ARCHITECTURE SANDWICHED

Tuning anisotropy through variable thickness and hetereogeneous laminar assemblies.

by

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Bachelor of Architecture
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Submitted to the Department of Architecture on May 21st, 2015
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Architecture Studies

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Abstract

Much of architecture's earliest material palettes and construction methods are often referred to today as legacy materials – those primarily consisting of various types of stone and masonry construction. While these materials are often conceptually thought of as being solid, monolithic, and even homogeneous, in actuality they rely on logics of assembly more akin to contemporary sandwich structures, which are laminar assemblies typically composed of two or more stressed skins and either a solid or cellular core that binds them together. While it is still common to use ancient materials in contemporary architecture, the construction methods and techniques used several hundred years ago are no longer appropriate for today's buildings. This thesis however, argues for a newfound relevance of their influence on contemporary and even future material selections and methods.

Specifically, this thesis explores the potentials of composite sandwiches varying in thickness and material in search of architectural possibilities whose structural, formal, and aesthetic implications are a result of tuning multiple influences. Variable thickness is used here as a strategy for enabling a range of architectural and tectonic conditions, all within the same heterogeneous but integrated laminar assemblies. While most commercial products in the realm of composite sandwiches are of uniform thickness in section, this thesis suggests a method for constructing sandwiched elements with variable thickness. This is done primarily through a process of infill and backfill using expanding urethane foam as a medium which creates the so called "core" of the sandwich between two skins. This investigation works through a series of small scale prototypes, each of which focus on a particular tectonic, spatial, or structural condition. These mock ups are meant to serve as didactic artifacts, providing feedback with which to incorporate and speculate upon larger architectural propositions through drawing and representation. The end result is a set of architectural proposals which suggest the beginnings of new design methodologies.

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This thesis would not have been possible without the support of family and friends, near and from afar, who have always encouraged me to do what I love.

Thank you to my advisors, Brandon Clifford and Mark Goulthorpe for your insights, suggestions, and for challenging me to pursue my ideas through writing and built form. Brandon, it's been a pleasure working with you from my first semester in Volumetric Robotics to the completion of this thesis. Mark, your wealth of knowledge and resources in composite materials, and critical thinking has benefitted me immensely. Thank you for sharing your experiences and introducing me to the experts in Rhode Island.

Thank you, Nader! You've been extremely welcoming to me well before Day 1 and have continued to do so till now. Working with you professionally and academically has been a great pleasure and in fact has not felt like work at all. I have learned a great deal from you.

Thank you to the Department of Architecture at MIT for your financial support and facilities. Thank you to John Fernandez and the IDC for your support and resources which have played a huge role in the production of various prototypes throughout my time here. Thank you also to David Costanza for sharing your knowledge and expertise with me.

Big thanks to Carrie, Madeline, Jeff, Gabriel, David and the entire SMArchS team for all the laughs, adventures, and all around good times over the last two years. Here's to many more!

I'd also like to thank Eric Kahn, my first studio instructor at SCI-Arc, who passed away nearly a year ago. Eric, while you were not directly involved in any of the work in this thesis, your energy, creativity, and spirit has always been with me throughout the duration of my time here.

Lastly I'd like to thank my father who moved to the U.S. nearly 30 years ago and swung a hammer in order to provide the opportunities for me to achieve greater things. Spending time with you on construction sites has undoubtedly influenced my desire to come this far. Mom, you know how much I love you too! Thank you for always being there for me regardless of circumstance.

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1.0 Background

1.0 Background

Apart from visits to manufacturing facilities and construction sites, industry collaborations, and catalogue-based specifications, architects for the most part have historically remained disconnected from direct, material-driven making. Standardized architectural practice often operates in a relatively linear sequence of processes beginning with conception, through representation, towards development, eventually leading to actualization (although this sequence may often be cyclical in nature until the thing is completed). Regardless, even within this practice, it is specifically the act of architectural representation itself that tends to be the dominating mode for design production, at least prior to construction.

In recent years, a handful of contemporary practitioners and theorists have alleged the disappearance of the orthographic architectural drawing, for reasons related to the obsolescence of its technical apparatus; stating it has been replaced by post-orthographic, electro-topological models which contain within them "all possible future object scenarios." These include but are not limited to metrics surrounding energy consumption, tectonic specifications, maintenance costs, etc. This is nothing new to us. In fact, it has become the new standard by which many practitioners now operate.

Yet no matter how advanced, robust, or capable our various new representational apparatus have become, the fact remains that they still operate independently from the material manifestations which they aim to determine and realize. The very act of representation itself is an altogether distinct act from that of making. Let us for a moment consider the basis of the claims made surrounding the disappearance of orthographic architectural drawing and its replacements. At its core, it is simply the means and methods used to produce drawings and information which are being cited as the reasons for its non-existence. Thinking through this, we might say that architecture is as much a product of its means and methods as it is the conceptual, economic, regional, and cultural forces that shape it.

2.0 Introduction

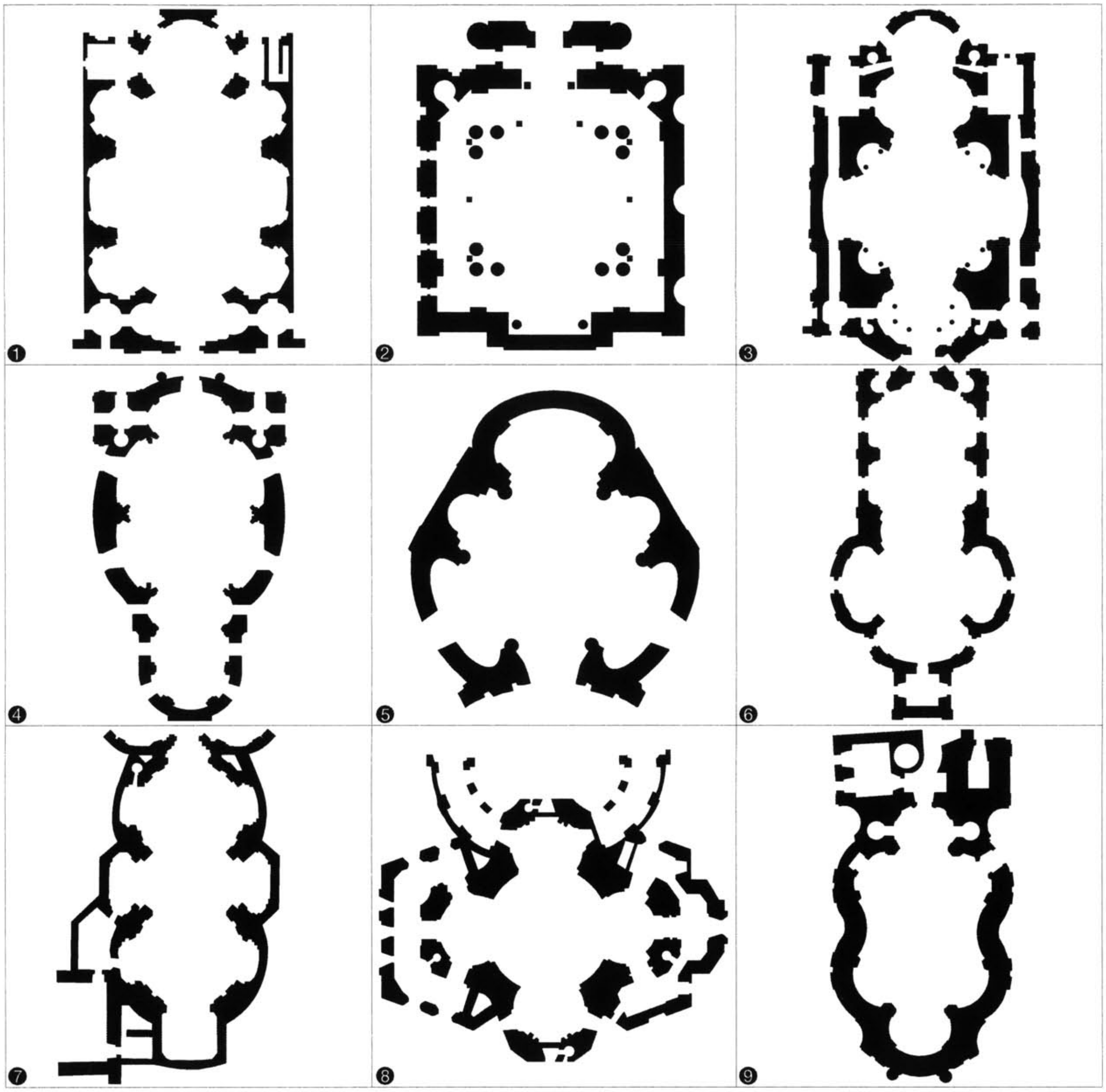
2.0 Introduction

2.1 HISTORIC REFERENCES

The term poche in architecture refers to a representational technique used to describe moments of uninhabitable solid mass in section. This typically includes elements of a building that make up the envelope and any other spatial partitions, such as floor, ceiling, walls, etc. The concept of poche in architecture is one of the oldest disciplinary conventions, made apparent in the widest range of works from ancient temples to contemporary buildings. While it is commonly attributed to methods of making surrounding volumetric masonry construction dating as far back to Greek temples, we insist on continuing to use it to describe moments of section in today's buildings regardless of construction method. However, to be clear, the use of the word poche here is intended to suggest variability in thickness and material.

When working with extremely thick materials, such as masonry or even cast concrete, there lies the opportunity for variation or difference between interior and exterior spatial conditions. However when the shift towards lighter, thinner, industrialized materials took place our building envelopes allowed for a liberalization of spatial and programmatic constraints – as evidenced by modernism. Thinking through this 'in section' allows us to consider these implications as a result of the materials themselves which are used to produce the buildings. More often than not, we witness variable thickness (but not variable material) in 'the ancients' – masonry and stereotomic construction – while we witness the contrary in 'the modern': variable material but not variable thickness.

The following are 9 cathedrals from the 1600's – 1700's drawn in terms of figure ground, to focus on the relationship between interior/exterior through variation in material thickness which produce conditions of anisotropy or difference. The thickness of their envelopes is partly the result of the materials and methods used to construct them – specifically stone and masonry.



❶ Abbey Church of Santa Anna, Munich

❷ St. Mary Woolnoth, London 1727

❸ Church of St. Lorenzo, Turin 1687

❹ Monestary Church, Walstatt 1733

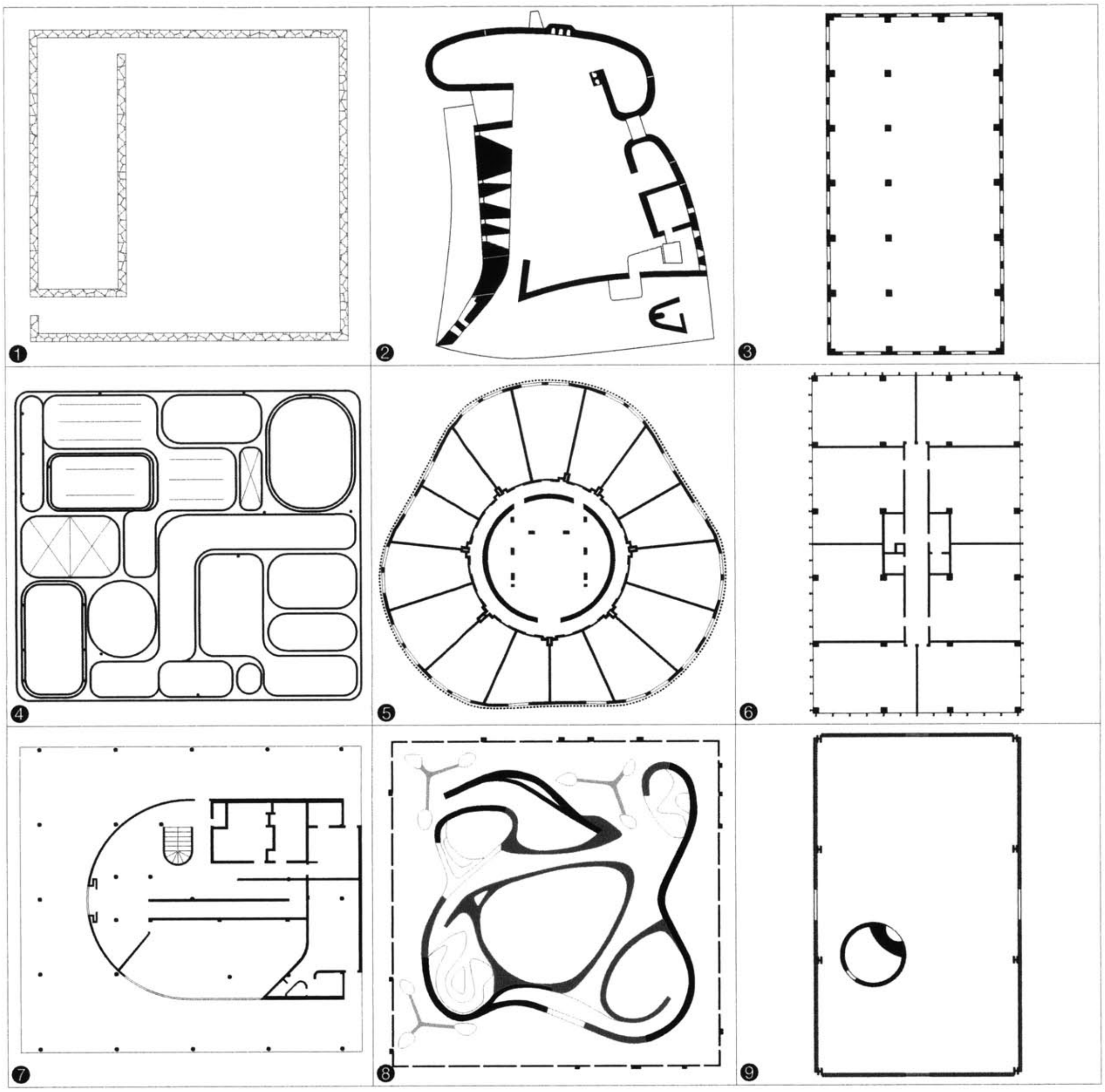
❺ Chapel St. Luigi, Corteranzo 1700's

❻ Parish Church, Gailbach

❼ Church of the Imaculate Conception, Guarini

❽ Pilgrimage Church, Krtiny 1750

❾ Castle Chapel of the Epiphany, Smirice 1711



❶ Beijing National Aquatics Center (Watercube), Beijing 2003

❷ Chapel of Ronchamp, 1957

❸ Ingalls Building, Cincinati OH 1903

❹ Glass Pavillion at Toledo Museum of Art, Toledo OH 2006

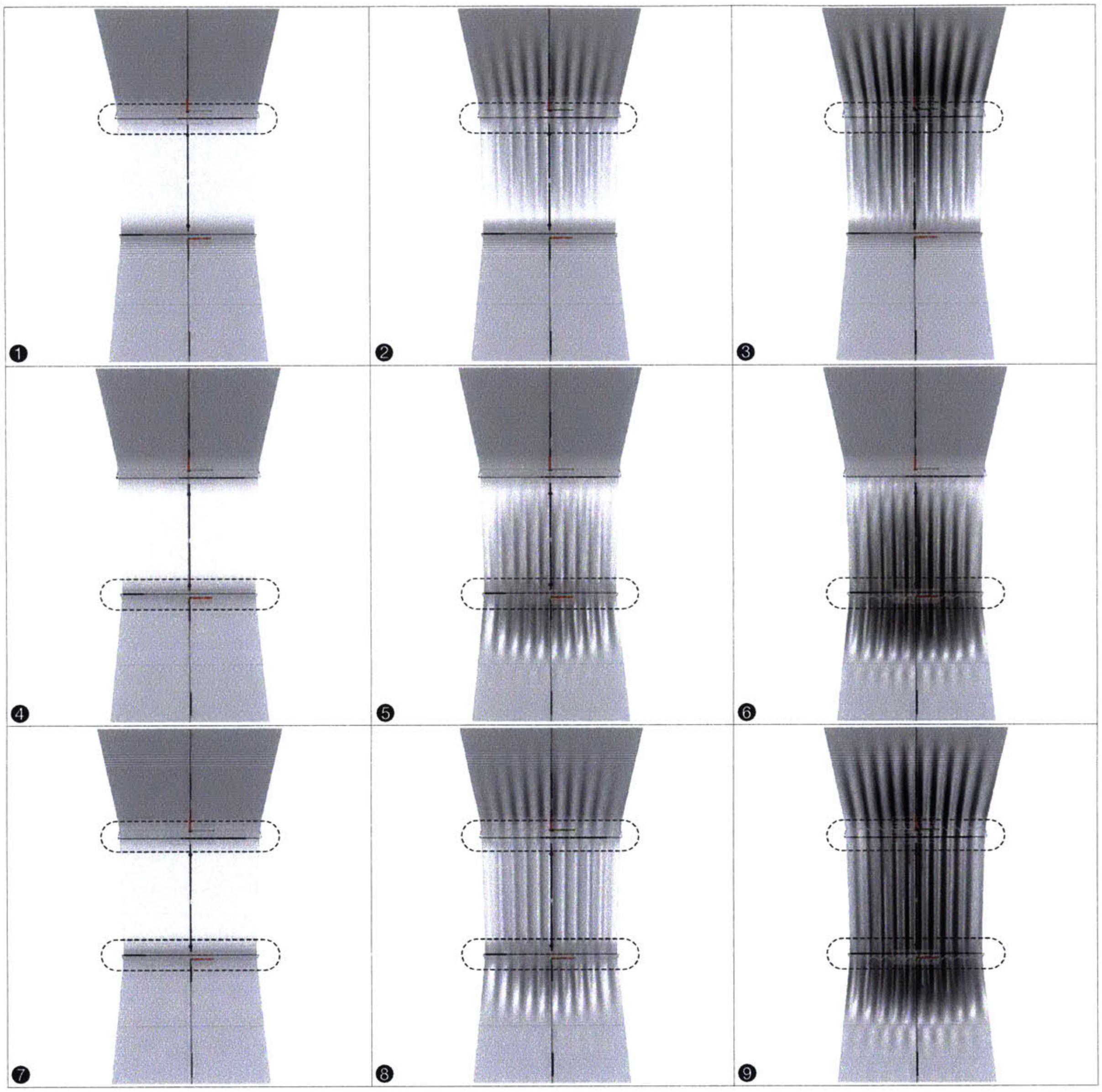
❺ Porta Fira Towers, Barcelona 2009

❻ Lake Shore Drive Apartments, Chicago 1951

❼ Villa Savoye, Poissy, France 1931

❽ Leonardo Glass Cube, Bad Driburg, Germany 2007

❾ Glass House, New Canaan CT 1949

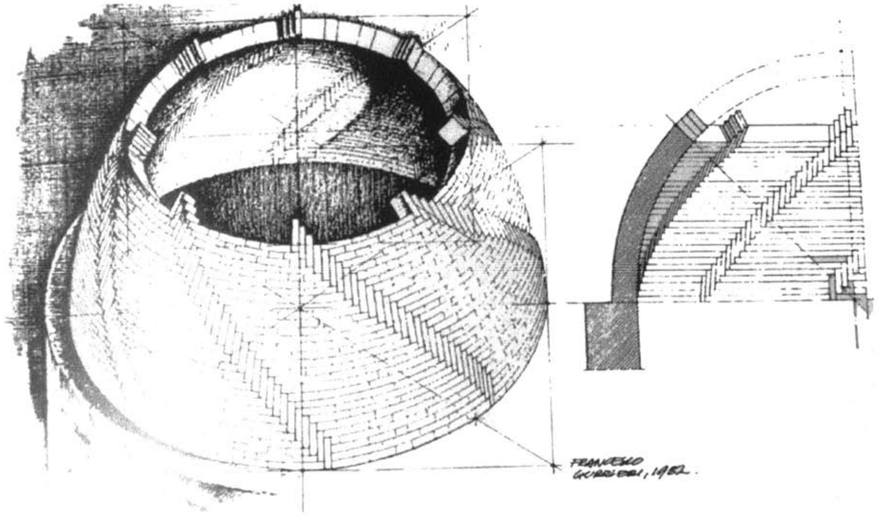


Matrix constructed of 9 different instances of a parametric model, which controls the depth of corrugated profiles. Top row shows upper profile, middle shows bottom profile, and bottom row shows both. This allows for fine tuning of geometry for structural performance and surface articulation.

The previous drawings are 9 modernist and contemporary buildings also drawn in terms of figure ground. There are two main things worth pointing out. One is the extreme difference in thickness of envelope compared to the cathedrals, and the other is the clarity of their structural systems as evidenced by the inclusion of recognizable building elements such as I-Beams, columns and so on. While the cathedrals also rely on the use of columns (and other structural systems like arches) to support themselves, when we look at them in plan we often find them hidden in the poche of the envelope, whereas here they're quite visible.

As technologies in the building industry increased over time, the thickness of building envelopes has decreased, resulting in progressively thinner sections of lighter weight material assemblies. This progression is evidenced by the advent of numerous industrialized processes bringing forth a wide array of primarily sheet-based, standardized building materials. Common examples include plywood, drywall, and sheet metals, even steel and lumber. From an engineering point of view, such advancements yield the production of lighter buildings, eliminating excessive weight and reducing material consumption; all great proponents of efficiency. However in the broader context of design, such a transition from thick volumetric materials to thinner industrialized materials seems to have also diminished our ability to construct variation between the interior and exterior.

In the interest of clarity and specificity, it's important to distinguish different logics and types of material formation and assembly. This is critical to note here, as some materials are able to be more clearly represented and therefore accounted for than others simply due to the nature of their composition. For instance, the dimensional and morphological properties of some industrialized materials – such as plywood, lumber, and steel – are more stable and therefore easily representable than those of, say, textile based composites and industrial foams or resins. The latter class of materials could be described as being more amorphous or dynamic, and by nature therefore more easily susceptible to non-standard geometries. Composites, commonly cited for their ability to produce incredibly rigid structural surfaces, are conceptually understood as being extremely thin. And while they are sometimes capable of providing sufficient structural properties on their own, composite surface structures also bear the potential for more complex geometries able to produce depth and variation in section, which allow for a rethinking of layered building envelopes.



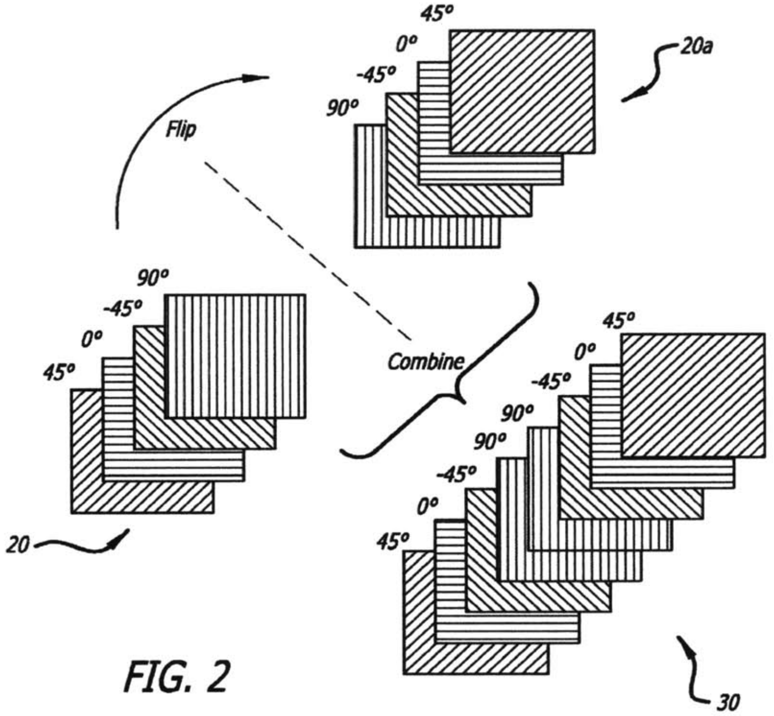


FIG. 2

Though stones and bricks themselves are solid and isotropic, often times they're oriented and configured within larger assemblies in ways that can produce anisotropic conditions. For instance, if we look at Brunalleschi's Dome – on one hand we can perceive it as a solid mass but on the other hand if we look closer into its construction methods, we see that the stones are arranged in a herringbone pattern which is an assembly of standard discreet elements in particular ways to resist the shear forces of the massive structure. Composite laminar assemblies, however, are often made up of several layers of unidirectional fibers alternating in orientation and compressed together into a single surface construction.

2.2 SANDWICH STRUCTURES

Sandwich panels are typically defined as structures where two rigid surfaces are both bound together and separated by a lightweight core material. Both the surfaces and the cores themselves can vary however. Common examples include fiber reinforced composites for skins; foams, honeycombs, and other cellular solids for cores. In Cellular Solids, published in 1988, Professor Lorna Gibson goes into great detail and describes the mechanical behaviors of sandwich panels from stiffness and optimization, to bending and failure, strength and density of surfaces and cores. She claims that sandwich structures appear frequently in nature, citing various examples such from animal bones to iris leaves to human skulls.

Current applications of composite sandwich structures vary widely from aircraft components to architectural building products to prefabricated housing panels. While these applications are effective in their execution, their development is driven primarily by performative agendas. This makes sense in certain industries like aerospace where every pound of material has a significant cost impact. The end goals here are very much driven by engineering concerns. However, composites have been present in architecture for thousands of years. Some of the earliest huts built from a combination of mud and straw or thatch can be conceptualized as fiber reinforced composite structures. Today an entirely new class of modern composite materials allows for unprecedented feats of engineering to take place. However, due to economies of production composite sandwich structures in particular tend to take on the form of prefabricated panels, uniform in thickness and limited in their potential for more compound architectural building elements. Cast polymer honeycomb panels are a great example of one such product, which are now commercially available and ready to be specified by any architect for almost any project.

THE DESIGN OF SANDWICH PANELS WITH FOAM CORES

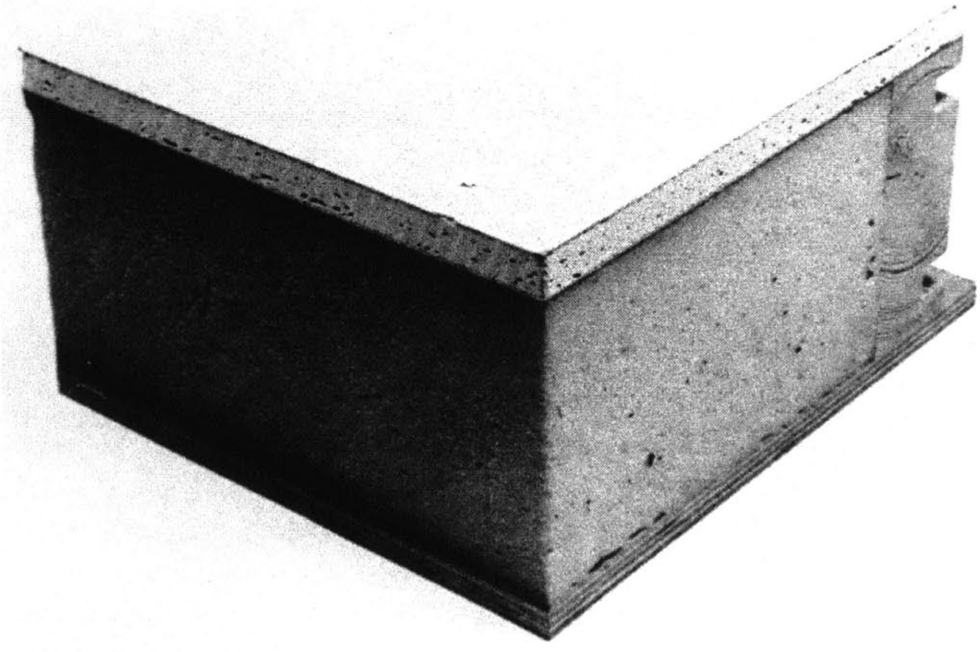
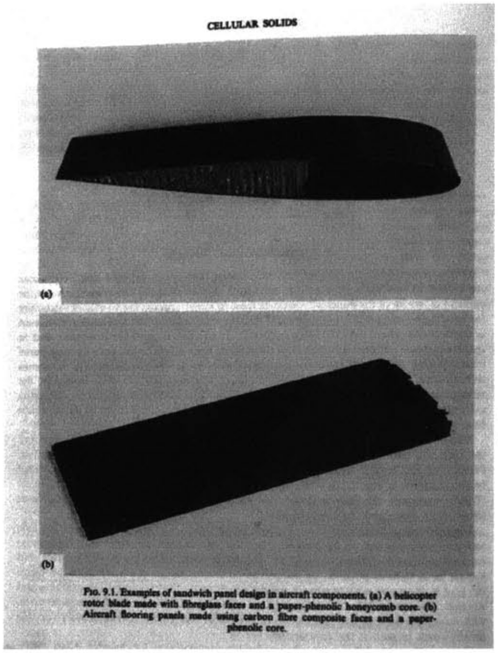


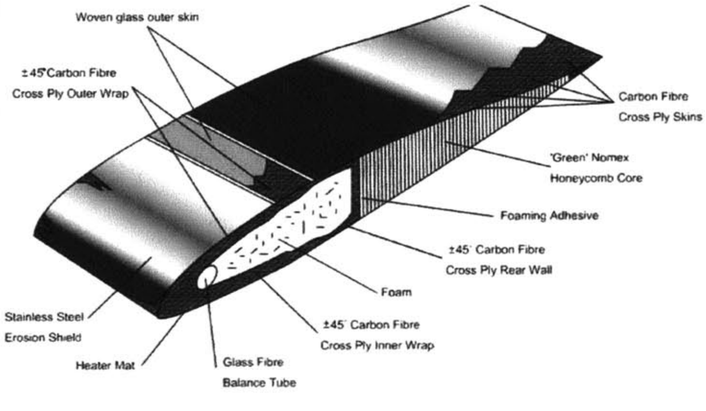
FIG. 9.2. A section of a prefabricated housing wall panel. The plywood and gypsum faces are separated by a polyurethane foam core.

From “Cellular Solids” by Prof. Lorna Gibson. Sandwich panel.



CELLULAR SOLIDS

FIG. 9.1. Examples of sandwich panel design in aircraft components. (a) A helicopter rotor blade made with fibreglass faces and a paper-phenolic honeycomb core. (b) Aircraft flooring panels made using carbon fibre composite faces and a paper-phenolic core.



Cross-Sectional View of a Composite Blade

From “Cellular Solids” by Prof. Lorna Gibson. Section of airplane wing.

3.0 Methods

3.0 Methods

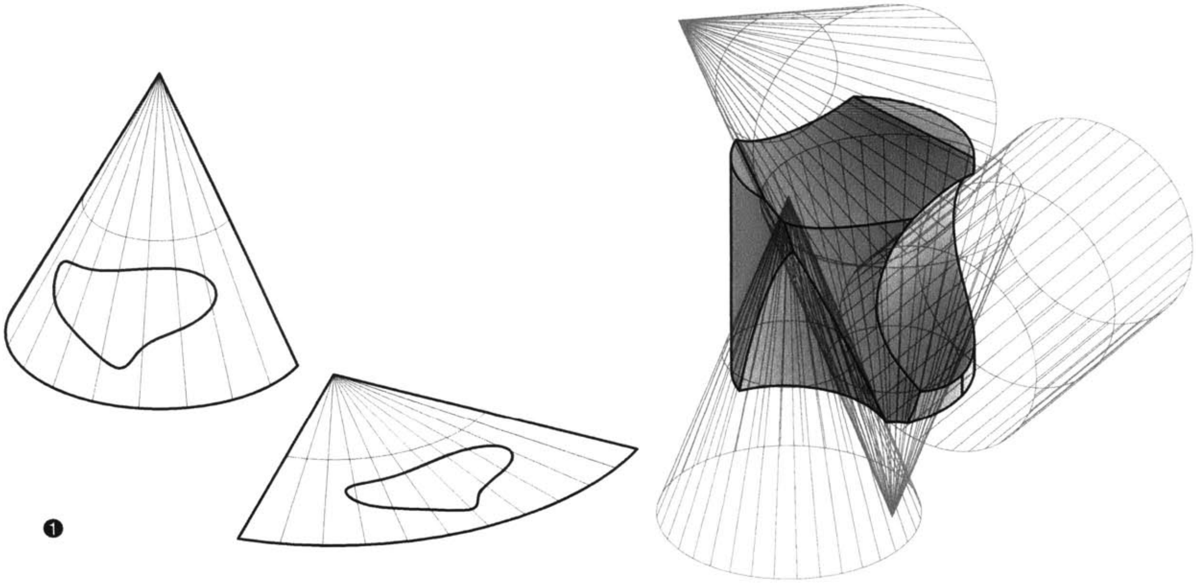
3.1 MOLD MAKING

The amorphous nature of most composite materials requires some shaping process to achieve their final form. There are a wide range of methods available to do this including pultrusion, extrusion, thermoforming, filament winding, weaving, roll-forming, pull forming, etc. In the case of woven textiles (which is to say two-dimensional surfaces) however, there are mainly two approaches to giving shape to these otherwise flat sheets – inflatables or molds.

One important thing to note here is the distinction between developable and non-developable geometries. A developable surface is a surface with zero Gaussian curvature. That is, a surface that can be flattened onto a plane without distortion (i.e. “stretching” or “compressing”). Conversely, it is a surface which can be made by transforming a plane (i.e. “folding”, “bending”, “rolling”, “cutting”, and/or “gluing”). Non-developable surfaces are commonly referred to as having “double curvature”, “doubly curved”, “compound curvature”, “non-zero Gaussian curvature”, etc. A sphere is a common example of a non-developable surface.

While inflatables are often cited for material efficiency, they also have certain limitations when it comes to form finding. For instance, inflatables rely on the use of seams to stitch together multiple flat sheets of material. This tends to limit inflatable structures to developable geometries. Furthermore, they often tend to only produce convex curvature as a result of positive air flow pressure from inside the part, and are rarely seen to contain any concave curvature to their form. Where they do prove to be fruitful, is in their capacity to scale quickly and in potentially less forgiving environments through flat packed deployment. The use of molds however, allows for significantly more precise and repeatable geometries while also providing greater morphological freedom, such as non-developable geometries and compound curvatures.

Developable Surfaces vs. Non-developable Surfaces



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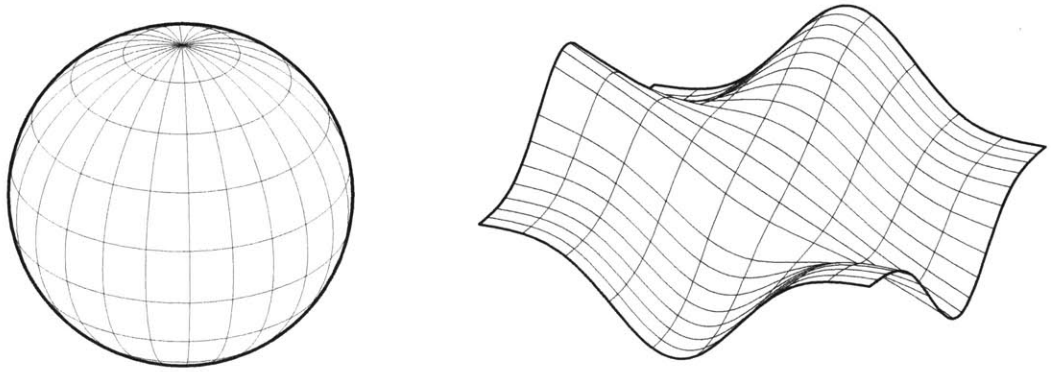

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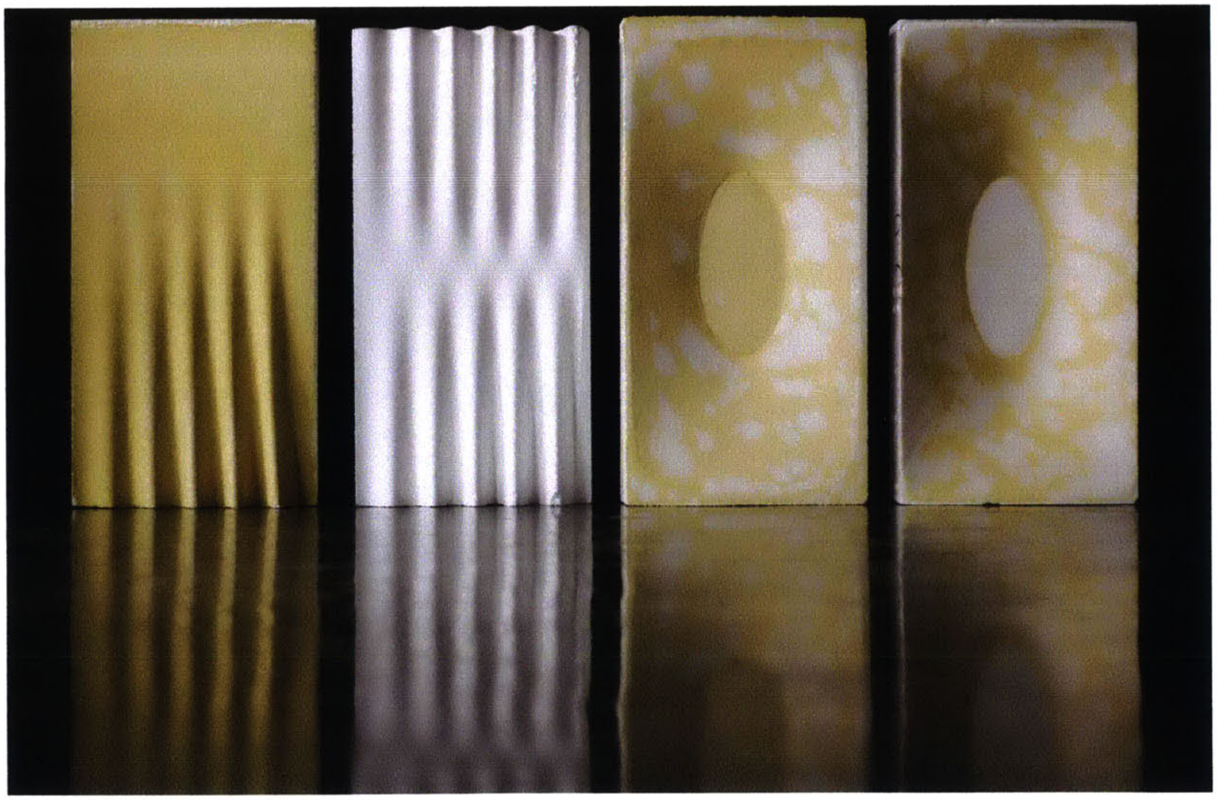
Expanded polystyrene (EPS) foam serves as a great material for mold making due to its low cost, ease of machinability, and recyclability. One potential downside to using EPS for molds is that it's a relatively soft material, even in its high-density version. This means it's able to deform under excessive pressure or dent easily. Currently the necessary technology and facilities exist for large scale CNC manufacturing. Such resources are capable of producing parts at the scale of large building components. Often times high end boat construction utilizes these technologies to produce extremely large and precise molds – upwards of two sheets of paper thick in tolerance over 100 ft. in length. EPS can also be cut using heat, typically transmitted through a nichrome blade or wire. This technique is often used in shaping foam by a number of people.

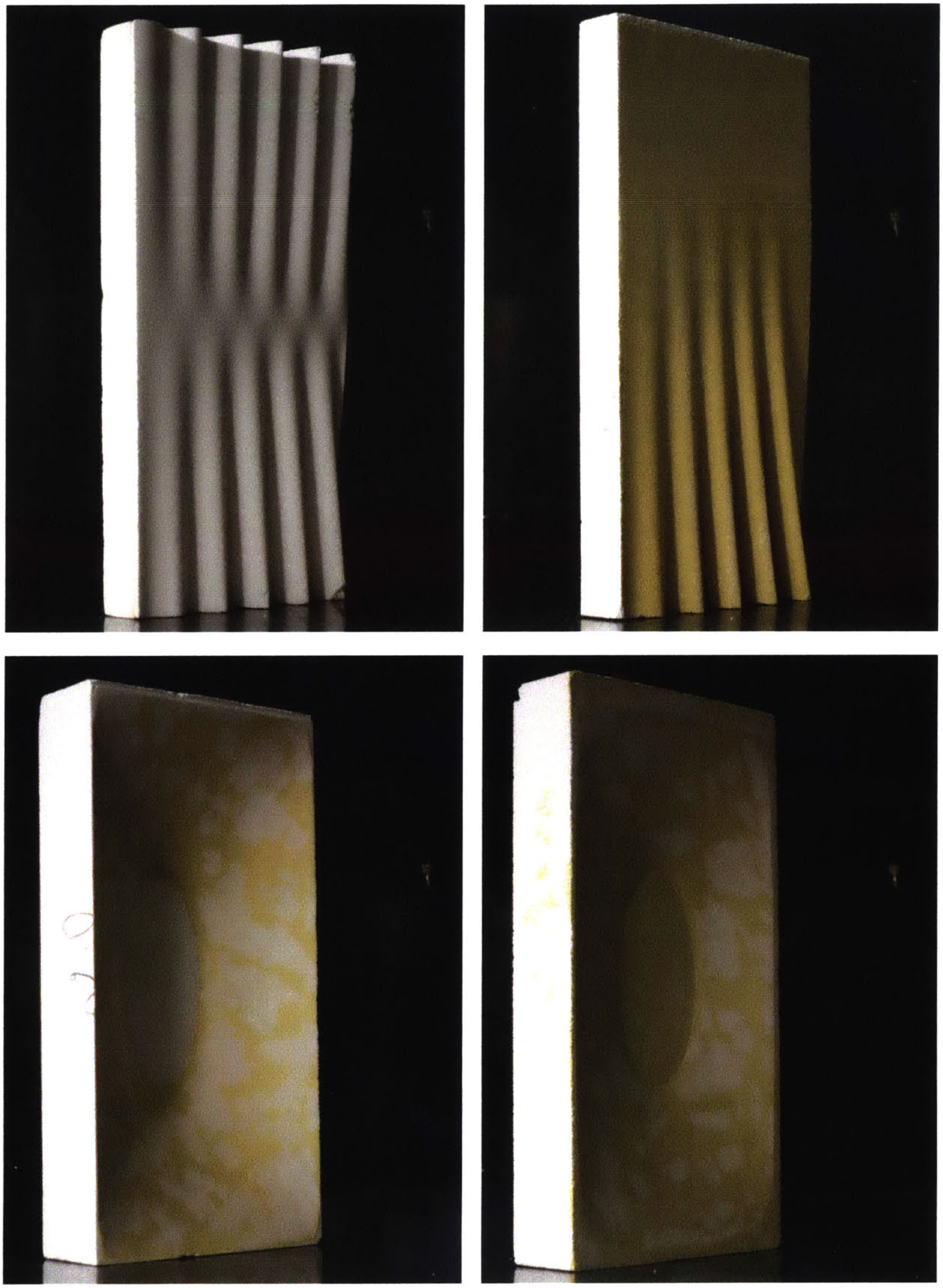
As part of the lineage of research that has informed this thesis, a paper titled Variable Carving Volume Casting was published in the proceedings of RobArch2014 held at the University of Michigan coauthored by myself, Brandon Clifford, Andrew Manto, and Patrick Little. (Clifford, Ekmekjian, Manto, Little 2014) In this paper we developed a set of tools and strategies for rapidly carving large amounts of foam with a KUKA robotic arm to fabricate low cost molds for casting. This research began in a workshop titled Volumetric Robotics, taught by Brandon Clifford at MIT and provided a starting point for further exploration though independent studies and other productive venues. While the core of the research focused on developing a method for mold making, much of the work included investigations into the use of glass fiber reinforced gypsum (GFRG) as a medium for casting unique architectural elements.

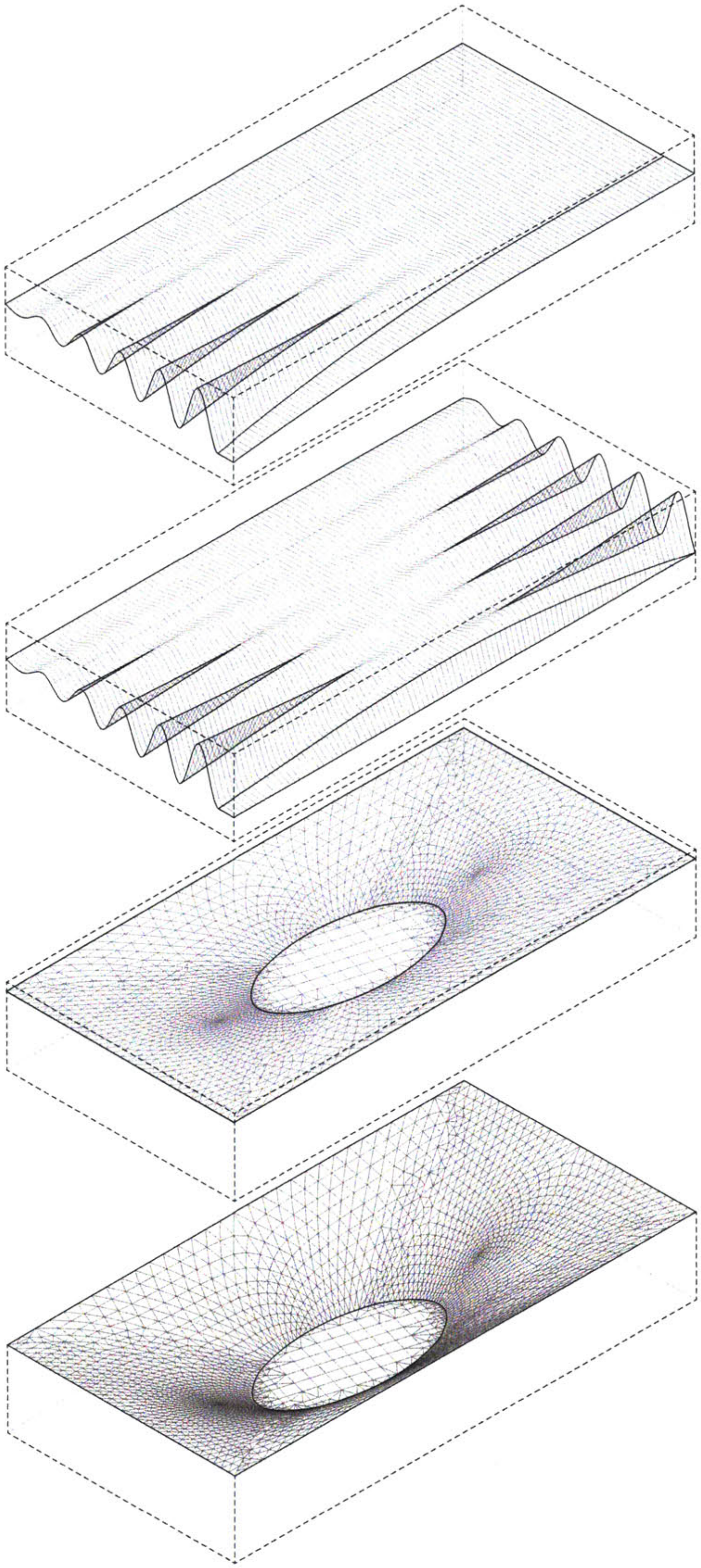
From Volumetric Robotics. A workshop taught by Brandon Clifford at MIT in Fall 2013.

The prototypes constructed throughout the course of this thesis use 2 lb. density EPS as a medium for a series of 24" x 48" x 6" molds which were machined on a 3 –axis CNC mill. The surface of these molds then had to be protected with water based wood putty in order to prevent the epoxy from sticking to them. It was later discovered that an additional sheet of nylon film between the mold and the part could be used in lieu of putty; however that sheet would have to be replaced with every part that was made. Since EPS is 100% recyclable, the use of nylon release film is preferred in order to maximize the amount of recycled material and also minimize time and labor with putty. The putty however, does provide a more rigid surface for the part to conform to, resulting in higher resolution parts with greater fidelity. This becomes important when two or more surfaces are joined together and require greater resolution and detail in order to successfully meet at any seams.



Four EPS Foam molds. Each one machined from 2lb. density foam measuring roughly 24" x 48"

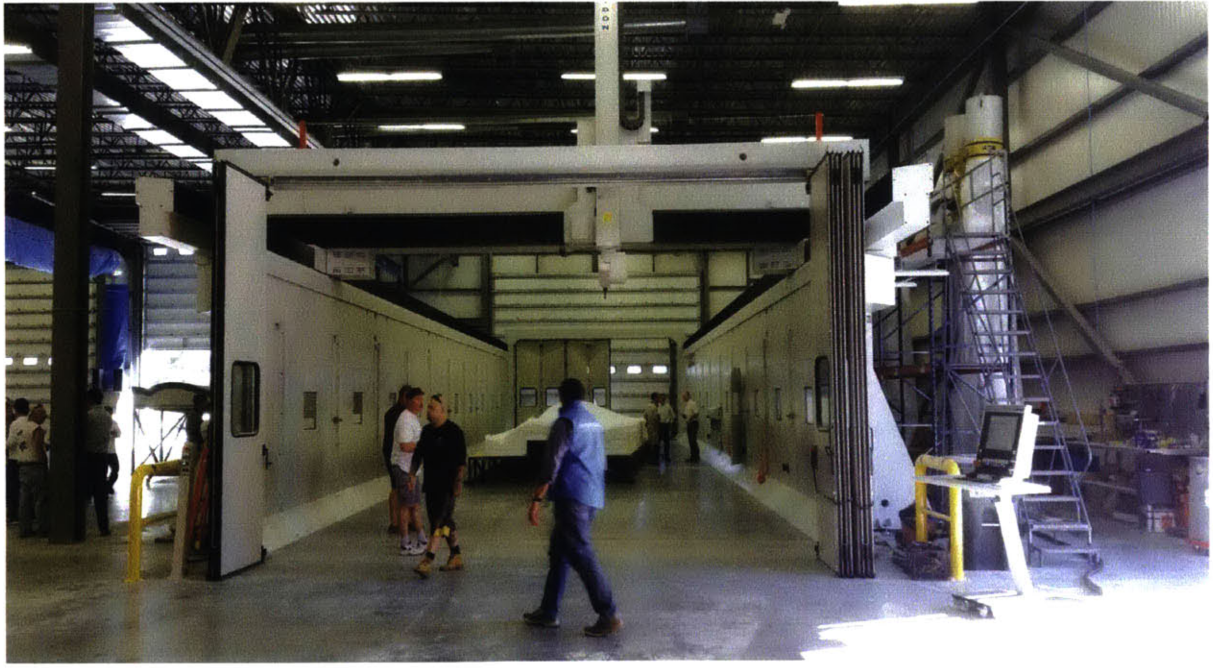




Drawings of Four EPS Foam molds of 2lb. density foam measuring roughly 24" x 48"

During a recent visit to Bristol, Rhode Island, I was able to take a tour of two manufacturing facilities specializing mainly in high performance boat building and composite material applications. Mouldcam is one company that provides custom mold making services to a range of industries by utilizing a multi-axis CNC machine fitted onto a 100'+ long gantry, which allows them to produce parts at the scale of building components at unprecedented accuracies. These molds are often pieced together using a system of integrated plugs, machined to such high tolerances that they are held together by the vacuum they create when they are joined. Mouldcam has also developed their own method for rapidly producing molds at such large scales. Generally they start with a steel frame which is then clad with several individual blocks of foam that approximate the final geometry. They may or may not perform a roughing pass to remove any large amounts of EPS in order to closer approximate the final part. In either case, once these blocks have been set up, they then apply a thick layer of putty which dries into a rigid medium. This is the material that is then machined into; resulting in what is the final finished surface of the mold, after some sanding. This method of course is only used for extremely large parts and only when the specific shape is such that requires is. Often times they will also simply machine away at large blocks without the use of frames or putty, all dependent on the scope of work as specified by the client.

Mouldcam facilities. Bristol, Rhode Island. Large scale CNC gantry milling.

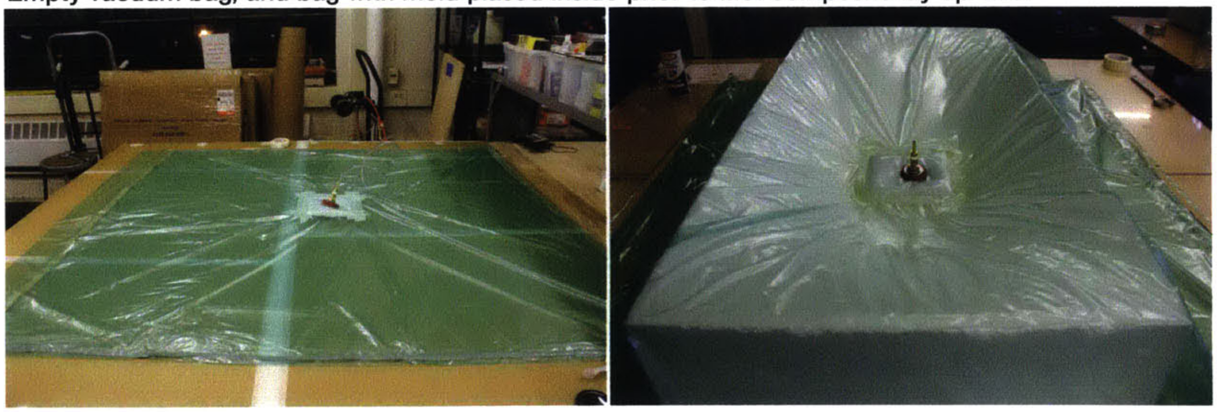


3.2 VACUUM BAGGING

Vacuum bagging is a commonly used process for producing composite parts against the surface of a mold under pressure, and sometimes heat. Vacuum bags can be custom made to fit to size and are often times reusable. The bags themselves are typically made of a high stretch nylon which is capable of conforming into complex geometries with no webbing if accounted for properly. In this case, the bags were made from a single sheet of nylon bagging film which were folded in half, and taped shut on the remaining three edges using an extremely strong putty tape. The "middle edge" was left to be sealed shut only after the mold and materials were placed inside. The tape is strong enough to provide a completely airtight seal, while allowing the bagging film to still be pulled apart from it cleanly in order to open the bag and remove the part.

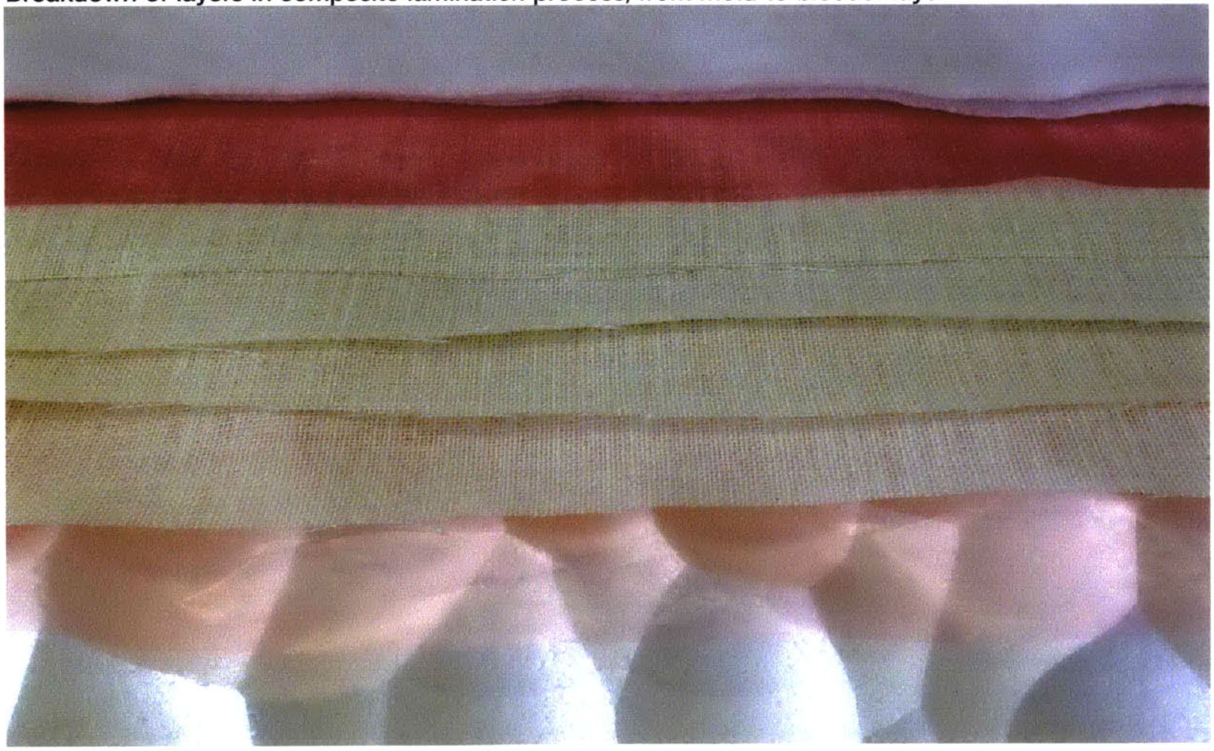
There are two main types of vacuum bag curing processes when dealing with composites. One is Vacuum Assisted Resin Transfer which relies on negative air pressure to not only suck down the part to the mold, but to also slowly infuse the resin across the part automatically. This process generally leads to more evenly infused parts, but can require a more complex setup than the second process: wet lay-up. This process uses negative air pressure only to conform the part to the mold; however the fibers themselves are infused with epoxy manually before it is placed inside the bag. This process can sometimes be messier, but it also has its advantages when dealing with larger parts or short time constraints. All of the prototypes made throughout the duration of this research were made using the wet lay-up method.

Empty vacuum bag, and bag with mold placed inside prior to first composite lay up. IDC.

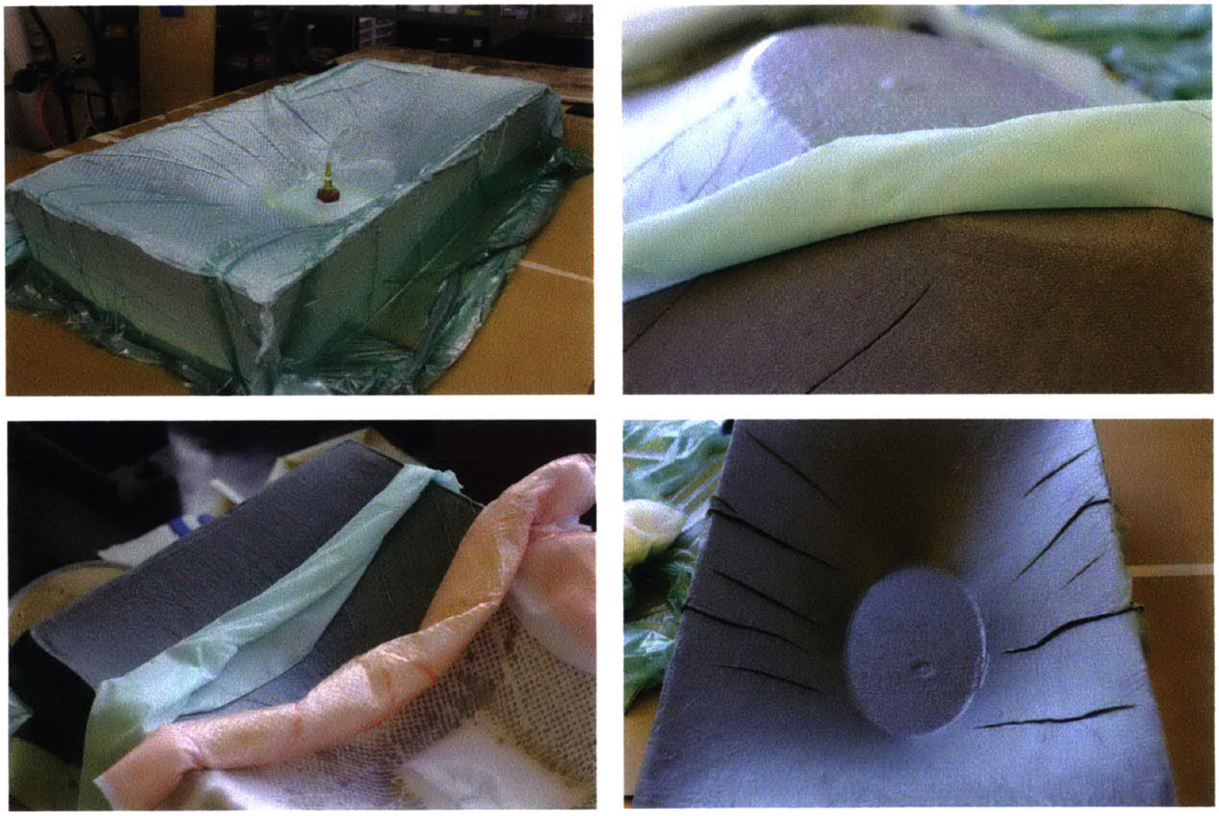


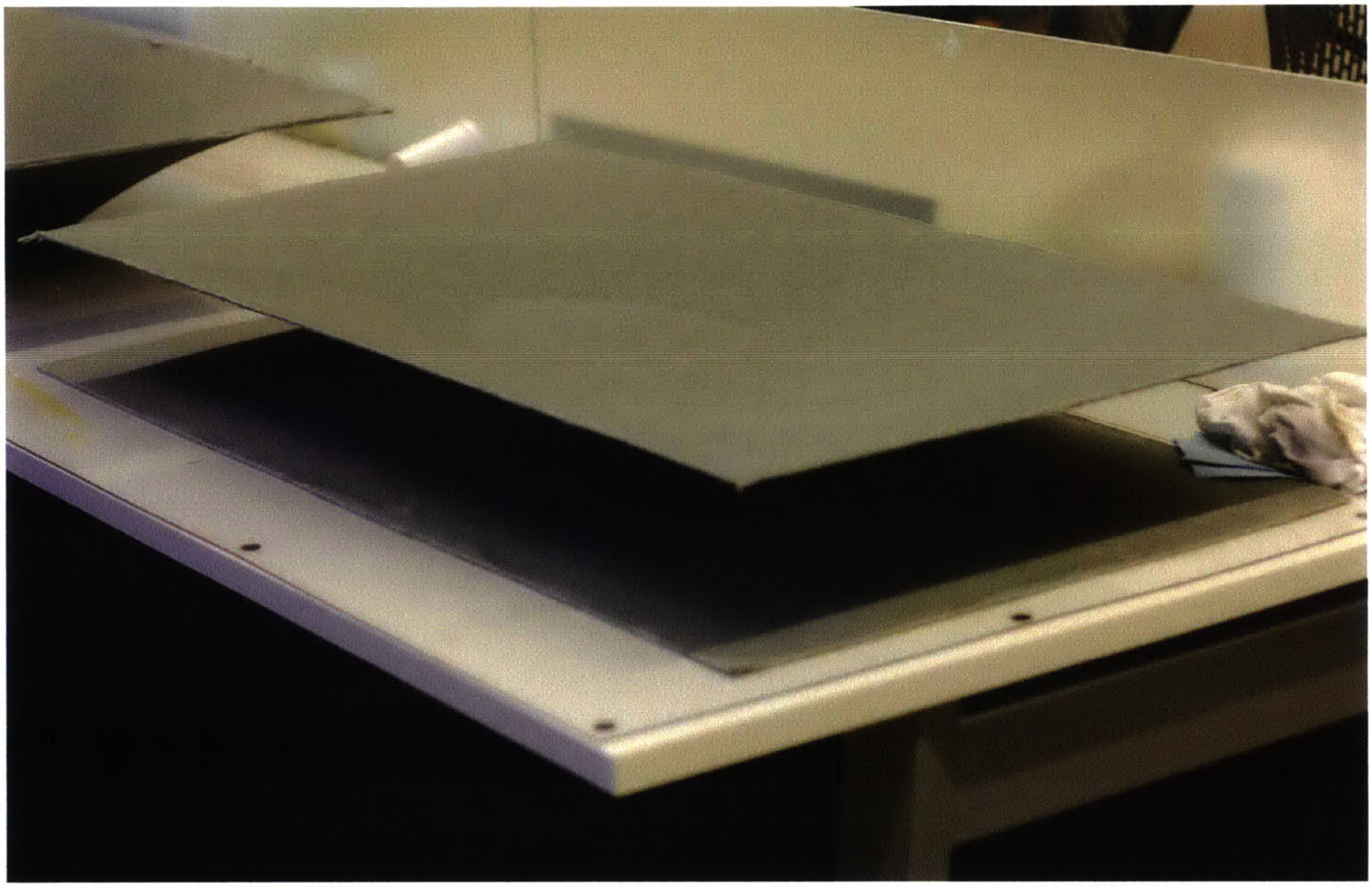
The bag houses the mold and contains all of the layers of materials needed to produce a rigidized surface. At the base is the mold itself, in this case machined EPS foam. Directly on top of the foam is a layer of release film to protect the mold from any epoxy that might come into contact with the finished surface. This is typically spray mounted down to prevent it from sliding and to also conform to the mold more neatly. Next lies a layer of peel ply. Similar to a release fabric, the peel ply is a finely woven nylon fabric often treated with a release agent that makes direct contact with the part. Peel plies are available in different finishes and textures. I used a nylon release peel ply to achieve a smooth yet somewhat gritty texture on the surface in order to better adhere to the expanding urethane foam core. On top of the release film then lies the multiple layers of fiber reinforcement, in this case burlap – a two directional woven cloth made of natural fibers. These layers are sequentially infused by hand with a marine grade epoxy from U.S. Composites and laid on top of one another inside the mold. On top of the final layer of fiber reinforcement rests another layer of peel ply, then the breather layer, which is a perforated film meant to allow for excess resin to flow through and into the bleeder layer. This is a thick layer of cotton cloth which absorbs any excess resin. A small handful of this material is generally placed at the base of the vacuum line where it meets the bag in order to prevent any excess resin from traveling into the vacuum.

Breakdown of layers in composite lamination process, from mold to bleeder layer.

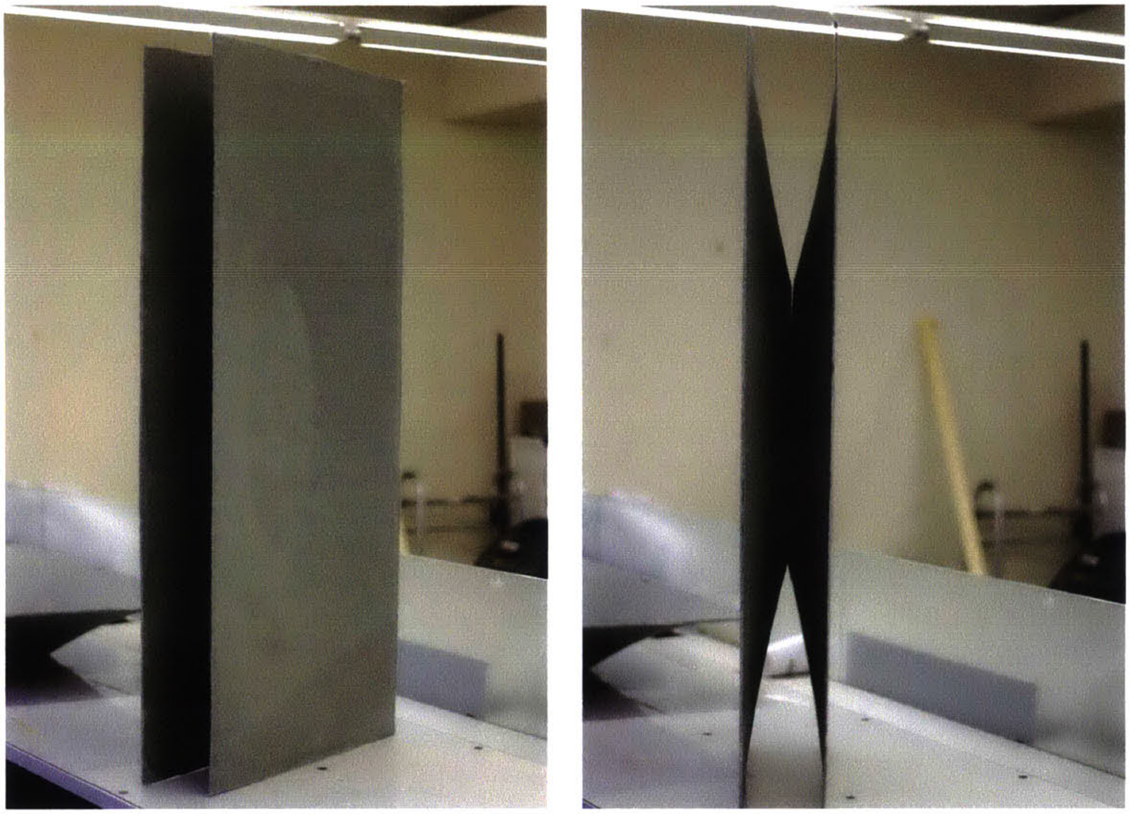


Depending on the type of epoxy used, the curing process will vary in duration. All of the parts produced throughout the course of this thesis were left to cure overnight anywhere between eight to twelve hours. Typically in professional applications, especially when using pre-preg composite fabrics, parts will be placed inside of a kiln during the curing process. This is done mainly due to the use of thermoset resins, but also because of the additional strength provided by the application of heat. Once a part has been set to cure in a vacuum bag overnight, the next step is to demold. This process is relatively straight forward, yet it requires careful attention as the possibility of puncturing the vacuum bag is at risk. Once the bag is opened, the mold is pulled out while all of the layers are still tightly attached to it. Each layer is pulled away from the mold, beginning with the outermost layer of bleeder and breather material and finally with the two layers of peel ply attached to the part itself. In the best case scenario, the result is a rigidized yet somewhat flexible part that has been thoroughly infused with epoxy in a balanced ratio of fiber to resin matrix. These parts are then taken to a band saw and their borders are trimmed neatly, providing a clean edge to work with.

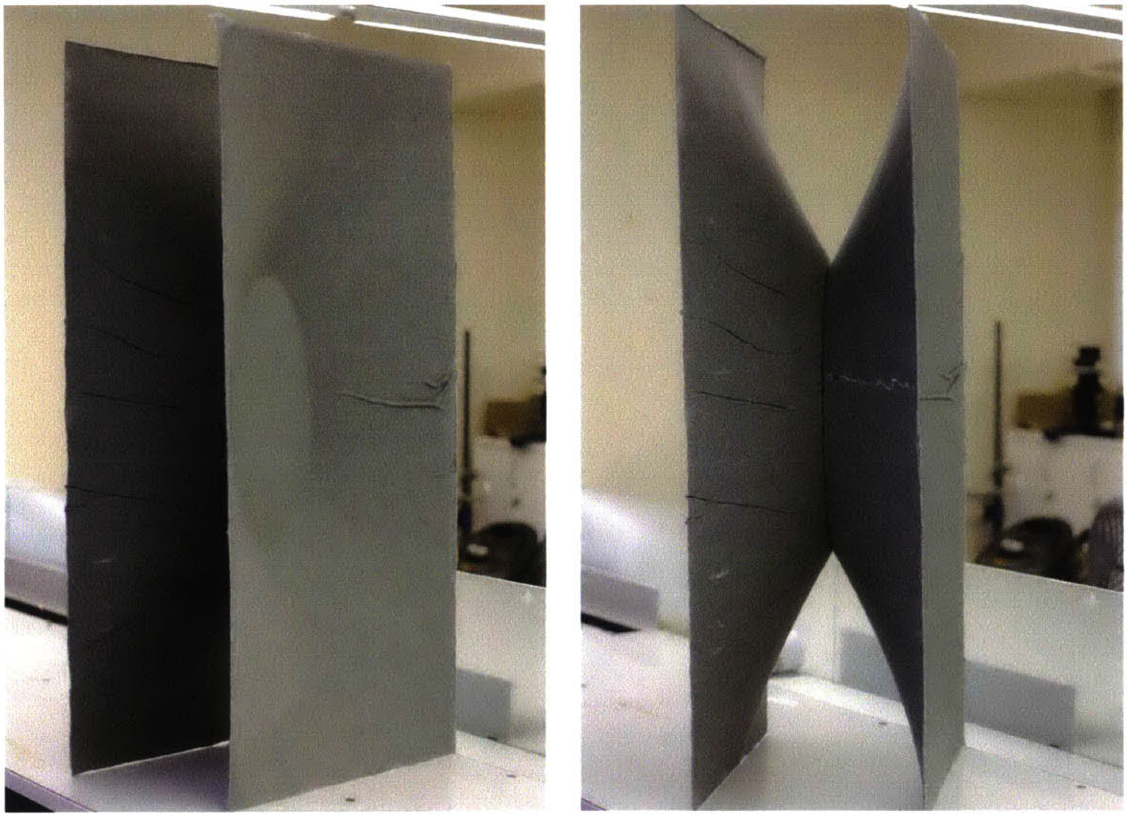


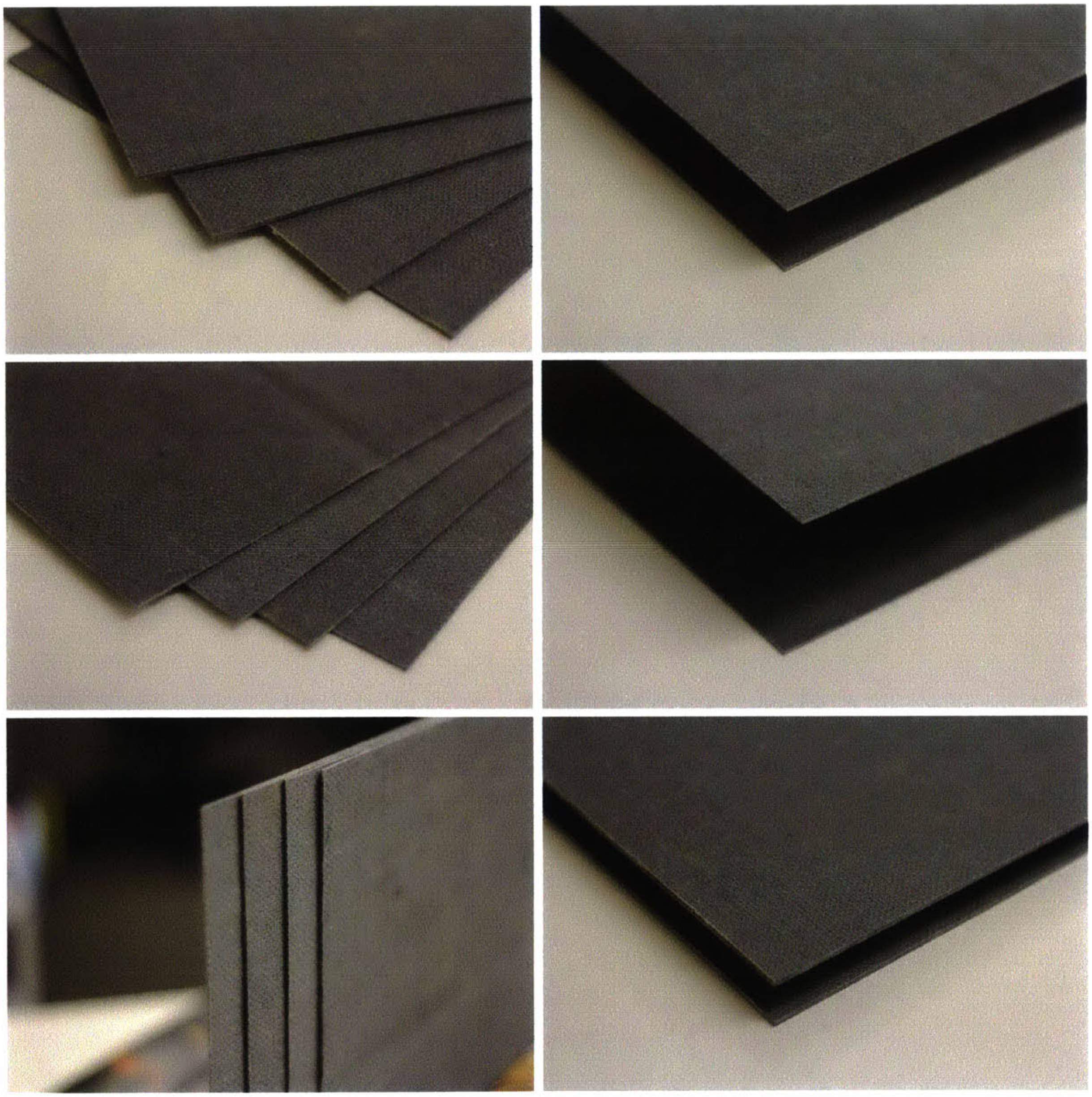


Early prototypes. International Desin Center, MIT.



Early prototypes. International Desin Center, MIT.





Early prototypes. International Desin Center, MIT.

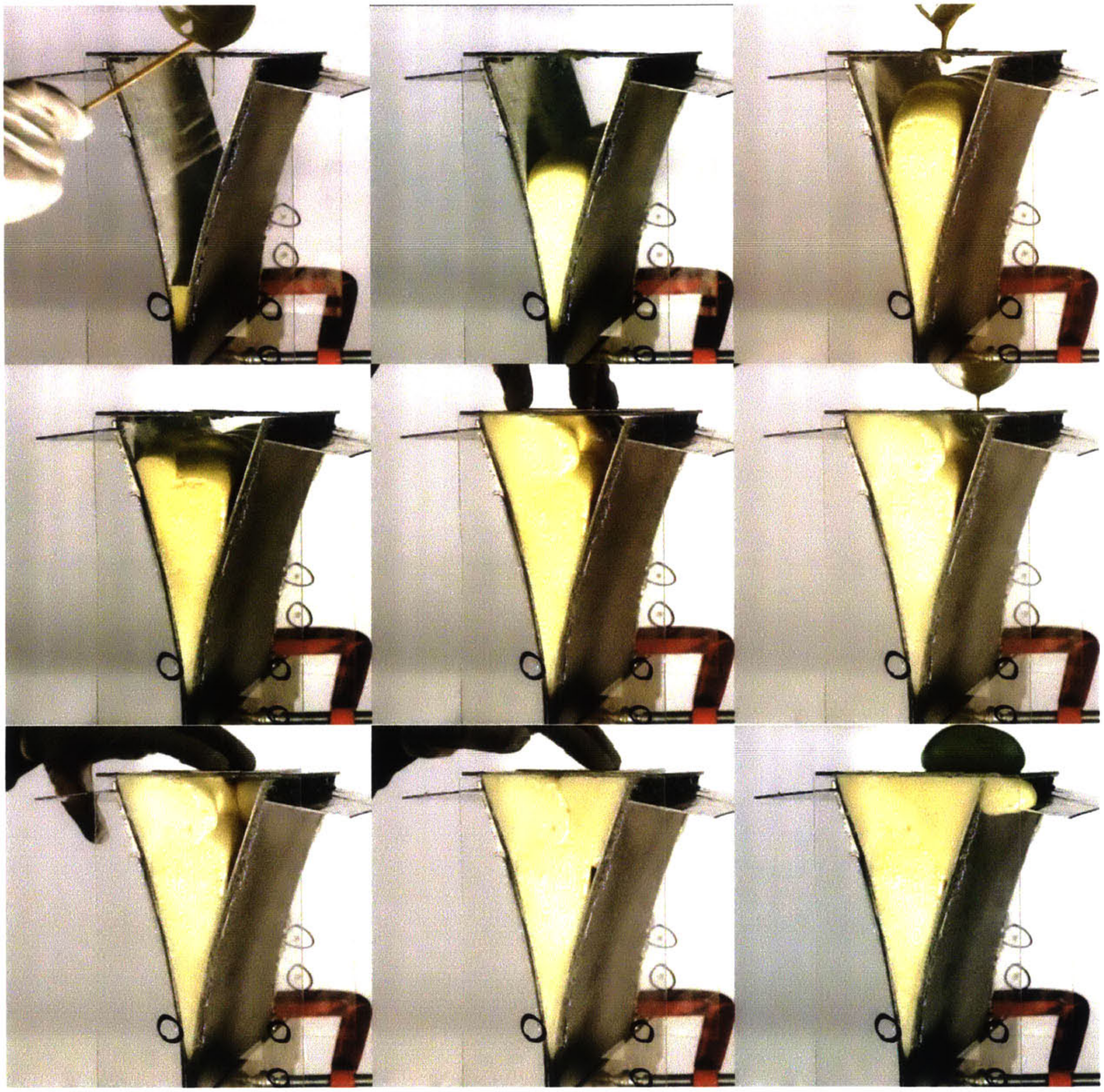
3.3 BACKFILLING / INFILLING

Perhaps the most important process involved with the construction of variable thickness sandwich structures is the act of backfilling or infilling the core between the two skins. Backfilling and infilling are two methods used to describe the process of joining an inner and outer skin, creating what becomes the poche of the sandwich. This process uses rigid closed cell expanding polyurethane foam which is poured in between the two skins.

Expanding urethane foam is widely used in a number of applications ranging from architectural insulation to decoration to acoustic applications. Originally developed by the military in the 1940's for use in airplanes it later became used as an insulation material through a spray on application. Today it is commercially available and also widely used in the production of props and large composite sculptures. It varies in density and expansion rate and is generally manufactured as a two part mixture. The foam used in the prototypes here has a density of 3 lbs. per cubic foot and an expansion rate of 1:18 by volume.

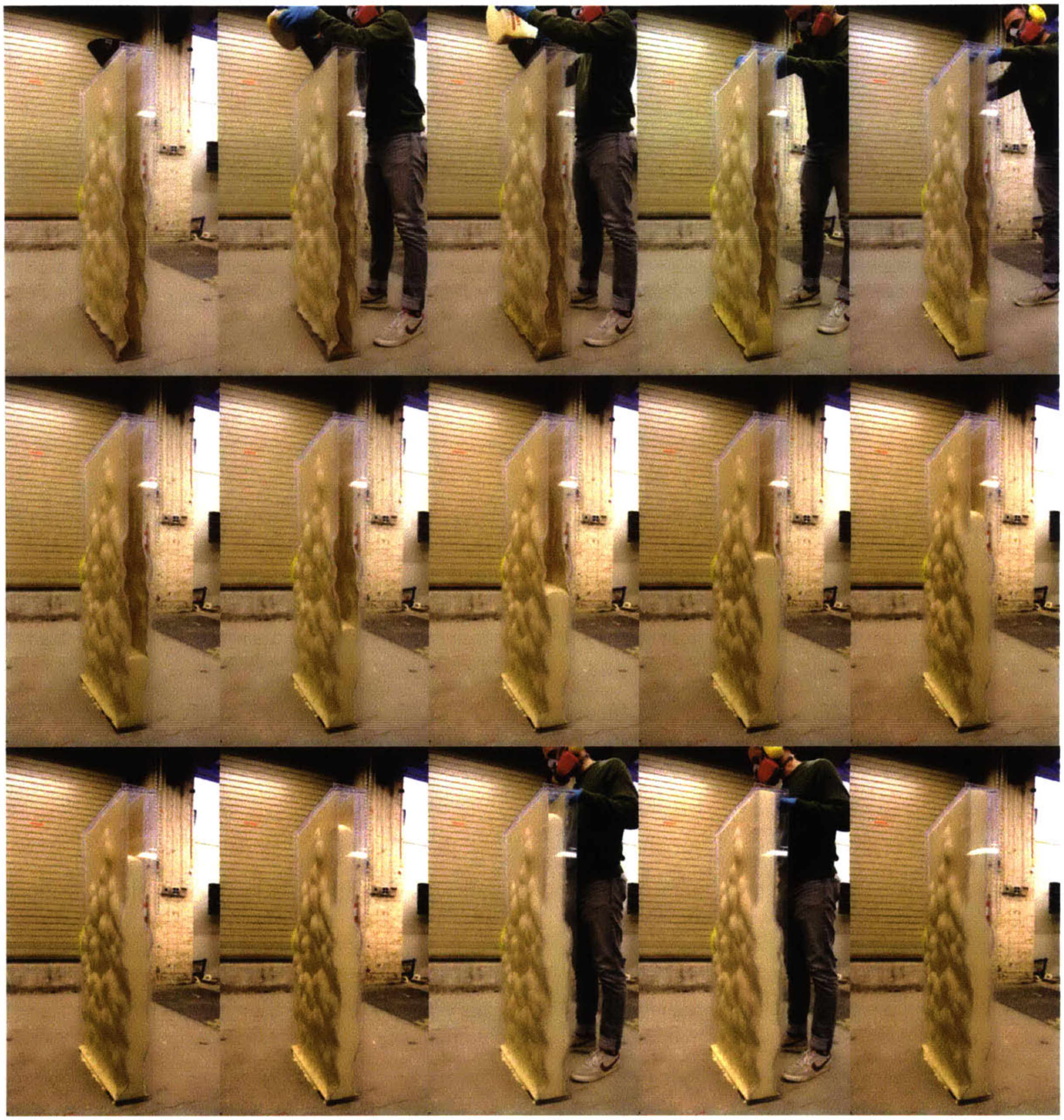
Conceptually, the process of infilling between two surfaces is different than simply casting a distinct volumetric element even though both may result in a single 3-dimensional object. One can perceive infill as a strategy for implementing solid mass in areas where it's necessary for a variety of reasons, be it structural, architectural, functional, etc. The purpose of using infill here is mainly to allow for variable thickness within laminar assemblies. For instance, in areas where two surfaces are pressed together to form a single surface, the space between them becomes increasingly smaller. It is in these tight areas in particular where an expanding medium such as urethane proves to be advantageous, resulting in maximum contact between the two skins in all possible moments.

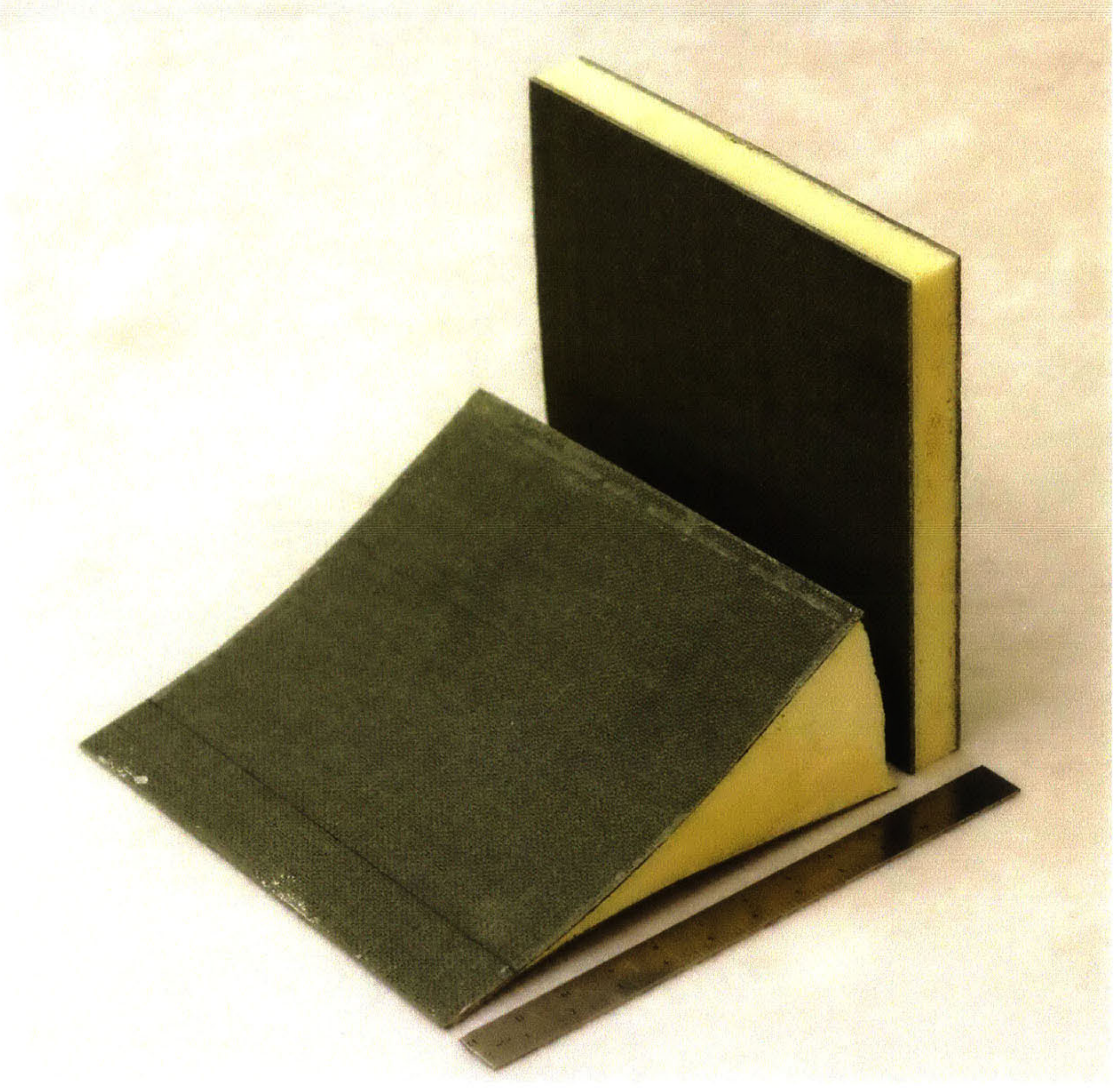
Technically, the process of infill is carried out in a relatively simple method. First, the two skins are trimmed down to the same perimeter on both parts. This allows them to be held in place together by a number of other pieces, typically a sheet material like acrylic or aluminum. As shown in the figure below the two skins are each adhered to pieces of aluminum and acrylic using hot glue and are separated by a space in between. The foam is then mixed and poured in from a hole on top. It expands rapidly, and is ready to be de-molded after about an hour. The result is a rigid, lightweight assembly composed of two skins and a cellular solid core in between.

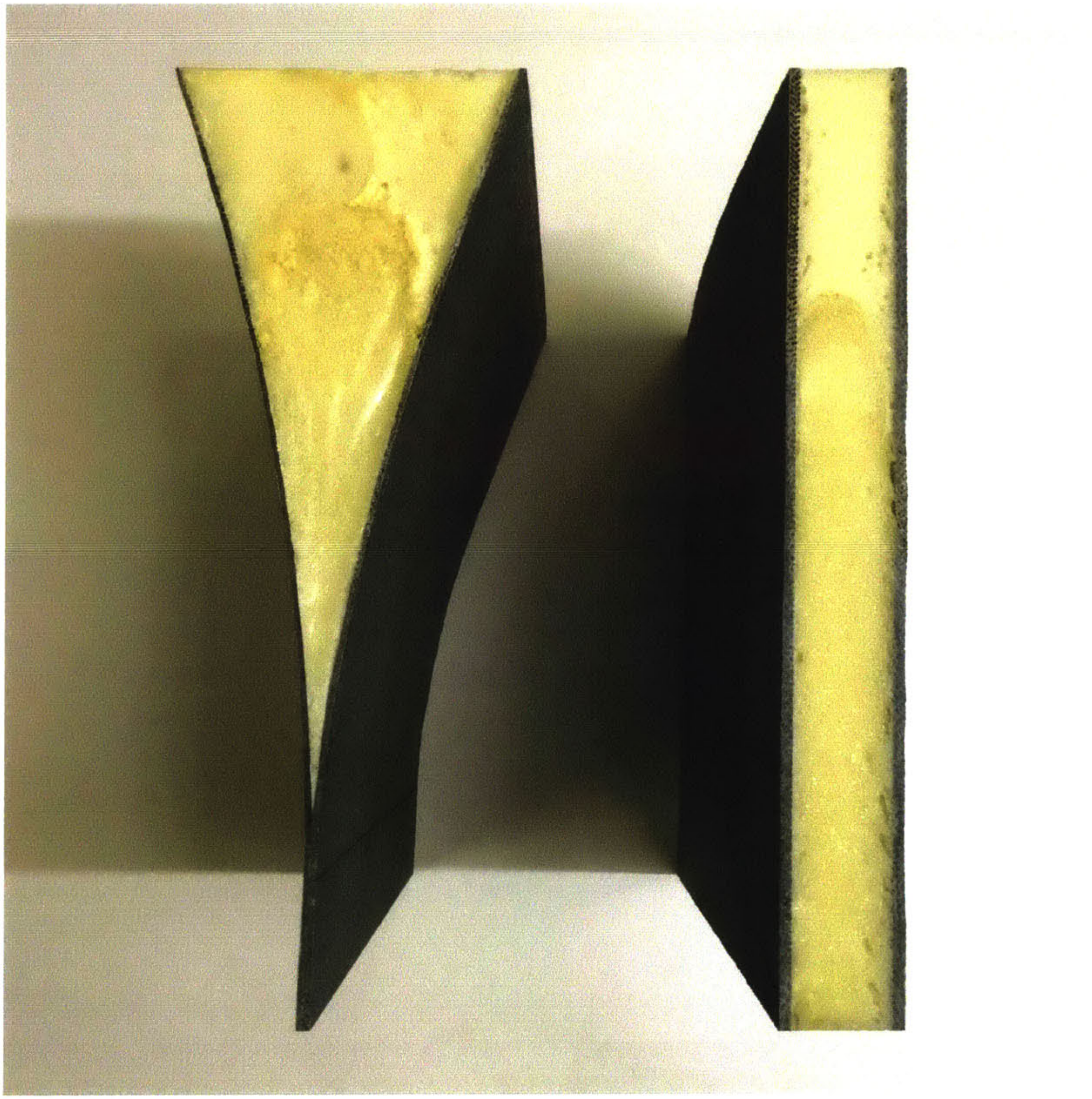


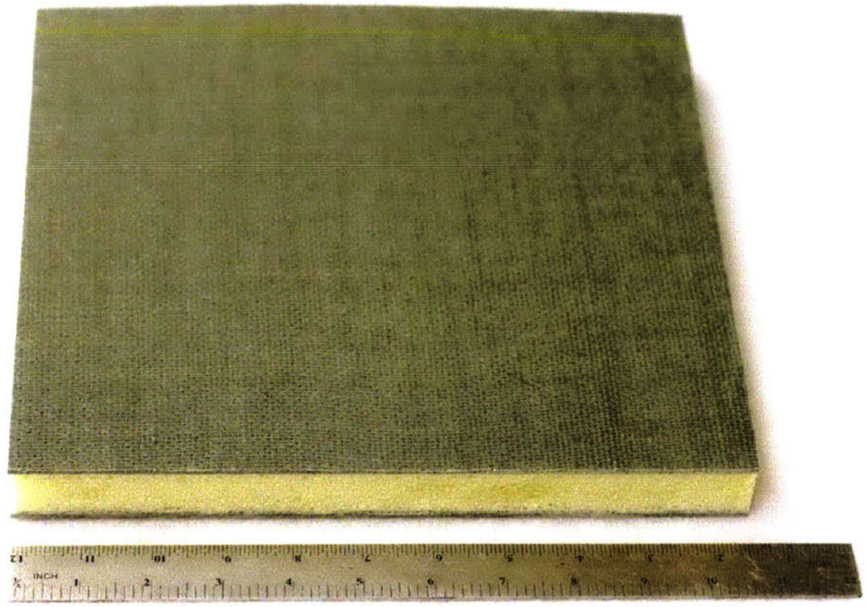
Early infill sequence. International Desin Center, MIT.

Early infill sequence. International Desin Center, MIT.

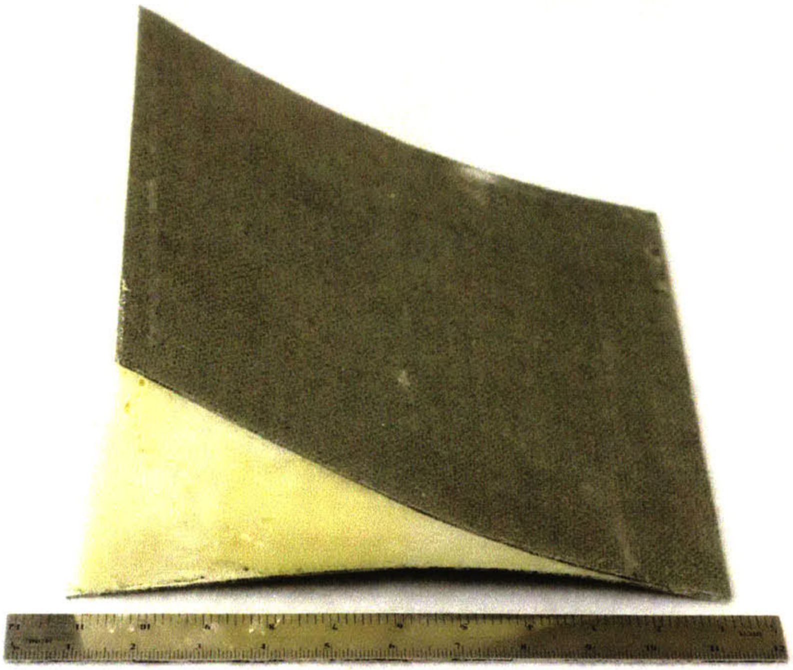

Early infill sequence. International Desin Center, MIT.





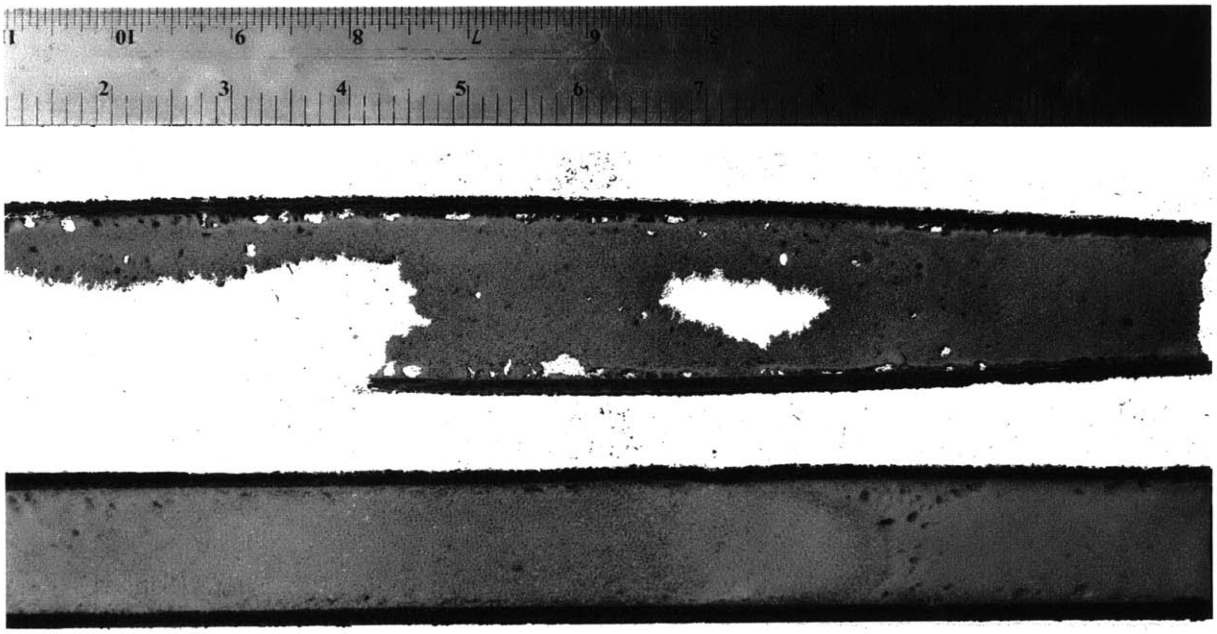


Standard thickness composite sandwich.



Variable thickness composite sandwich.

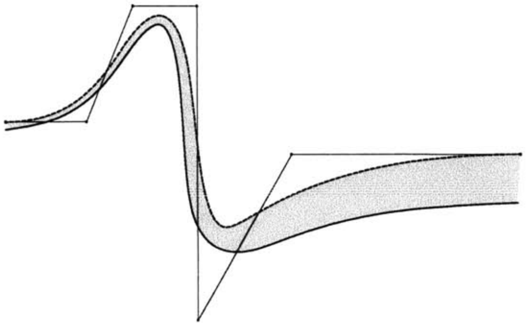
It is important to note that foam tends to expand in a particular manner; first horizontally until it either reaches its limits or a physical boundary, then vertically. This information is useful when considering the physical orientation of a part in space and how to best accommodate for core expansion. Also, because expanding urethane is exothermic, it's best to pour multiple times in smaller amounts in order to minimize heat from off gassing. While this may seem as a burden at first, in actuality it has many benefits. For instance, it's possible to vary the density of the core simply by controlling the number and location of pours between the two skins. Also, by varying the density of the foam itself within the core, one can apply higher density foams closest to the skins where more strength is required and lower density foam towards the center where less weight is desired. Due to the adhesive properties of urethane foam, performing multiple pours will ensure the material will always bond to itself.



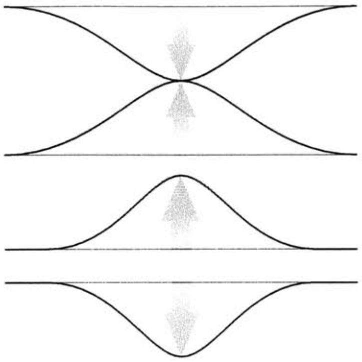
Early standard thickness prototype sections.

Strategies for Variable Thickness

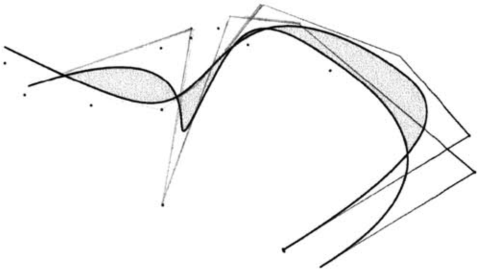
variable offset



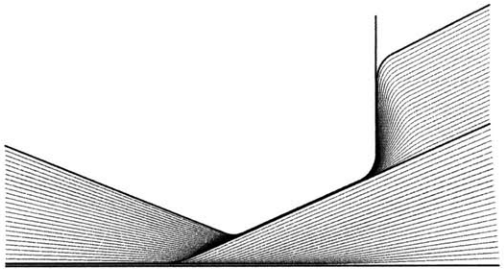
pinching / pulling



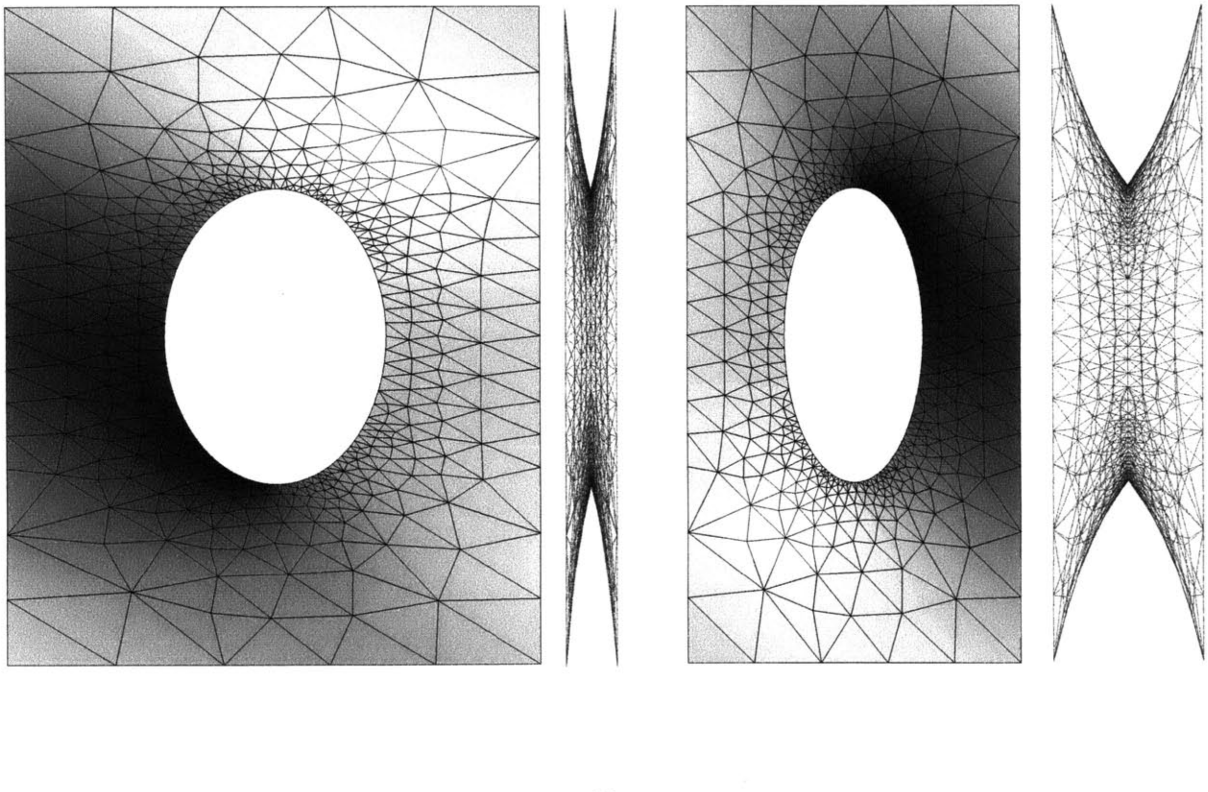
intersecting geometries



splitting / bifurcating



strategies for apertures

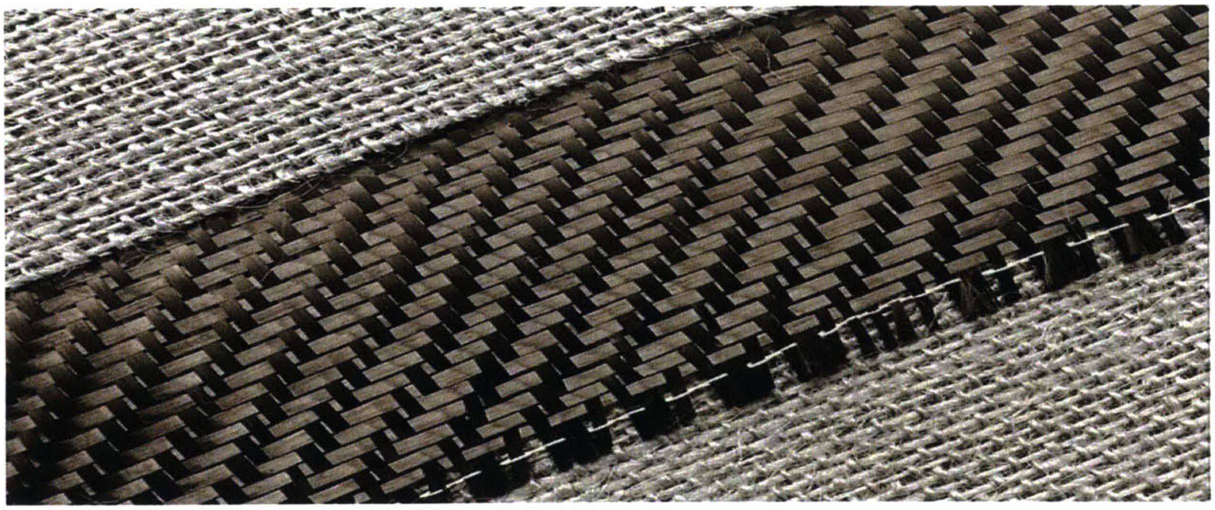


4.0 Results

4.0 Results

Overall, the process of constructing variable thickness sandwich structures proved to be fairly tedious, labor intensive, time consuming, full of unknowns, yet rich with potential. Given this work is in its earliest stages of development at this time, the process is still being invented. Variable thickness, by nature implies non-standard logics and customized methods as opposed to standard, commercially available composite sandwich panels which are generally flat and parallel. What this process does produce however, is an incredible rigid part with the ability to perform differently on either side of the structure. For instance, the use of corrugation on one surface can provide both acoustical and structural properties simply from its shape, while the opposing skin can provide a flat surface for walking or working on. This allows us the ability to think more freely about internal and external functions, and to be able to shape their spatial qualities independently from one another, similarly to the 9 cathedrals drawn though figure-ground.

The process of laminating several layers of burlap infused with epoxy proved to yield surfaces of complex geometries with relatively high fidelity to their digital counterparts. While burlap was used as an inexpensive and natural analog to carbon, it still demonstrated that it could provide a strong enough surface to produce a sandwich structure capable of withstanding at least the weight of a human being. It's no question that carbon is superior to burlap in terms of strength however it also much more expensive. Burlap was also chosen for its aesthetic qualities over carbon as well, further demonstrated by the use of a carbon layer sandwiched between two sheets of burlap to hide its presence yet benefit from its structural capabilities. This was done in only one prototype.



Specifically, the process of infilling is one that requires significantly more development as it is currently the most unknown. At the level of small scale prototypes infilling is quite feasible, however when we start to think about scaling up, the execution must be reconsidered. While it has not been tested in this thesis, the possibility of on-site foam injection is a worthwhile option to consider, especially when speculating on larger scale structures which may need to be erected on site. Polylevel, is a product/service of Foundation Supportworks Inc which specializes in foundation support and repair. Trained contractors are hired to repair misaligned or sunken concrete floor slabs by drilling a hole and injecting high strength expanding urethane foam into the gaps between the slab and the earth. This foam is strong enough to lift the slabs where needed in order to level the floor to its original state. If we try to conceptualize this process, we can think of it as on site infill, rich with potential for large scale construction of walls, floors, and roofs.

5.0 Speculations & Projections

5.0 Speculations & Projections

5.1 SMALL SCALE TESTING

This thesis aimed to develop a series of methodologies ranging from design logics via computational and parametric modeling to physical and material testing via small scale prototypes. Using strategies such as adaptive corrugation, variable offsetting, pinching, and pulling to create various conditions responding to certain demands, I was able to develop a sense of understanding on how certain design moves would behave physically. For instance a surface which transitioned from a corrugated section to a flat section showed most structural integrity in moments of depth as opposed to flatness. Or perhaps a more nuanced example, where by testing the number of laminations within a single burlap assembly I was able to discern a range of stiffness to translucency and how the porosity of a single surface affected the amount of urethane foam that might seep through during expansion. These and other characteristics of specific material behaviors often times were only made apparent through hands on experimentation. The relationship between hands on material experimentation and design speculation is one that I feel must be reciprocal, continuous, and informative through exchange.

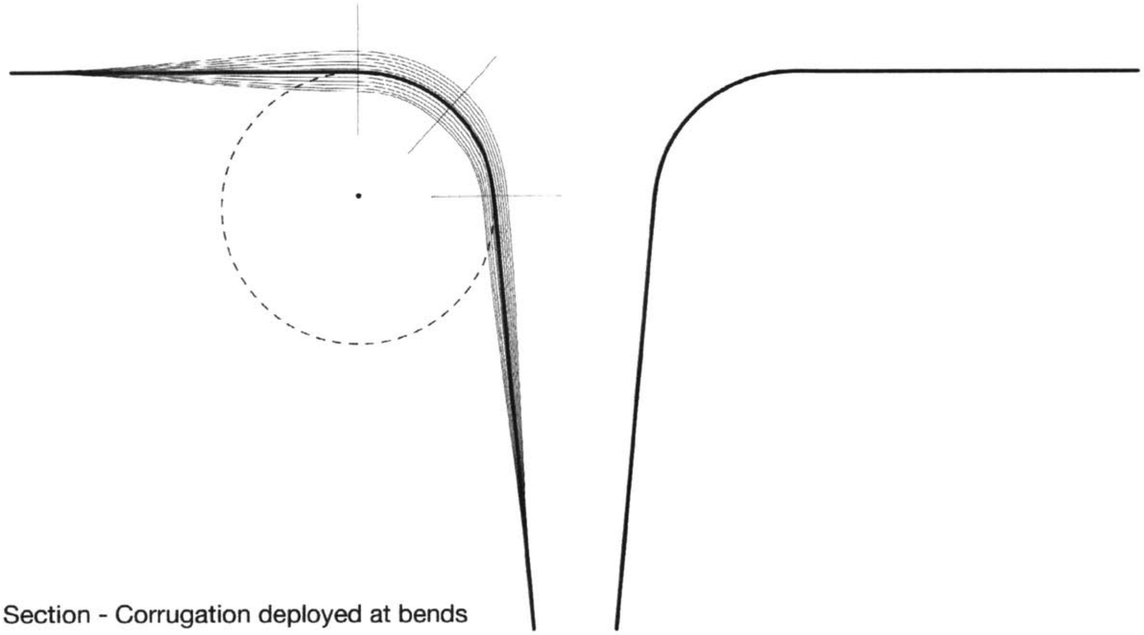
5.2 ARCHITECTURAL PROPOSITIONS

Utilizing these experiments and reciprocal relationships, this thesis explored two small design proposals as a means of testing architectural intentions with previously developed design and construction methods. The first proposal, a public seating canopy stationed at a rest area, aimed to explore variable thickness in section by transforming between moments of extreme thickness to extreme thinness. The second proposal, a more intimate canopy aimed to explore this same variation not only in section, but also in plan as well as in terms of its program.

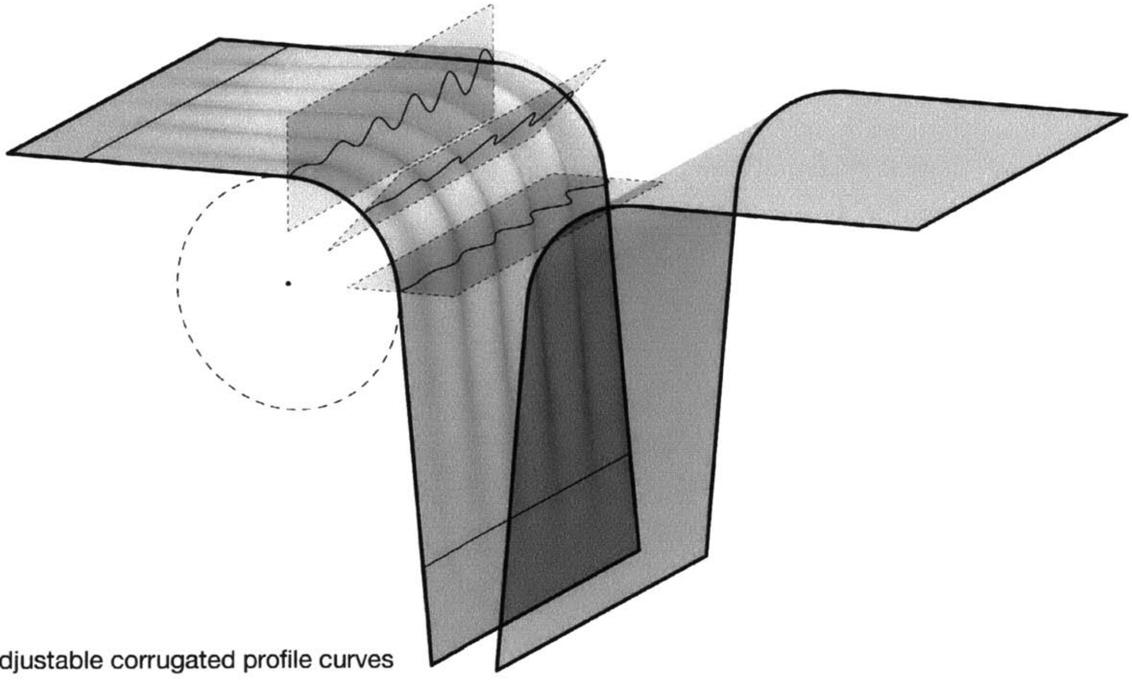
Proposal 1 embodied strategies of adaptive corrugation and bifurcation by demonstrating two main features visible in any given section of the structure. One is the moment of transition between thick and thin, evidenced by the change in profile from seating to overhang, and the other - is the moment where once two surfaces merge to become one, they now rely on shaping rather than thickness to perform structurally. This is seen by the crenulation in the areas of overhang.

In both plan and section, this scheme is clearly symmetrical. This is the result of an effort to minimize the number of unique elements within the structure and reduce the amount of molds, labor, and time required to construct it. This is also simply a first attempt at jumping to an architectural scale with the given system and therefore proceeded with more caution than perhaps should be. Non-standard material deployment meets standardized symmetrical construction types – potentially a less interesting design scheme however perhaps more economic.

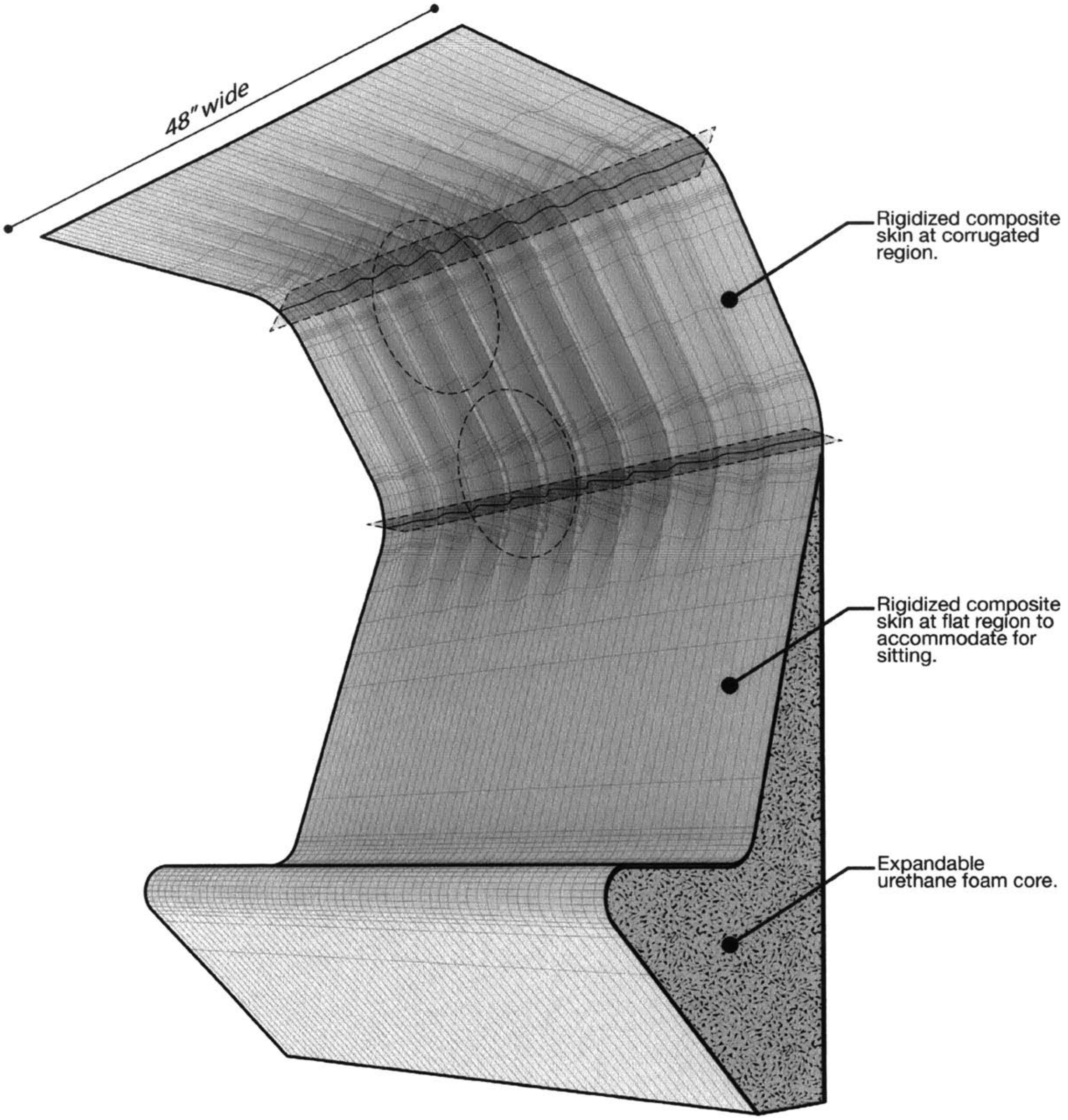
Adaptive Corrugation



Section - Corrugation deployed at bends



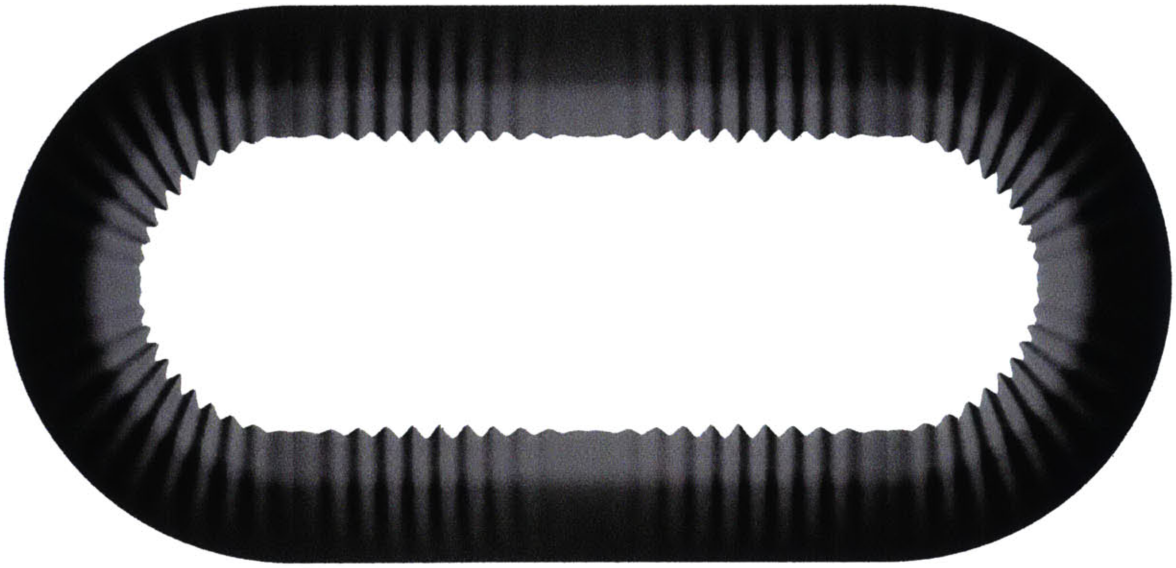
Adjustable corrugated profile curves



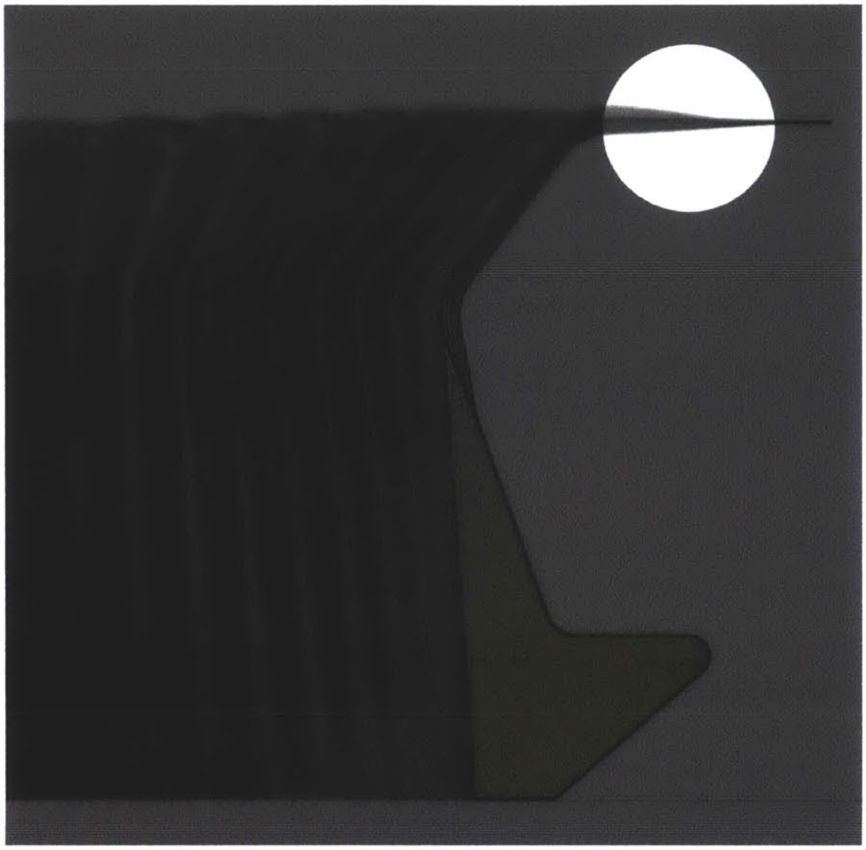
Proposal 1 - Sectional Perspective

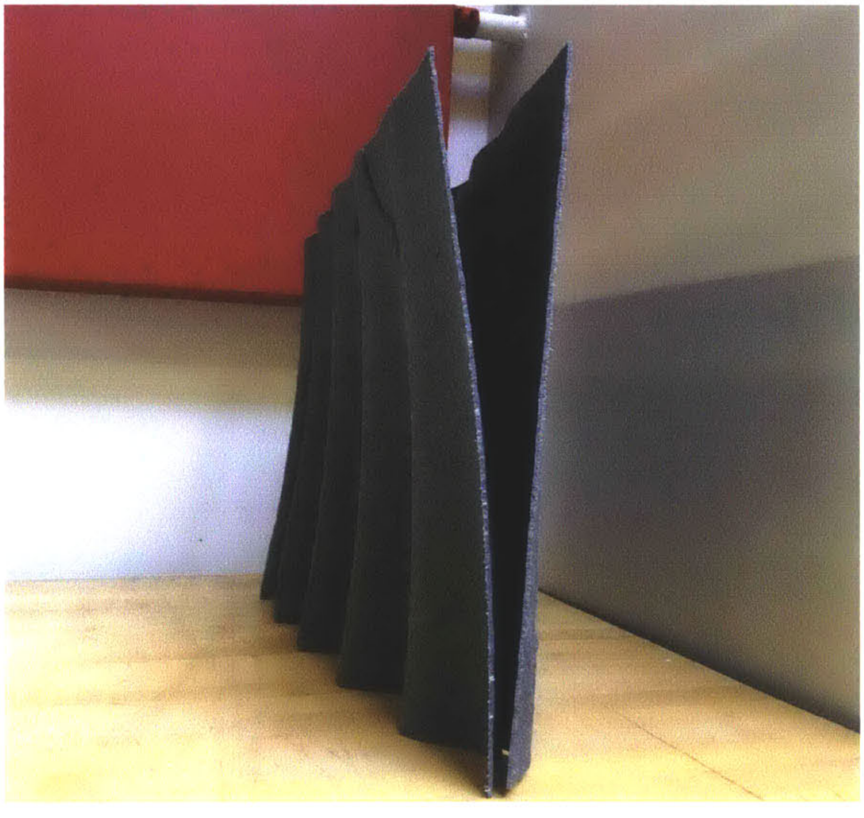
Proposal 1 - Section

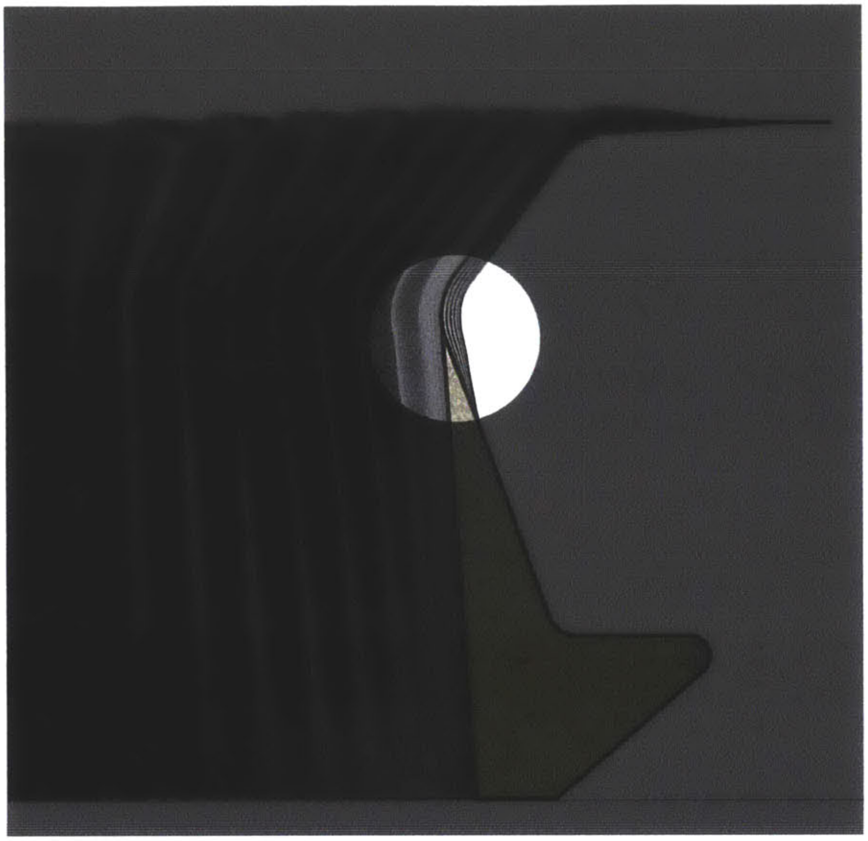
Proposal 1 - Elevation

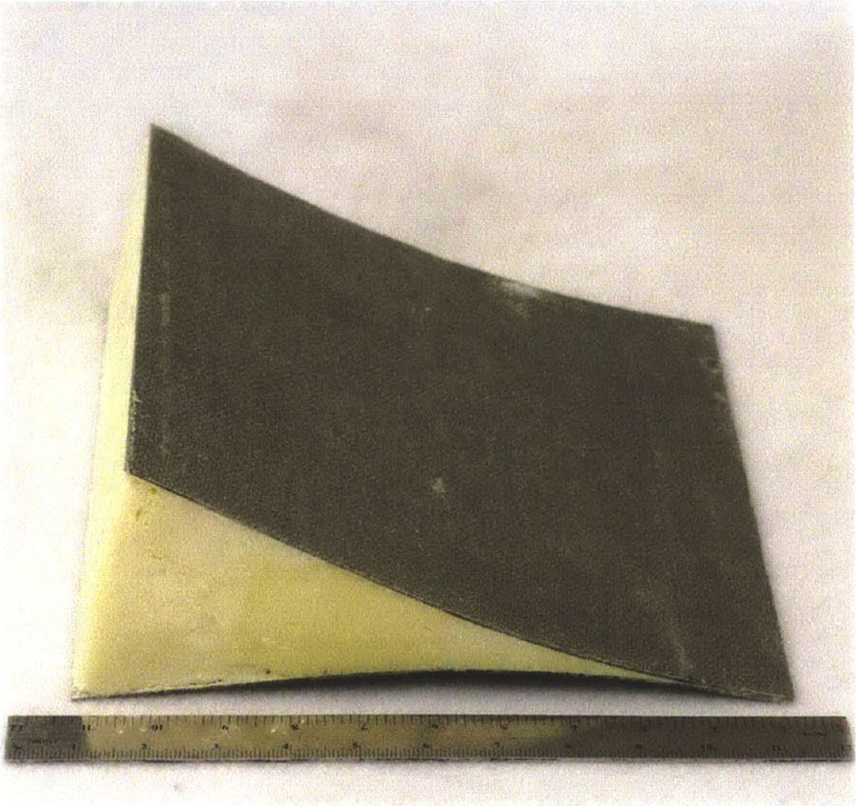


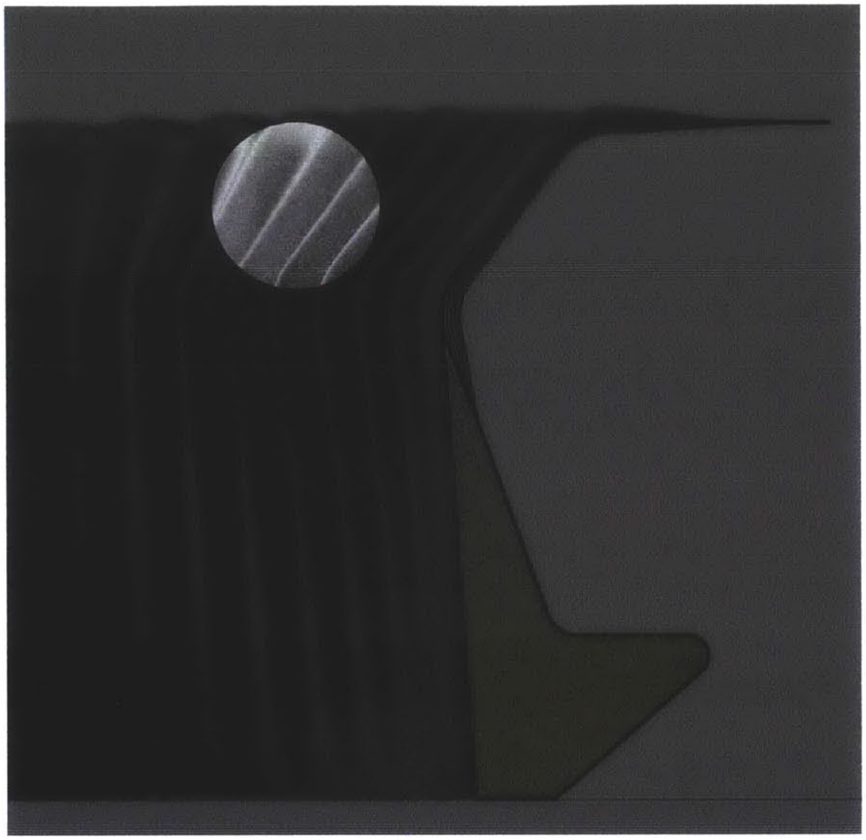
Proposal 1 - Plan





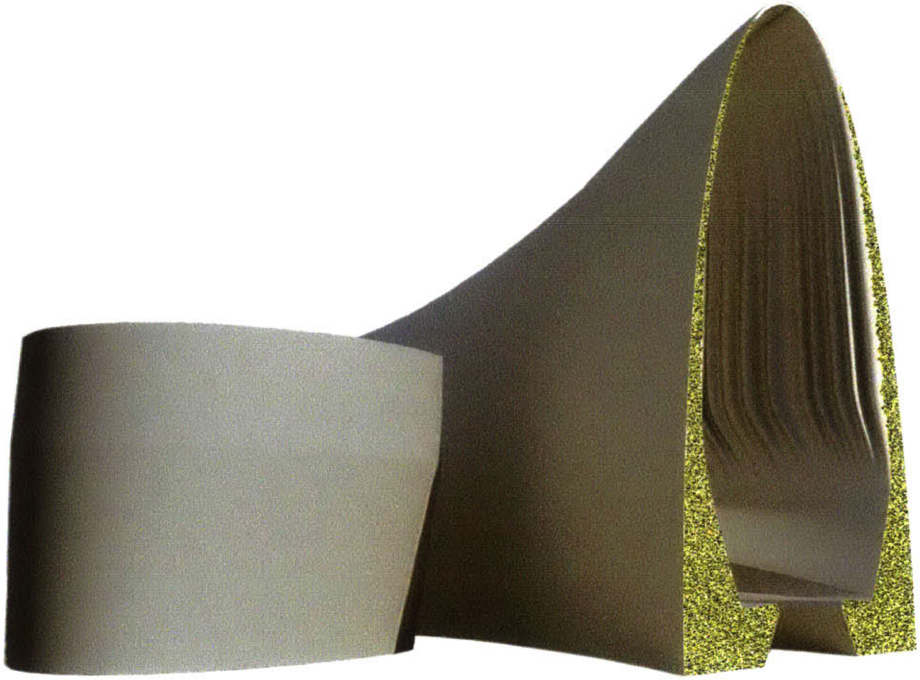




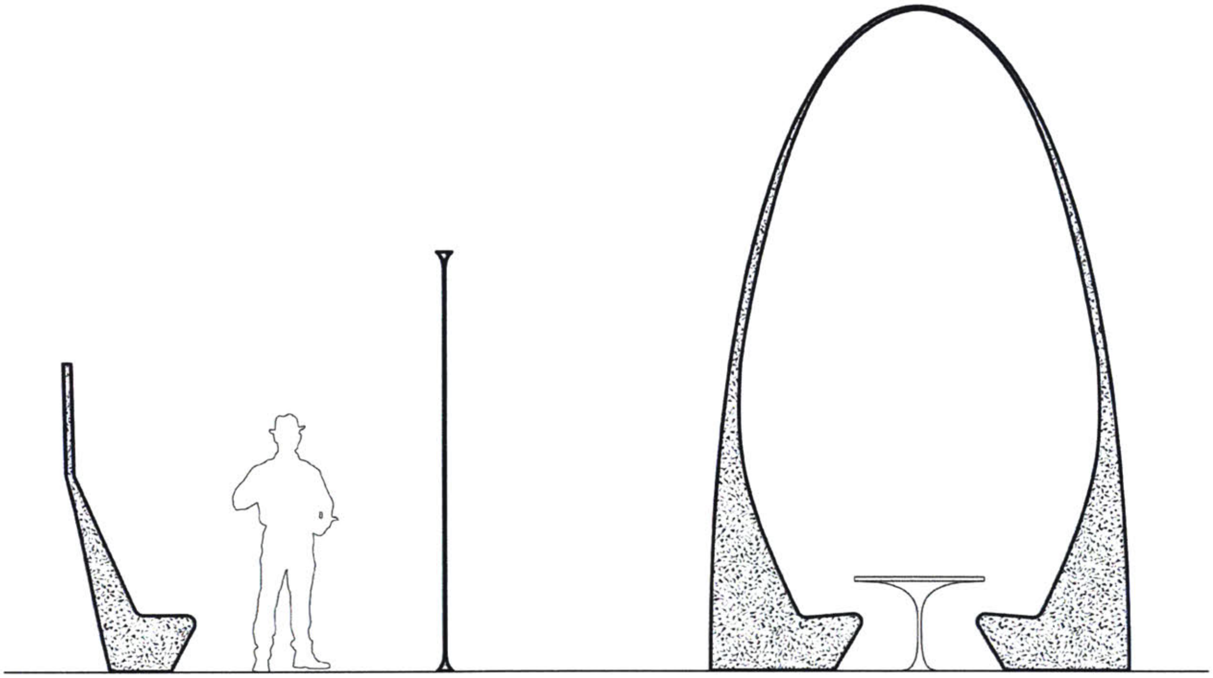


Proposal 2 focused on creating three distinct moments of section, each of which vary in function as well as in thickness, however all three moments are joined through a singular structure which creates both an outdoor area and a more enclosed space simultaneously. In plan, the structure transforms from a bench, which wraps around and becomes a thin translucent screen and gradually thickens to create an enclosure with integrated seating on the inside, providing a small and intimate space for dining. Much like Proposal 1, Proposal 2 also deploys structural crenulation on the interior surface of the enclosure where is becomes much thinner in section in order to reduce weight, while still maintaining a relatively smooth surface on the exterior. While not intended to perform under the same conditions, this is a technique that is commonly used in the construction of high performance racing boats, where the exterior requires smoothness in order to cut through hydrostatic forces while the interior is crenulated to provide structural stability.

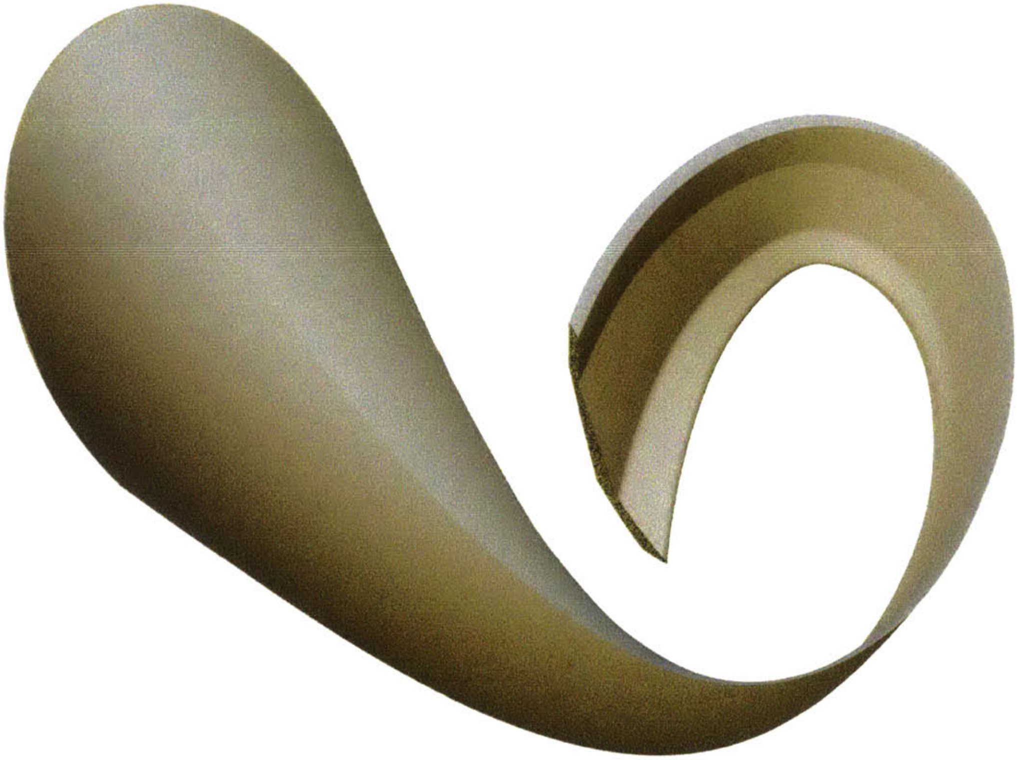
One thing that is very clear about this scheme unlike Proposal 1 is that is has no standardized or repeated geometries, and therefore requires a greater number of unique molds in order to produce all of the surface area. Naturally this could increase the cost of manufacturing along with the amount of time needed for construction.



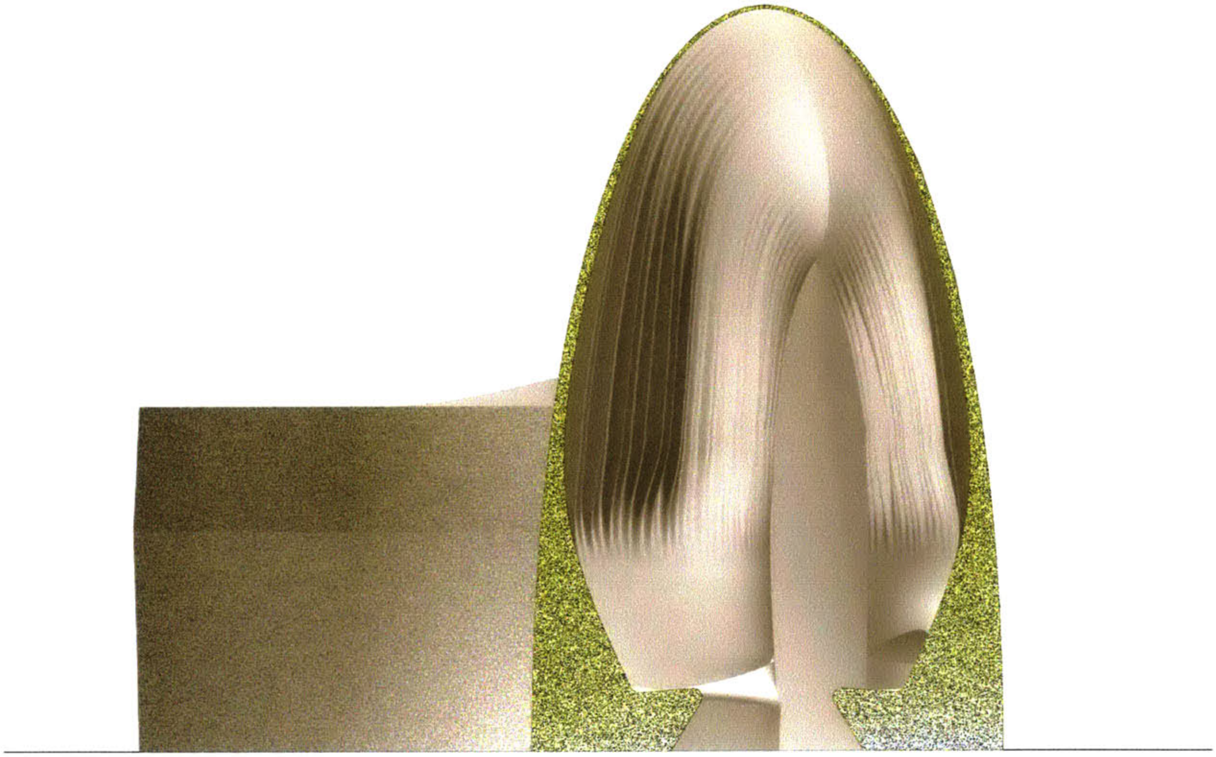
Proposal 2 - Perspective



Proposal 2 - Section



Proposal 2 - Plan



Proposal 2 - Elevation

5.3 FUTURE RESEARCH

Although this research has touched on a number of issues surrounding the design and development of variable thickness sandwich structures, there is much to be learned from future explorations. There are a wide range of variables to be explored, from the range of textiles, resins, foams, lamination methods, mold making techniques, infill strategies, joining techniques, and shaping logics to highlight a few. In addition to these topics, this research may benefit greatly from feedback received from closely monitored structural testing. Currently there have been no structural load tests performed to test the capacity of these systems. Although that is not the focus of this research, it may still prove to be beneficial especially when taking on architectural proposals more seriously.

It would also be necessary to expand the authorship of this work into a diverse group of expertise which may take on the form of collaborations across industries. Much of these methods are standard practice to many professionals in the boat building industry, who have a wealth of knowledge to share regarding composite construction. As the scope of contemporary architectural practice and pedagogy expands into other design fields and disciplines, it is critical to develop a mindset that allows for productive collaborations which blur disciplinary boundaries. Of course, this is already happening in some regards, yet it is still only the exception and far from the norm. One current notable example of this type of collaborative, cross disciplinary effort is architect Greg Lynn, who has recently completed the design and construction of GF42 – a 42' long yacht – in collaboration with Westerly Marine, Krysler & Associates, Courouble Design & Enginering, a structural engineer, two computational fluid dynamics engineers, and a rig designer amongst others. In order to successfully adopt skills and expertise from another discipline – in this case naval design and engineering – the architect must seem to act as a liaison between several specialized experts from a broad range of backgrounds. Much in the same way these collaborations take place, I speculate that similar efforts could be taken on to further develop the methods and results covered in this thesis.

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ARCHITECTURE SANDWICHED

Tuning anisotropy through variable thickness and hetereogeneous laminar assemblies.

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