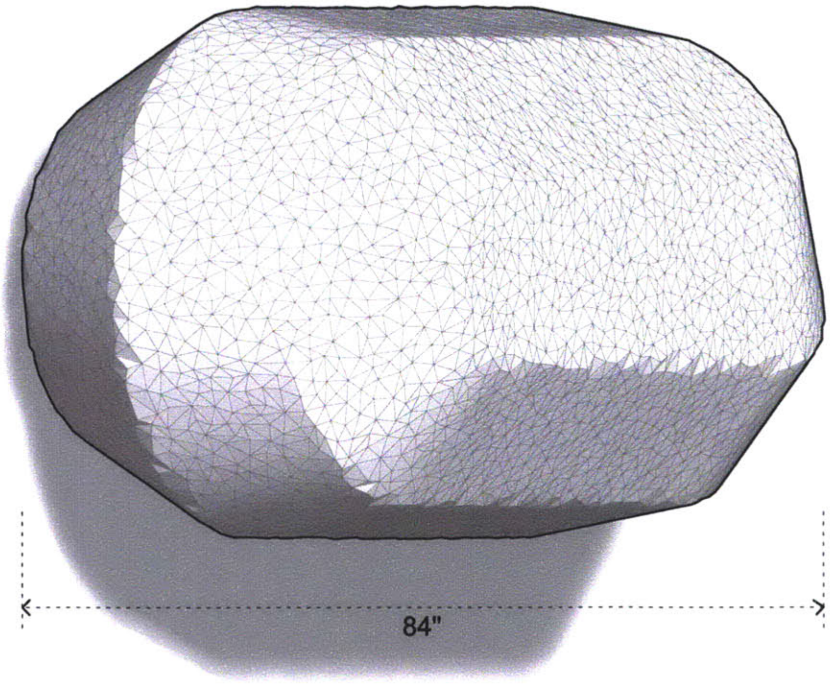
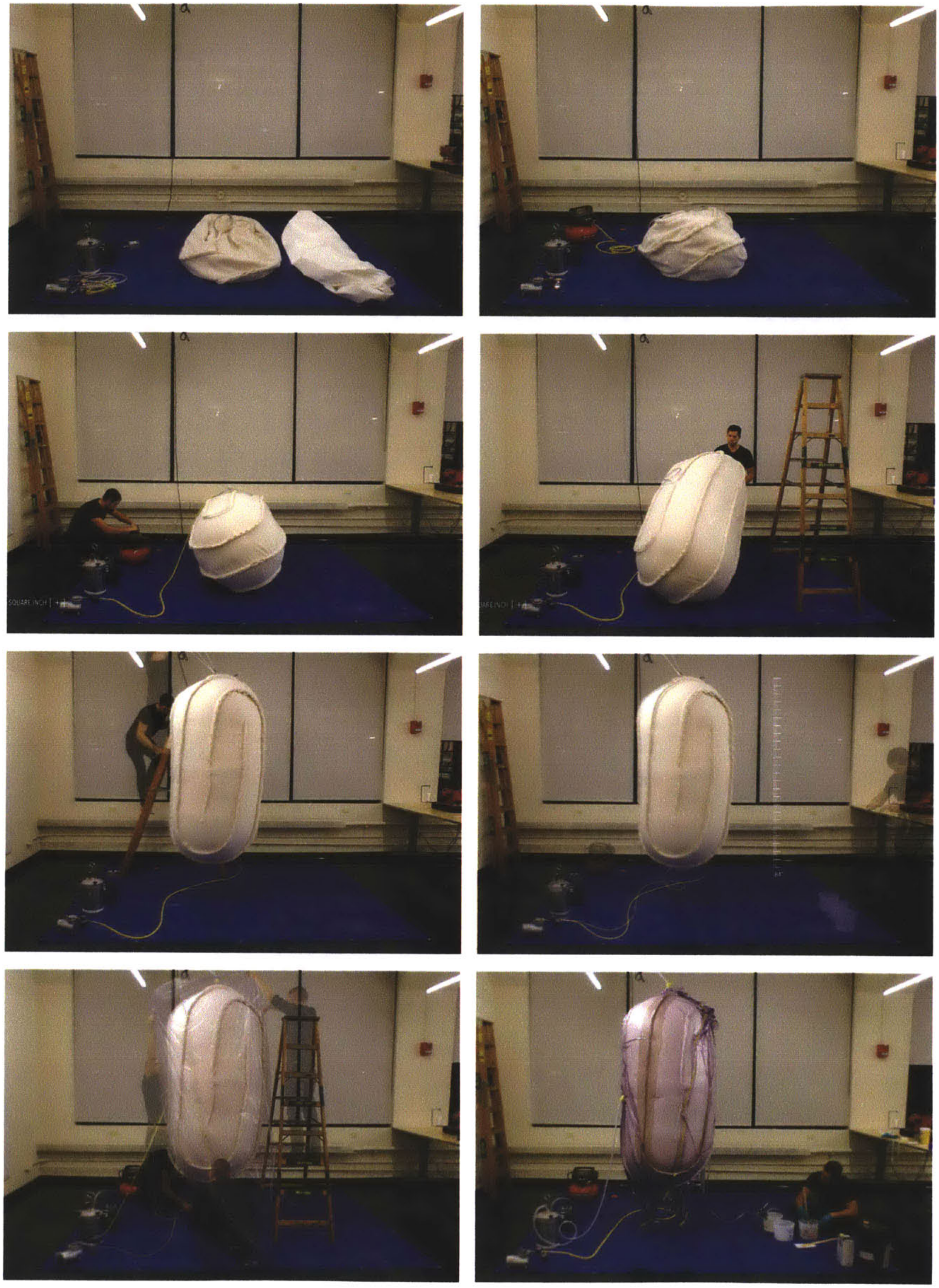
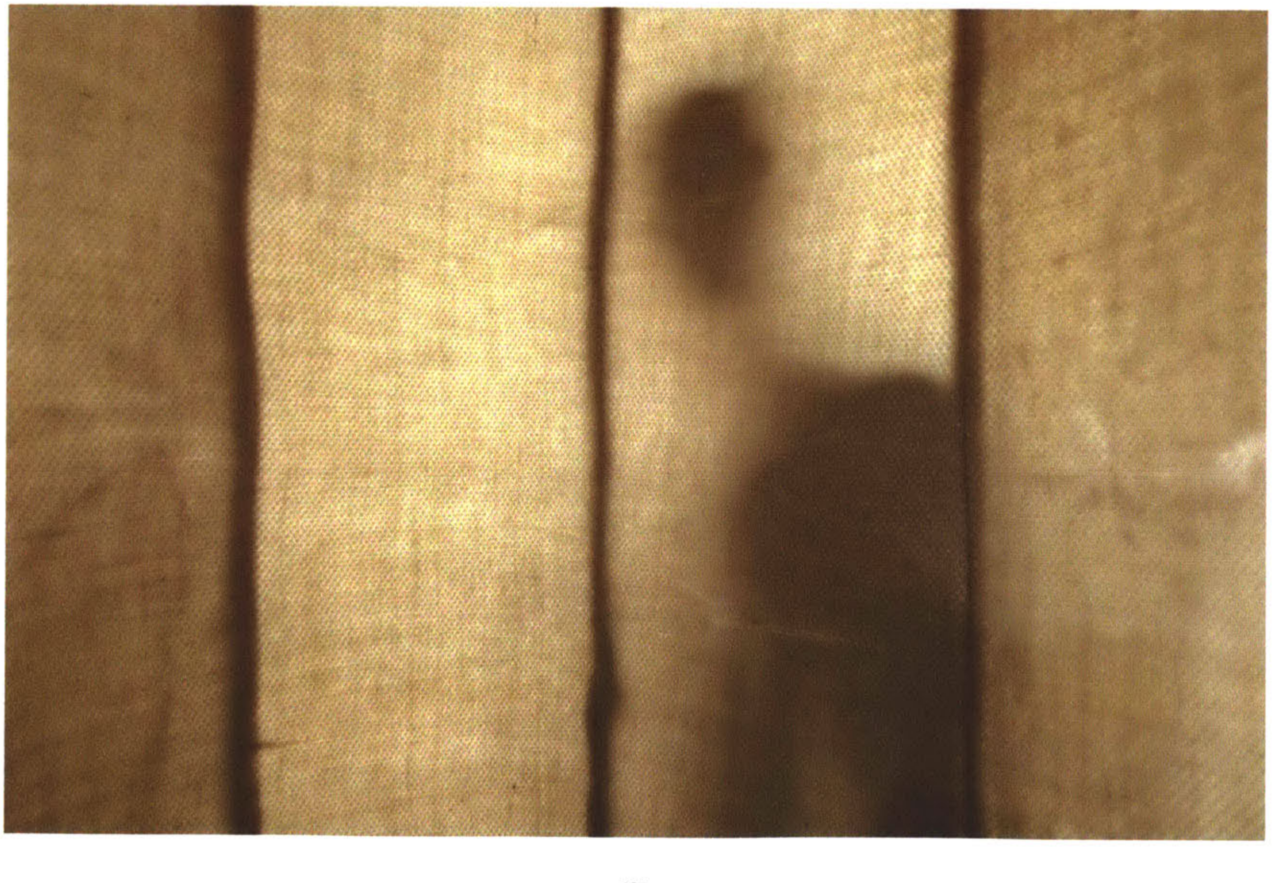
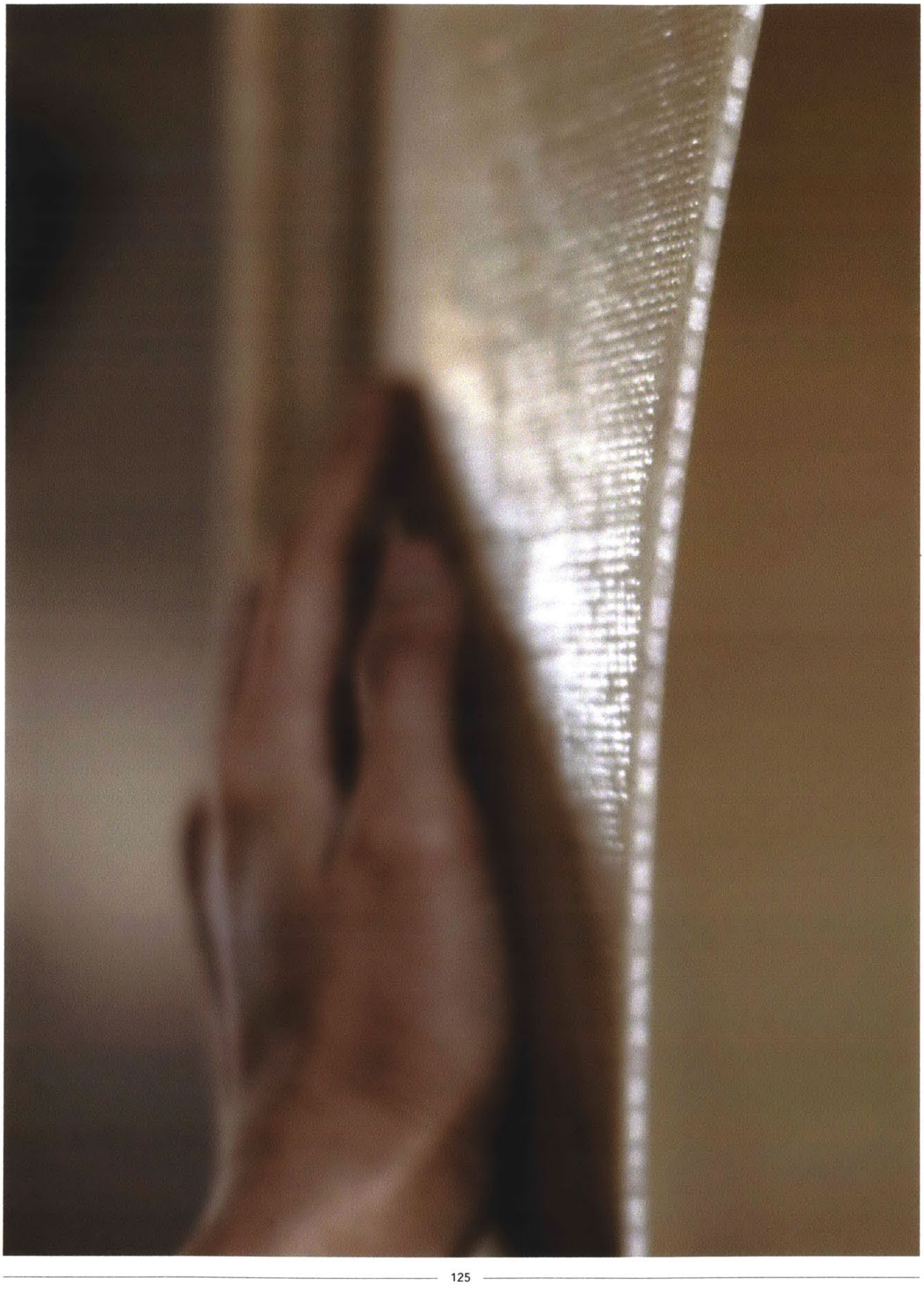


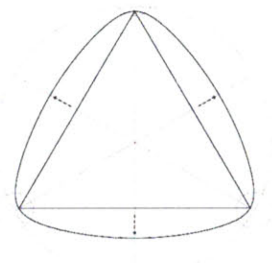




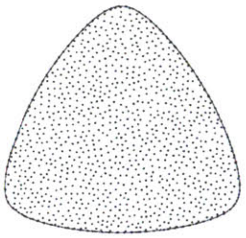




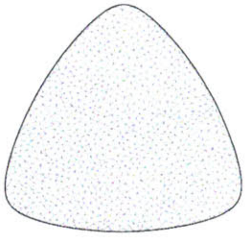
08 // SHELTERS



01 /// 2D CURVE



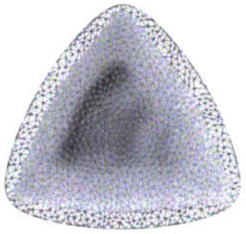
02 /// POPULATE GEOMETRY



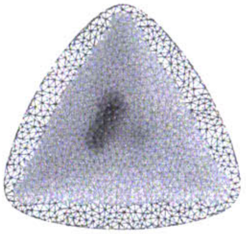
03 /// DELUNARY MESH

04 /// INFLATION SIMULATION 00:00

05 /// INFLATION SIMULATION 00:13



06 /// INFLATION SIMULATION 00:25



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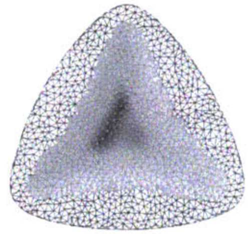

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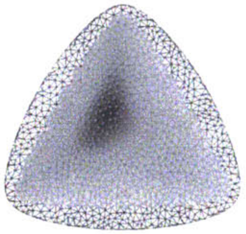

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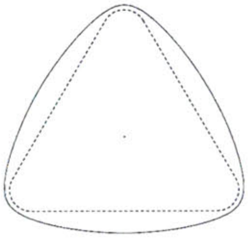
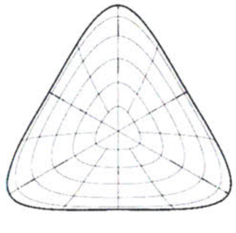
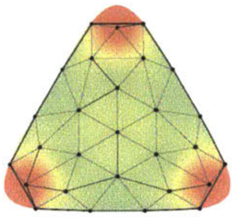


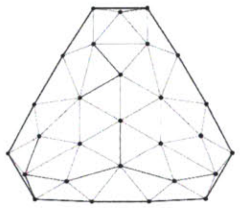
10 /// INFLATED MESH



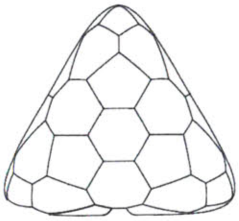
11 /// MESH TO SRF



12 /// GUASSAIN CURVATURE



13 /// TRIANGULATED POINTS



14 /// VORONOI

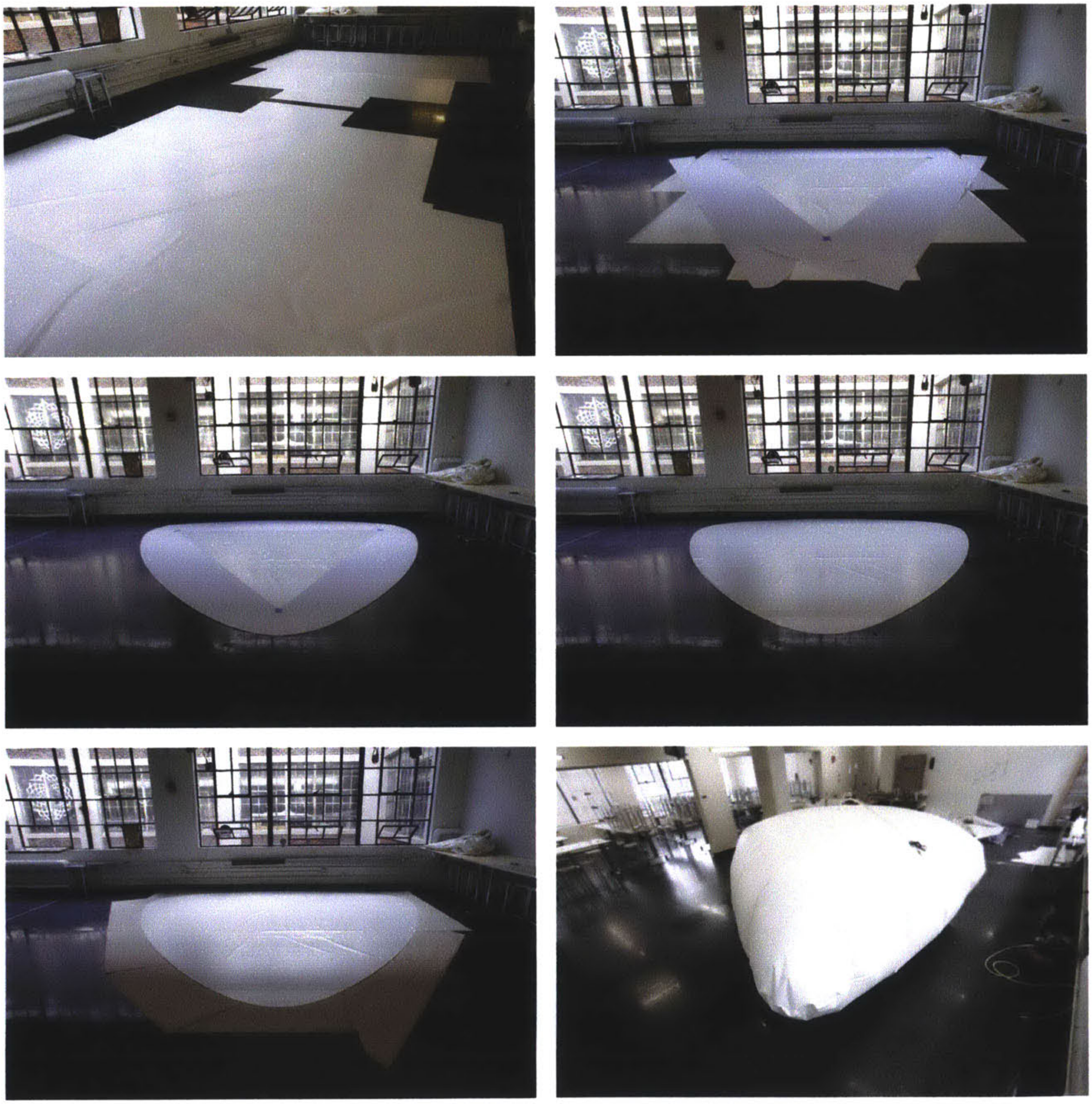
15 /// THICKENED MESH

8.0 /// SHELTERS

8.1 Geometry

The geometry of the shelter began with a 2D base curve, a reflection of the construction process of the inflatable bladder. The 2D curve is divided and populated with a number of equally distributed points. These points are then combined to form the delaunay triangulated mesh. The edges of the mesh work like springs in the simulation and allow for the 3D approximation of the inflated 2D shape.

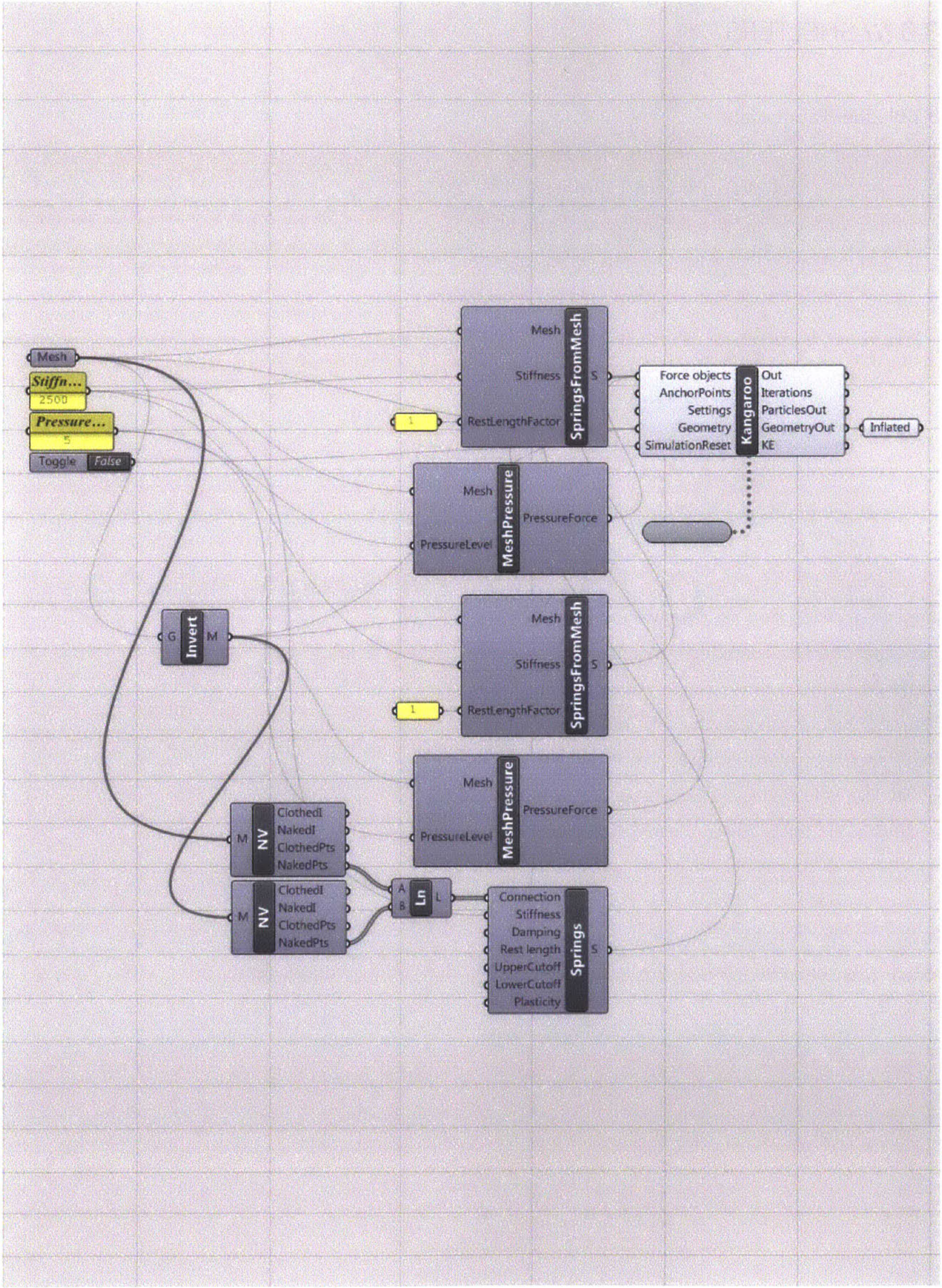
The overall geometry of the shelter was designed as an inhabitable space, tall enough for one to walk into. Before inflation the shelter can pack into a 2 ft x 2 ft x 4ft box, but once inflated and infused the shelter is 16 ft in diameter and 8 ft tall, serving as a basic refuge. The entrance is located centrally along one side of the shelter.



8.2 Bladder Fabrication

The 2D shape used to construct the bladder also emerged from material constraints. In order to limit the number of welds the bladder was conceived of in relation to the vinyl coated polyester roll which is 60" wide. The 2D bladder was cut out of four strips and continuously welded along the butt joint seams. After the strips were welded into a larger sheet, the top and bottom sheets were stacked and cut to the desired shape. The cutting of the bladder material was done by hand to reduce the number of seams resulting from the CNC.

After the top and bottom sheet were cut to size, they were chemically welded into a flange condition along the perimeter of the bladder. The chemical weld reacts with the vinyl infused in the fabric and creates an extremely strong, airtight bond. The weld requires 24 hours to fully cure, at which point the bladder is inverted so that the flange is now internalized, this strengthens the seam during inflation and provides a continuous surface on the outside for the infusion. The last step in fabricating the bladder was to add a inflation valve.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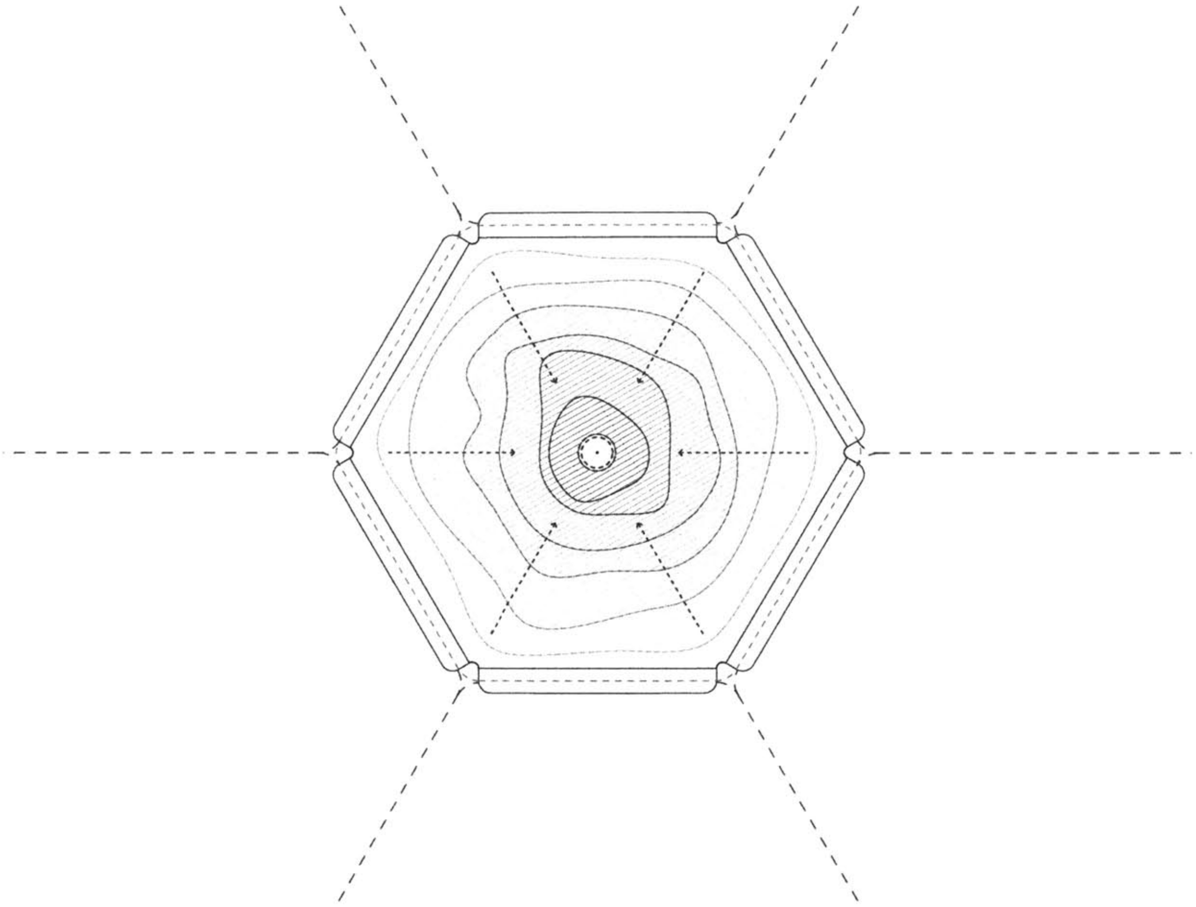
8.3 Simulation

Critical to the design and success of the thesis was the ability to simulate computationally the resulting inflated geometries. Simulation was used as a design tool to predict the 3D height of the inflated 2D shape, or to produce straightness along an edge by simulating an inflated spline curve. The inflation simulation was accomplished using addons for grasshopper through rhino, primarily weaverbird as a mesh editor and kangaroo as a physics engine.

The digital model builds off the delaunay triangulated mesh by first duplicating and inverting the mesh to produce a second mesh, which is symmetrical across its construction plane. The two meshes represent the top and bottom sheet of the vinyl coated polyester fabric used to create the bladder. The edges of the two meshes are stitched together digitally with line segments that act as springs, holding the two meshes together during the inflation.

The face polylines that define the triangulation of the mesh also act as springs in the simulation and are given a rest-length-factor which is determined by the elasticity of the bladder material. In this case one, meaning the bladder material has no stretch. The two meshes are decomposed into their constituent triangles so as to apply the pressure normal to each of the surfaces during the inflation.

Reisn Infusion Strategy

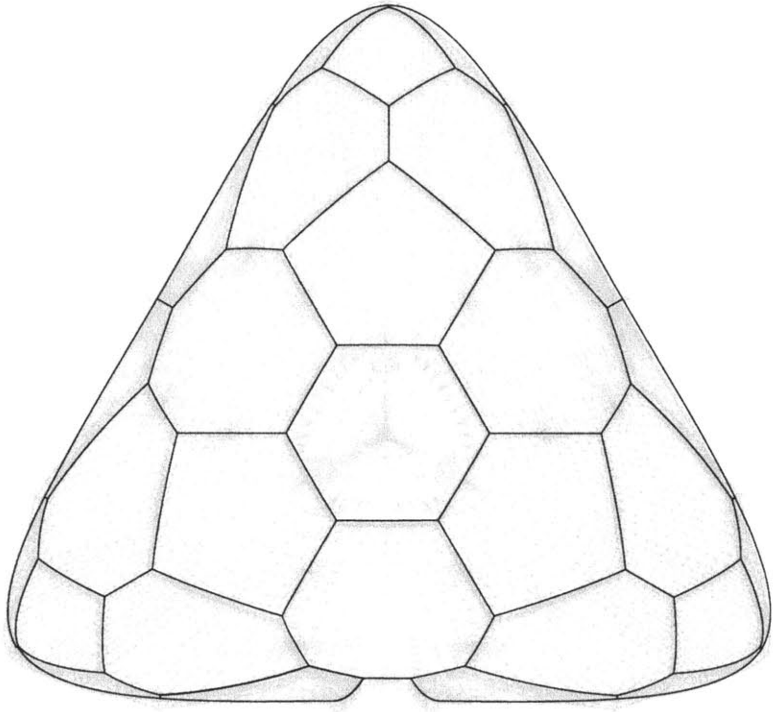


8.4 Infusion Strategy

The infusion strategy evolved out of the numerous prototypes that were constructed. Resin flow simulations are still not fully reliable and must be learned through experience and experimentation. For the shelter the infusion strategy places a line for resin around the edge of each of the panels and a vacuum point at the center. The infusion strategy influenced the geometry of the panels. The maximum resin flow distance of 18 inches - 24 inches was used as the parameter to define the panel sizes.

The infusion strategy must be carefully designed alongside the part. Common issues that come along with misplaced resin inlets and vacuum outlets are, race tracking which occurs along a sharp corner, or potential dry spots that may occur in the middle of large flat surfaces. During infusion the resin follows the path of least resistance between entering the inlet and the vacuum. Once the resin reaches the outlet, the vacuum will shortcut the system and no more fibers will be wetted out. Rather, the resin that has already reached the vacuum outlet will continue to be pulled through.

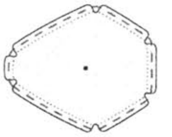
Shelter Plan



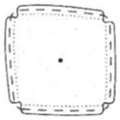
8.5 Descritization

The global geometry was defined by the simulation of the 2D base cure, this 3D mesh was then evaluated based on it gaussian curvature. Initially a perfect hexagon grid of points was mapped onto the mesh surface. These points were then distorted in relationship to the curvature analysis, increasing the density in areas with greater double curvature, such as the corners, and lessening in larger areas with only single degrees of curvature. The points are radially symmetrical around the mesh centroid. Together these points define the voronoi panelization of the shelter, with six perfect hexagon panels on top and bottom and compressed hexagon panels around the corners. The size of the panels were calibrated according to both the infusion strategy and also in consideration of the 4 ft x 8 ft CNC bed where they were cut.

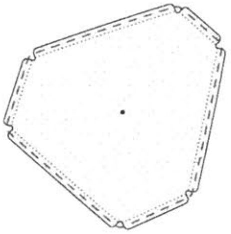
PART A
QUANTITY /// X6
RESIN LENGTH /// 95"
AREA /// 723 SQ IN



PART B
QUANTITY /// X6
RESIN LENGTH /// 87"
AREA /// 592 SQ IN

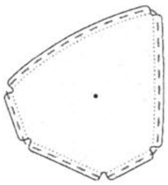


PART C
QUANTITY /// X4
RESIN LENGTH /// 156"
AREA /// 1831 SQ IN



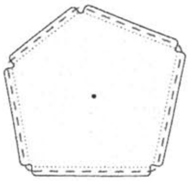
PART D
QUANTITY /// X10
RESIN LENGTH /// 126"
AREA /// 1226 SQ IN

PART E
QUANTITY /// X2
RESIN LENGTH /// 118"
AREA /// 1062 SQ IN

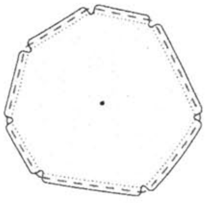


PART F
QUANTITY /// X2
RESIN LENGTH /// 128"
AREA /// 1303 SQ IN

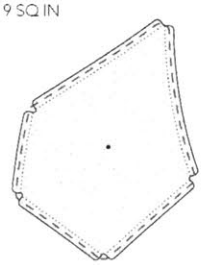
PART G
QUANTITY /// X4
RESIN LENGTH /// 128"
AREA /// 1272 SQ IN



PART H
QUANTITY /// X4
RESIN LENGTH /// 136"
AREA /// 1483 SQ IN



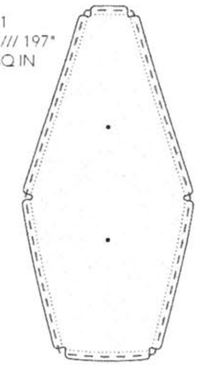
PART I
QUANTITY /// X2
RESIN LENGTH /// 147"
AREA /// 1519 SQ IN



PART J
QUANTITY /// X2
RESIN LENGTH /// 140"
AREA /// 1363 SQ IN

PART K
QUANTITY /// X1
RESIN LENGTH /// 136"
AREA /// 1466 SQ IN

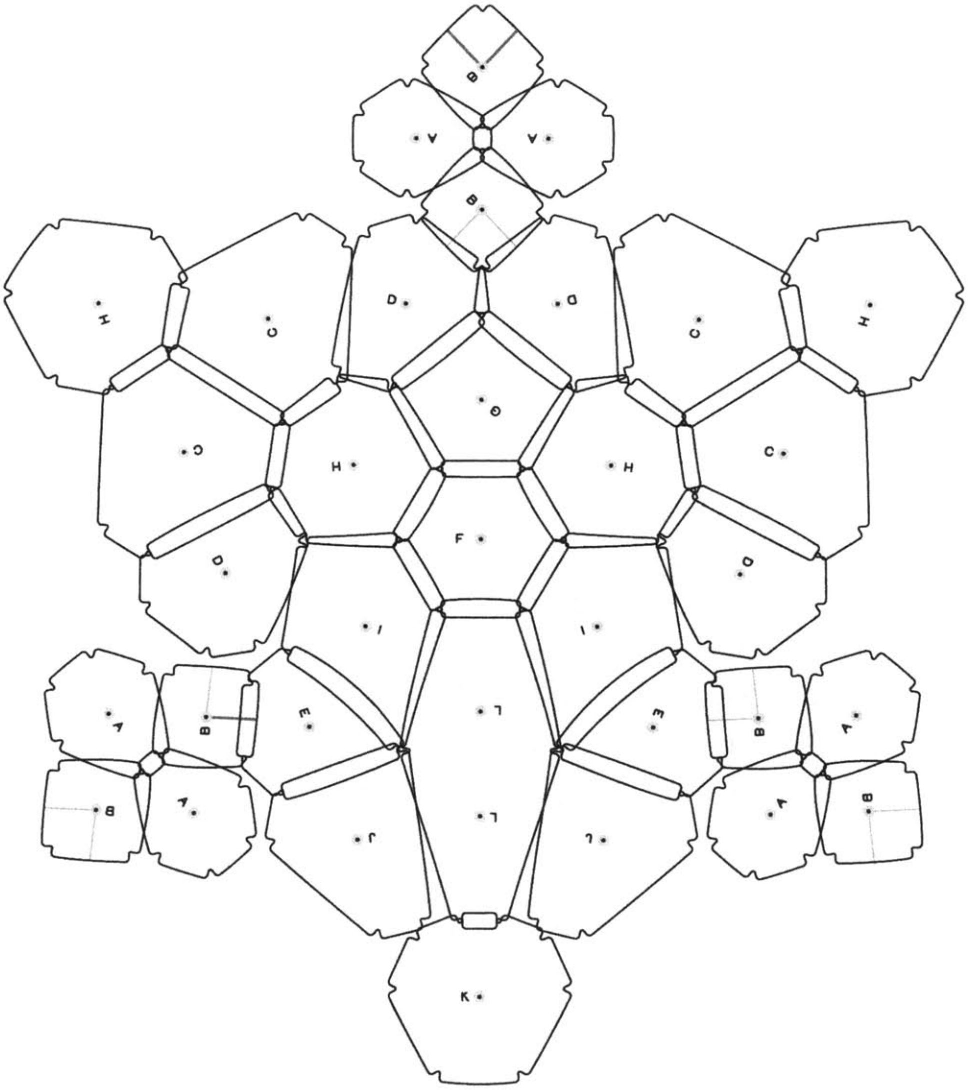
PART L
QUANTITY /// X1
RESIN LENGTH /// 197"
AREA /// 2339 SQ IN



8.6 Panels

The shelter is made up of 12 different panel types ranging in size from 600 sq inches to 2400 sq inches. Many of the panels are repeated symmetrically on the top and bottom and also radially on each of the three sides. The one exception is along one of the three sides, two of the panels were merged in order to create an elongated panel that could serve as the door. Because the door panel was custom the panels around it were also deformed to transition to the elongated panel type.

The panels were nested into 4 ft x 8 ft sheets using rhinonest and cut using a CNC mill and a free wheel drag knife. The sheets were made by layering three 8 ft burlap strips with 3M 77 spray adhesive to roughly fix the layers in place, followed by one layer of 3mm Soric infusion core followed by three more layers of burlap. This assembly of layers produced a ¼" panel thickness.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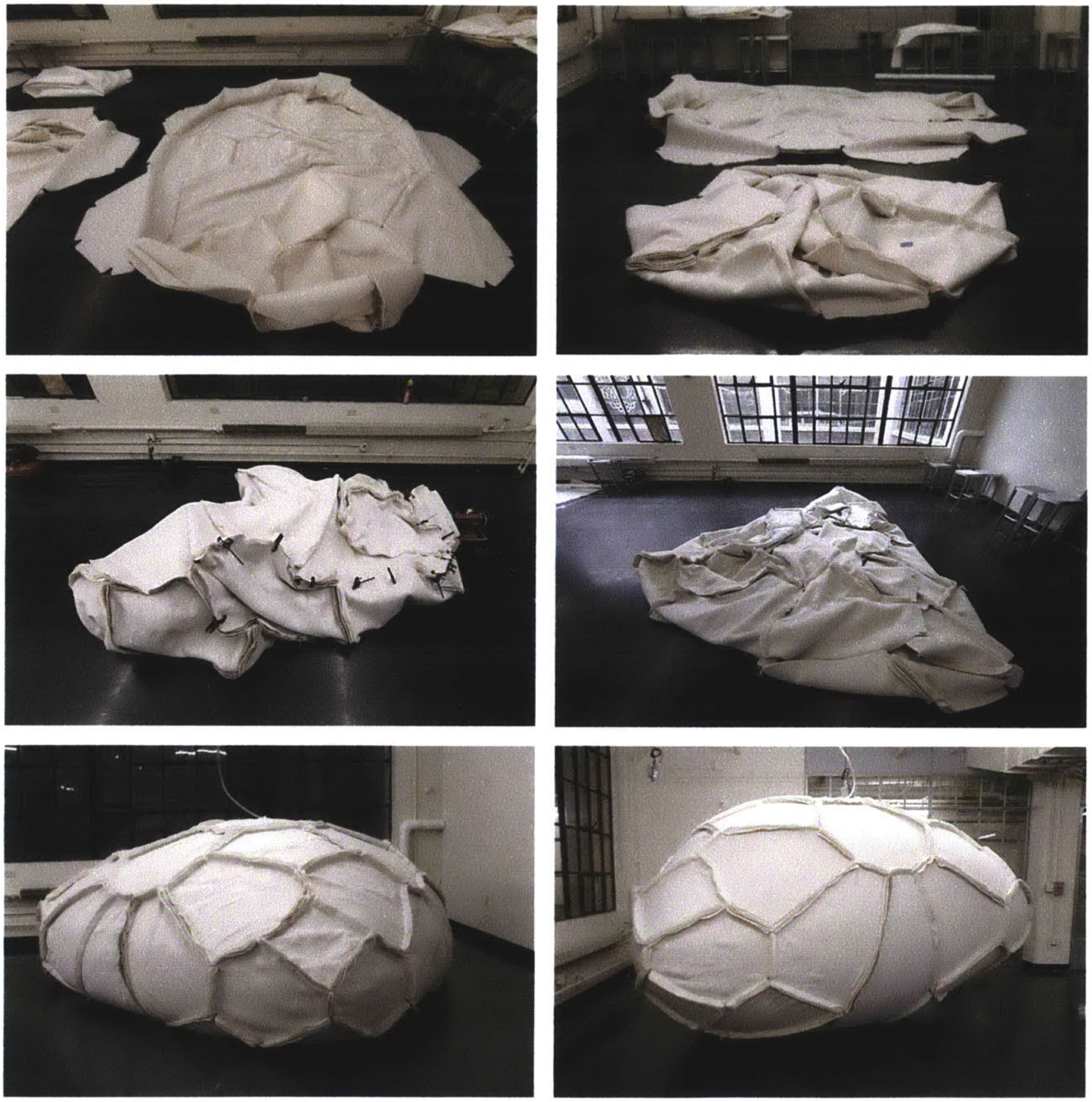
8.7 Stitching Preform

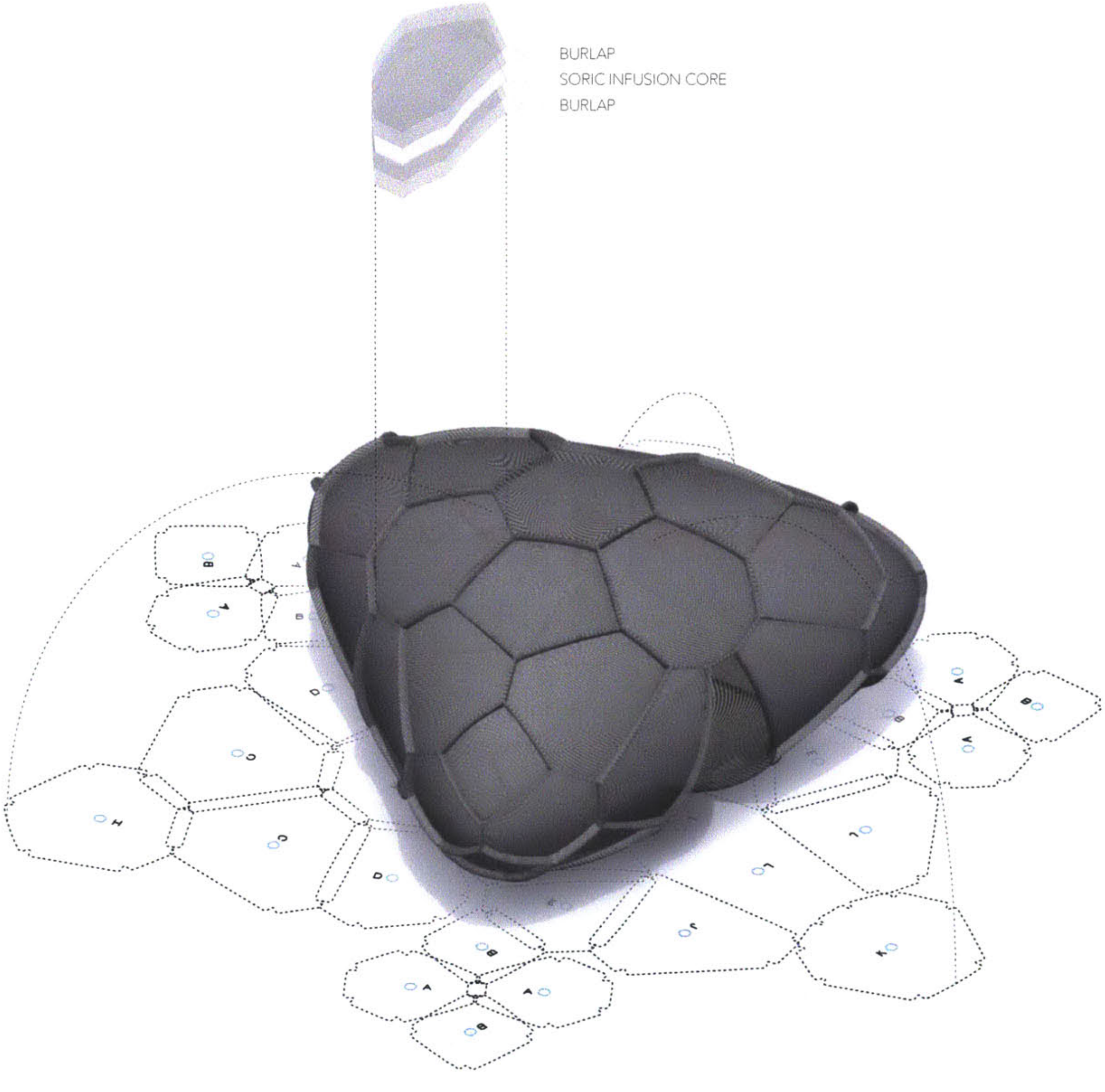
Once the panels are cut they must be stitched together into what is called a perform. In this case, the preform is what defines the geometry of the shelter with the pneumatic mold. The preform (composite assembly) is also sewn together using a heavy weight polyester thread. In order to stitch the 52 total panels together into the 16 ft diameter perform, a stitching pattern was drawn up as a type of construction document for the composite architecture.

The VARTM process requires inlet (resin) and outlet (vacuum) valves which are calibrated according to the geometry of the part. Inlets and outlets can either be point valves or distributed valves depending on the geometry and the infusion strategy. Linear distribution uses a 3⁄8" polyethylene spiral tubing sewn into the preform. The spiral tubing allows the resin (intake) or vacuum (outlet) to rapidly travel the length of the tube before penetrating the infusion core. This is an effective way to create an even distribution infusion.

The valves for the inlets and outlets are integrated into the preform at the same layer as the infusion core, reducing the setup time. The integration and robustness of the preform reinforces the research ambition for a compactable and shippable composite. By integrating all the complexity and intelligence into the perform, the entire assembly can be vacuum compressed, packaged and shipped.

EXIT



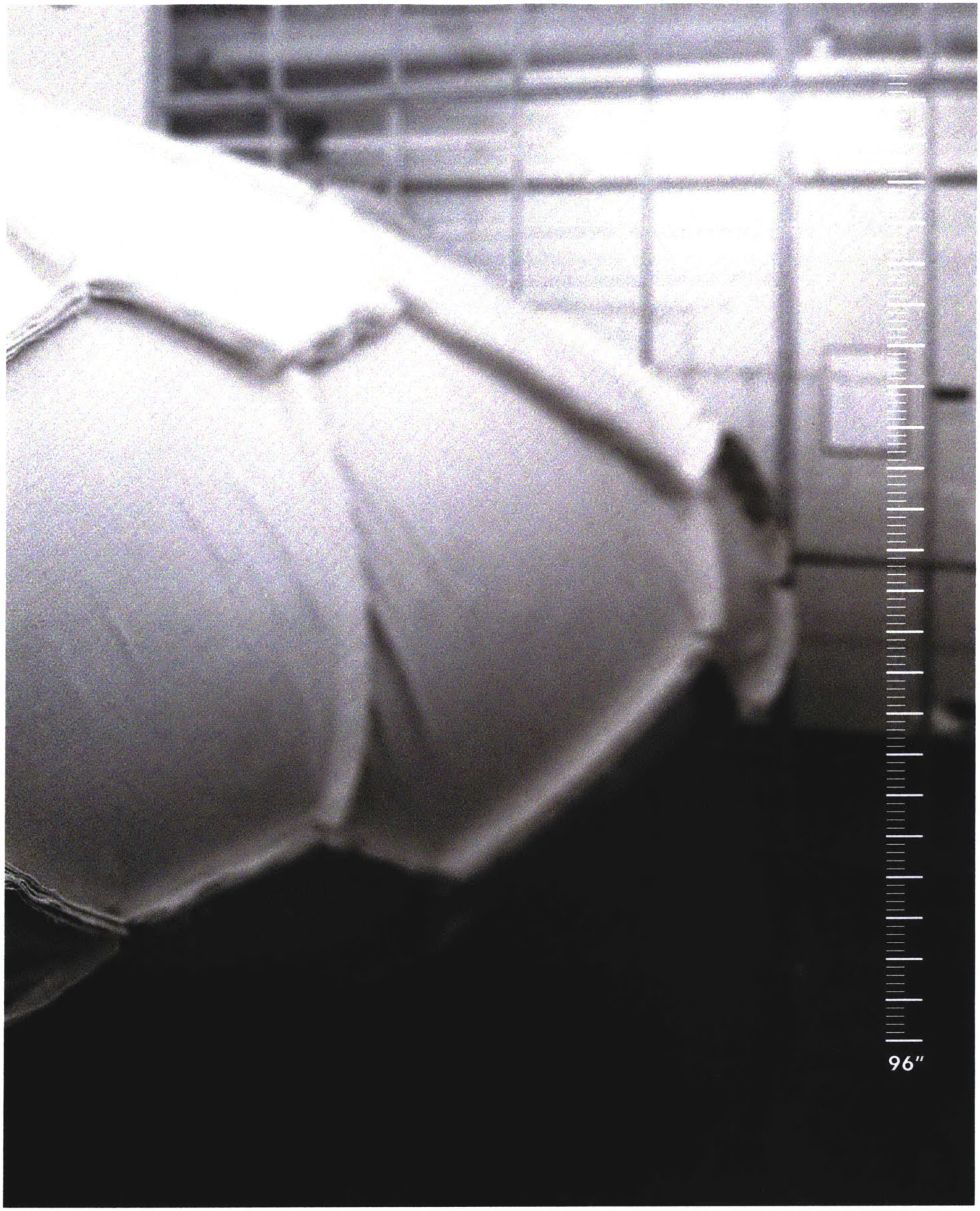


BURLAP
SORIC INFUSION CORE
BURLAP

8.8 Bagging and Infusion

The most conventional aspect of the process is bagging the assembly. Bagging the composite puts the entire assembly under compaction in order to produce a high performance composite structure. Because a high performance part must be bagged for compaction, the required elements for vacuum assisted resin transfer molding already exist. Using 300° F nylon bagging film and sealant tape an oversized bag is constructed, non specific to the geometry of the part.

Once the entire assembly is constructed the bladder is inflated to 5 psi and a vacuum is pulled on the sealed assembly at 26 -29 inHg. The assembly is checked for leaks to guarantee successful compaction and infusion. Once the assembly is surveyed, the inlet line is submerged in a low viscosity high bio content infusion epoxy resin. When the hose clamp is removed the vacuum pulls the resin through the linear infusion lines around the edge of each of the panels and into the infusion core which wets out the fibers as its pulled across the part towards the central vacuum outlet located on each of the panels. The infusion process is regulated by the viscosity and pot life of the resin and can be carefully calibrated as needed. Once the part is fully infused, the vacuum continues to compress the part extracting excess resin into a resin trap in order to remove all voids and create a uniform, lightweight composite.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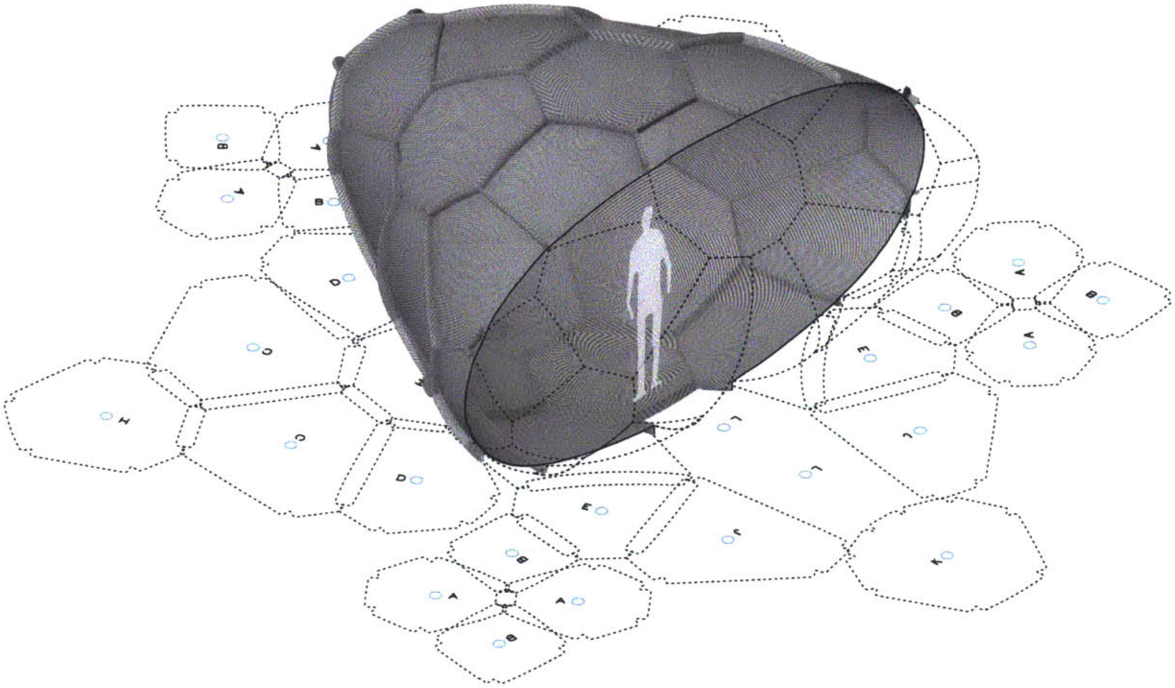
09 // CONCLUSION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9.0 /// CONCLUSION

Over the last 5 years I have become more and more fascinated by the potential possibilities present in composite materials. In 2011, I designed a house as part of a disaster relief effort after the earthquake in Haiti for rapid deployment in the countryside. For my MIT master's thesis I designed a composite house for southern Iraq as part of an effort to rebuild after the war. Consistently however, I found that the limits of the design process were reached, since the ability to produce such designs, do not in fact exist within architecture today. Composite manufacture thus far, has largely been tailored to high tolerances which entail extreme conditions, such as those found in aviation and aerospace.

This thesis, Fibrous tectonics has evolved over the last two year through hands on exploration of composite manufacturing techniques. The goal of the research was to develop a composites workflow that can be used in the field of architecture. The research combined, natural burlap fibers, VARTM and pneumatic structures as molds in order to reduce the production costs, accelerate turn around, and produce variance.

Embedded in the notion of architectural innovation is an intimate consideration of materiality. In the capacity to understand material systems and manufacturing techniques, the discovery for variable forms of architecture may unfold and present themselves as what was, previously unforeseen possibilities. In this unfolding, therein lies the necessity for full scale investigation and exploration in order to develop comprehensively the relationships and synthesis between materiality and constructibility. This direct method of working enables the designer to more accurately and pointedly evaluate a material's strengths and weaknesses, its advantages and disadvantages. In this process and exploratory development, composite material systems are no exception.

The workflow presented here, was advanced by working directly with the materials. Initial challenges existed in producing the inflated mold in which a number of different materials were tested. After a number of mockups the addition of sewing the heat sealed edge as a reinforcement and prevention of catastrophic failure was included. Another primary material that was tested was the infusion mesh. Most infusion meshes are applied to the exterior of the part and allow resin flow between the part and the nylon vacuum bag. However, the welcomed discovery of an infusion mesh core that is situated between the fabric plies, has significantly reduced the waste and helped simplify the process while adding notable structural properties.

The process is just beginning to prove to be reliable. Future works is based on the desire to scale up, and refine the process. Following the success of the initial prototypes and the established understanding of the material systems, rules, and constraints, I would like to continue developing and distilling the techniques in order that composite materials can serve as building material for architecture.

9.1 /// BIBLIOGRAPHY

MATERIALS /// CONSTRUCTION

Branko, Kolarevic. Manufacturing Material Effects : rethinking design and making in architecture. New York: Routledge, 2008.

Branko, Kolarevic. Architecture in the digital age : design and manufacturing. New York: Taylor & Francis, 2005.

Lynn, Greg & Mark Foster Gage. Composites, surfaces, and software : high performance architecture. New Haven, Conn. New York: Yale School of Architecture Distributed by W.W. Norton & Co, 2010.

Meredith, Michael. From Control to Design : Parametric/Algorithmic Architecture. Barcelona New York: Actar, 2008.

Brownell, Blaine. Material strategies : innovative applications in architecture. New York: Princeton Architectural Press, 2012.

Bell, Victoria. Materials for design. New York: Princeton Architectural Press, 2006.

Oxman, Rivka & Robert Oxman. The new structuralism : design, engineering and architectural technologies. Hoboken, N.J. Chichester: Wiley John Wiley distributor, 2010.

Iwamoto, Lisa. Digital fabrications : architectural and material techniques. New York: Princeton Architectural Press, 2009.

Farrelly, Lorraine. Construction and materiality. Lausanne Worthing: AVA Academia, 2009.

COMPOSITES

Campbell, F. C. Manufacturing processes for advanced composites. New York: Elsevier, 2004. Print.

Strong, A B. Fundamentals of composites manufacturing materials, methods and applications. Dearborn, Mich: Society of Manufacturing Engineers, 2008. Print.

Wanberg, John. Composite materials fabrication handbook #1. Stillwater, MN: Wolfgang Publications, 2009. Print.

Wanberg, John. Composite materials fabrication handbook #2. Stillwater, MN: Wolfgang Publications, 2010. Print.

Wanberg, John. Composite materials fabrication handbook #3. Stillwater, MN: Wolfgang Publications, 2012. Print.

Bank, Lawrence C. Composites for construction : structural design with FRP materials. Hoboken, N.J: John Wiley & Sons, 2006. Print.

INFLATABLES /// PNEUMATIC STRUCTURES

Topham, Sean. Blowup : inflatable art, architecture, and design. Munich New York: Prestel, 2002. Print.

Herzog, Thomas, Gernot Minke, and Hans Eggers. Pneumatic structures : a handbook of inflatable architecture. New York: Oxford University Press, 1976. Print.

Clausen, Barbara, and Carin Kuoni. Thin skin : the fickle nature of bubbles, spheres and inflatable structures. New York: Independent Curators International, 2002. Print.

Jenkins, C. H. Gossamer spacecraft : membrane and inflatable structures technology for space applications. Reston, Va: American Institute of Aeronautics and Astronautics, 2001. Print.

Krauel, Jacobo. Inflatable art, architecture & design. S.l: Watson-Guptill, 2013. Print.

Oñate, E, and Bern Kröplin. Textile composites and inflatable structures II. Dordrecht: Springer, 2008. Print.

Ballast, David K. Inflatable structures and air pressure supported roofs. Monticello, Ill., USA: Vance Bibliographies, 1988. Print.

Dessauce, Marc. The inflatable moment : pneumatics and protest in '68. New York: Princeton Architectural Press, 1999. Print.

Mallick, P. K. Fiber-reinforced composites materials, manufacturing, and design. New York, N.Y: M. Dekker, 1993. Print.

SHELL STRUCTURES

Bechthold, Martin. Innovative surface structures : technology and applications. Abingdon England New York: Taylor & Francis, 2008. Print.

Lämmler, Rahel, and Michael Wagner. Ulrich Müther shell structures in Mecklenburg-Western Pomerania. Sulgen: Niggli, 2010. Print.

Garlock, Maria E., David P. Billington, and Noah Burger. Félix Candela : engineer, builder, structural artist. New Haven, Conn. London: Yale University Press, 2008. Print.

Anderson, Stanford, and Eladio Dieste. Eladio Dieste : innovation in structural art. New York: Princeton Architectural Press, 2004. Print.