ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

FIBROUS TECTONICS: A RETHINKING OF COMPOSITE PRODUCTION THROUGH INNOVATION AND EXPLORATION OF MOLDING TECHNIQUES AND METHODOLOGIES (ECCOMAS CONGRESS 2016)

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Keywords: Vacuum Assisted Resin Transfer Molding; Bio-Composites; Inflatables.

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 sealed 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.

1. BACKGROUND

1.1. 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 the Monsanto petrochemical company, the Monsanto House was built in 1958 from fiberglass composites and challenged the accepted notions of building materials and construction. 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. However, nearly sixty years later with digital manufacturing, we now possess the technology to make the development of the Monsanto House feasible.

1.2. Composite Constraints

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.

1.3. Composite Advantages

Composite materials present many advantages and possibilities within the field of design that make them quite appealing. 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 architecture, there is the chance to negotiate a wide variety of tradeoffs in order to efficiently and economically incorporate 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. Meaning, 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. Perhaps less often considered, is the advantage of consolidation. Composite materials also present the opportunity to collapse many building systems into a single dynamically changing wall section. Much like a traditional wall section, a composite structure is made of many layers. Building systems, such as electrical and plumbing, can be integrated into this multi layered system. Composite parts are molded, allowing for extremely complex geometries to be produced in a single part. This reduces the number of required parts, greatly simplifying and expediting the assembly; assembly can be completed with a handful of individuals, rather than a large construction crew.

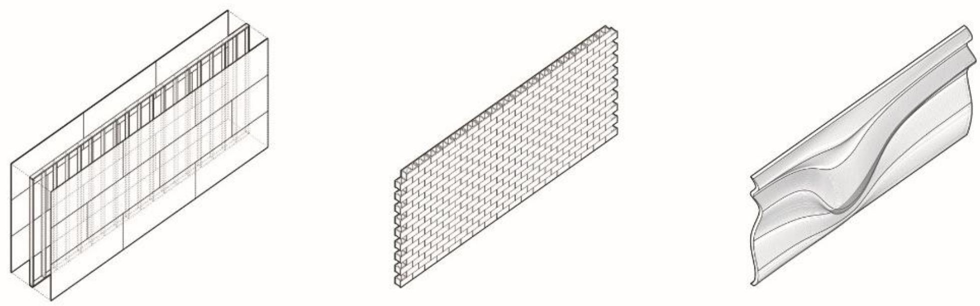

Fig. 1. (a) Wood Stud Wall 840 lbs; (b) CMU Wall 5,800 lbs; (c) Composite Wall 230 lbs.

1.4 Composite Manufacturing

Architecture presents an interesting challenge in that nearly every built project is unique. When we discuss automotive, 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. The possibility of a composite building 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.

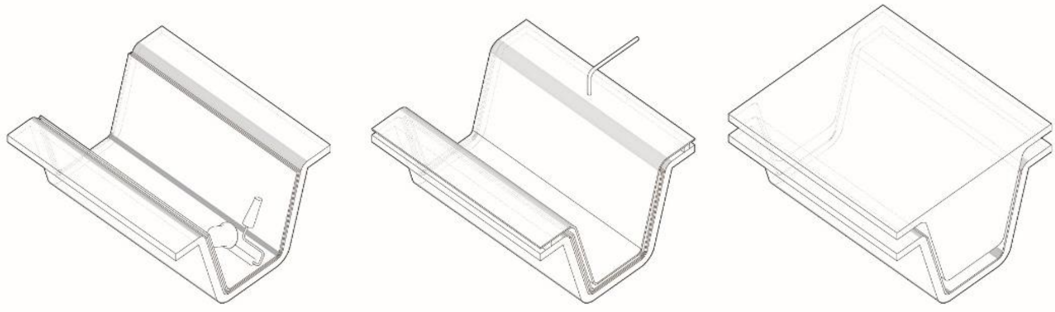

Fig. 2. (a) Hand Wet Layup; (b) Vacuum Bagging Wet Lay Up; (c) Wet Lay Up Compression Molding.

2. METHODOLOGY

More and more I have become fascinated by the potential possibilities present in composite materials. As part of a disaster relief effort after the 2010 earthquake in Haiti I designed a modular composite house for rapid deployment in the countryside. For my MIT architecture master's thesis, I designed a composite house for southern Iraq as part of an effort to rebuild after the war which considered petroleum as a building material. 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.

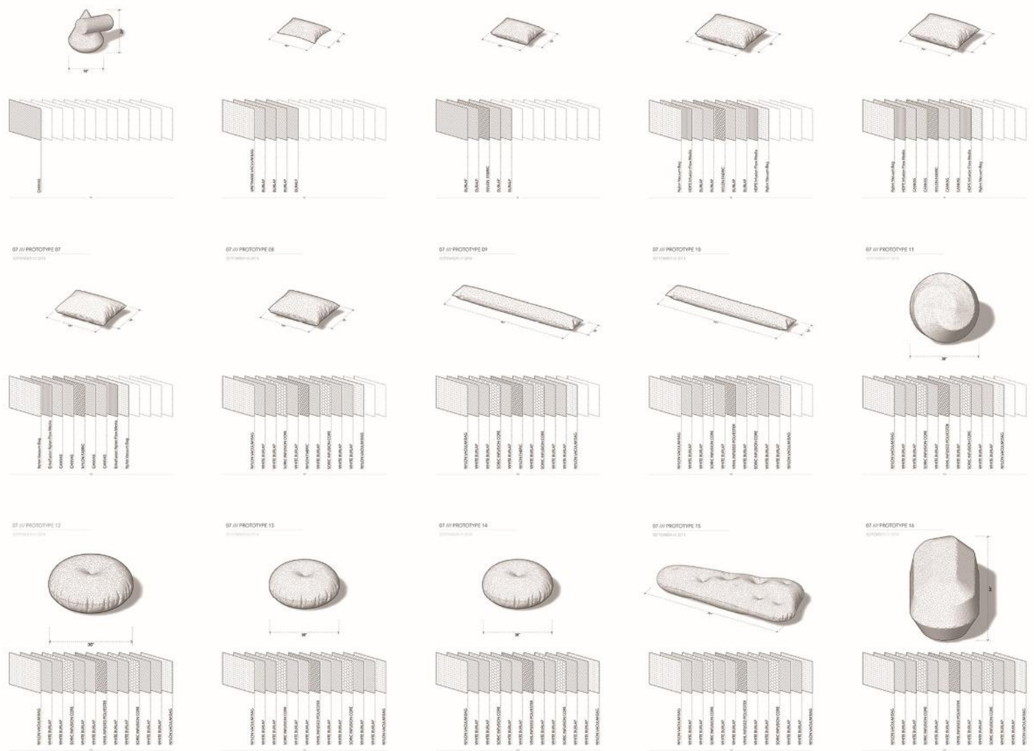

Fig. 3. (a) Prototypes 1 – 16, simulation and build-up.

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 constructability. 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.

Rooted in hands on material testing and making, the current tests have been modest in size partly due to funding and material costs. The opportunity to fully engage in one to one investigations, to confront and interface with composite materials on a full scale inquiry, has been instrumental in the enrichment of the research. Using hands on methodologies, and one to one scale investigations as a starting point has helped to identify and establish an effective composites workflow. The final goal of the research is to produce a full scale, one to one proto-architecture.

3. PROCESS

3.1 Inflated 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 architectural scale spaces. Typically, pneumatic structures require constant pressure but the use of inflated bladders 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.

3.2 Workflow

The work flow begins with the design of an equal pressure geometry such as spheres and cylinders with spherical ends and conics with spherical ends. The combination of these geometries can produce a wide variety of inflatable forms. These inflated geometries are then discretized and decomposed into flat unrolled shapes. Once the geometry has been broken down and laid flat onto the cut sheets the details of the part can be added to help form the bladder. This includes extending the edges to create lap joints or flange joints, adding registration lines and cut lines as well as annotating the disparate parts. The flat nested cut sheets are imported into a CAM (computer aided manufacturing) software where the part manufacturing is programed. This includes all annotation with a fabric pen, as well as cut paths with a free wheel drag knife.

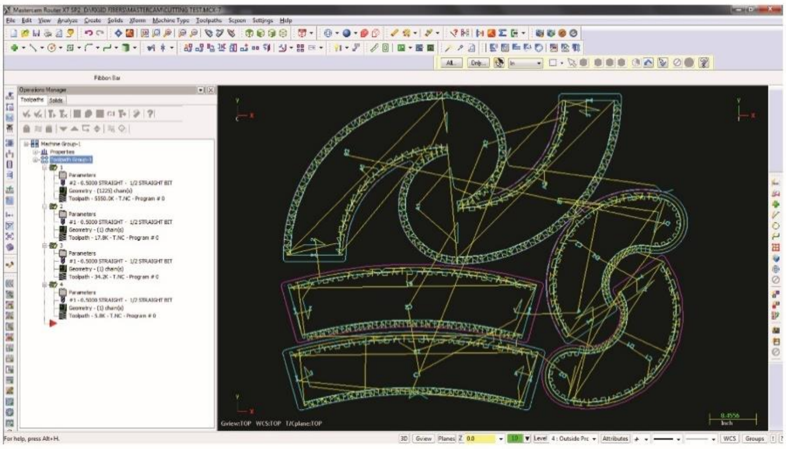

Fig. 4. (a) Nested cut sheets imported into a CAM (computer aided manufacturing) software.

The material is assembled into the anticipated composite before being placed on the vacuum table of the CNC machine. The layers of the assembly include three alternating directions of natural fiber fabric on both sides of a 3mm Soric infusion core. The bladder material, 18oz vinyl infused polyester fabric, is placed on top of the composite assembly and is used to tightly hold all the layers to the cnc vacuum bed. Once the parts are cut, the vinyl infused polyester fabric is stitched and chemically welded to produce the airtight seams of the bladder. The thread provides the strength and the chemical weld provides the air tightness. The two part chemical weld breaks down the polymers in the vinyl, fusing the material and creating a resilient airtight seal. The bladder itself is constructed of both lap and flange joints, which are designed to project into the inflated bladder to allow for a good infusion surface. During the stitching and welding process the through bag valve that is used to inflate the bladder is added.

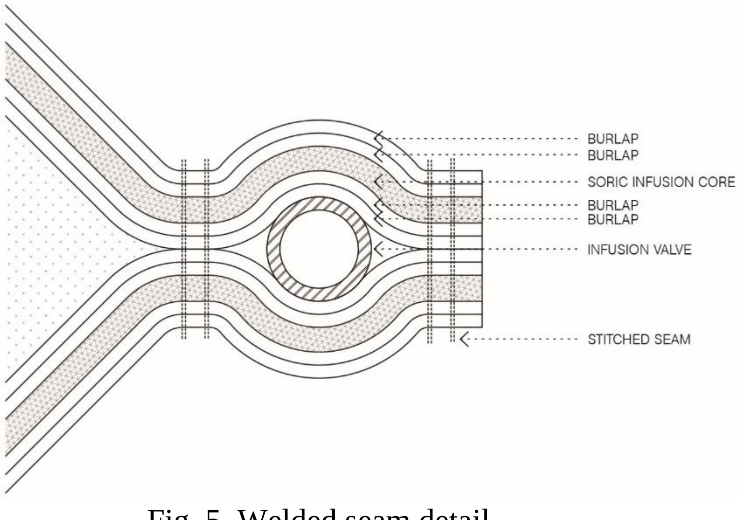

Fig. 5. Welded seam detail.

The preform (composite assembly) is also sewn together using a heavy weight polyester thread. VARTM (vacuum assisted resin transfer molding) 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 layout. Linear distribution uses a ⅜” 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. Point distribution uses a PLA 3d printed valve designed to allow rapid and even distribution of both resin and vacuum pressure. The 3d printed valve is sewn into the preform at the same layer in the composite as the infusion core. The integration of the inlets and outlets significantly reduces the setup time.

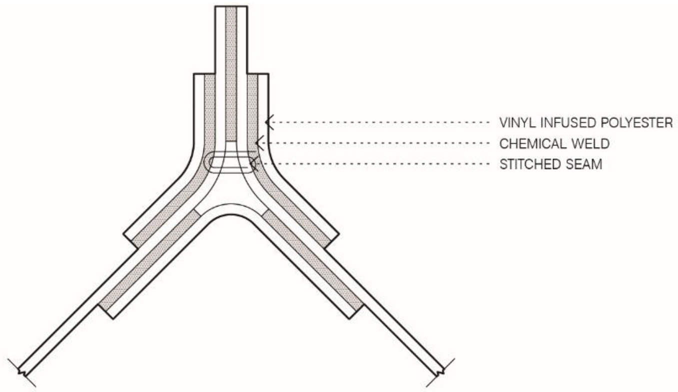

Fig. 6. (a) Infusion seam detail.

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.

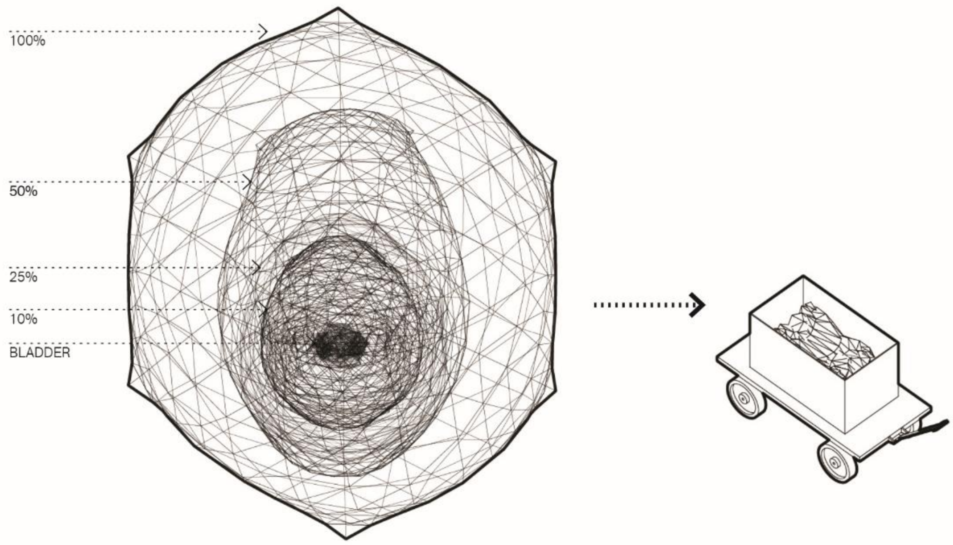

Fig. 7. (a) Inflation Process; (b) Transportation of deflated bladder.

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 300f 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 25 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 infusion epoxy resin. When the hose clamp is removed the vacuum pulls the resin through the linear / point valve and into the infusion core which wets out the fibers as it is pulled across the part. 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.

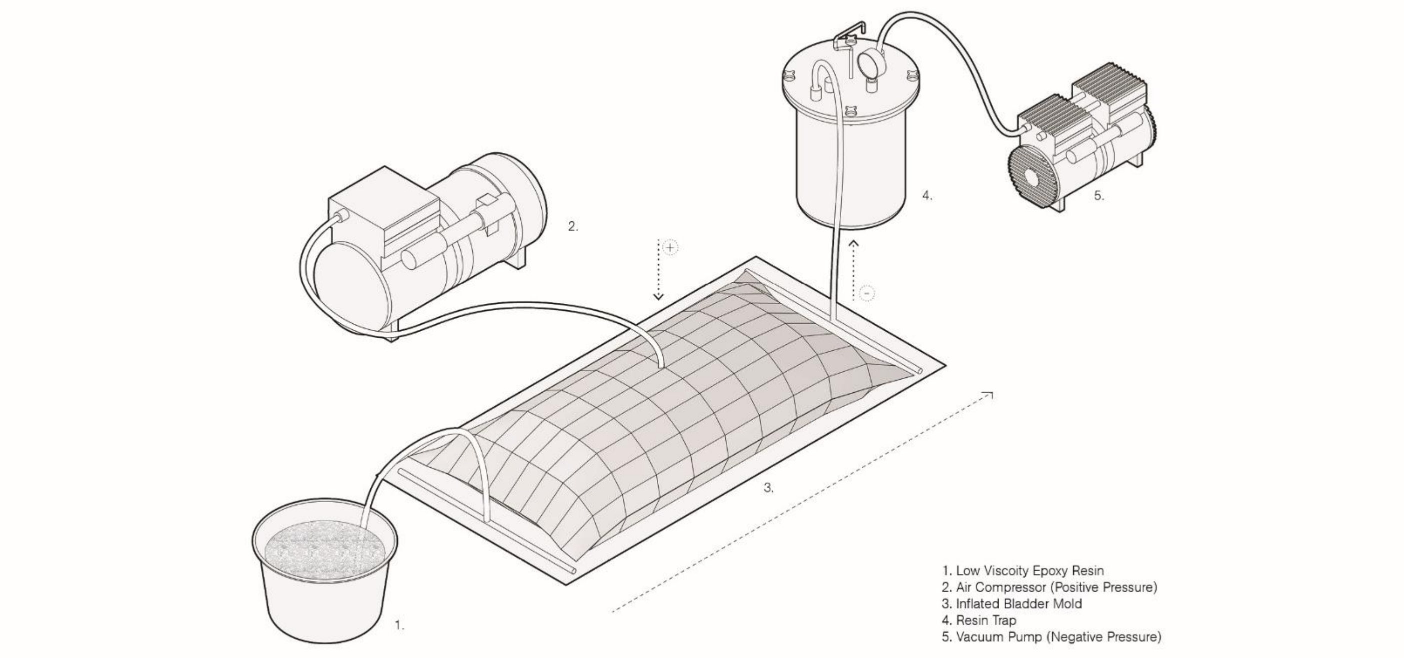

Fig. 8. (a) Intlated and infused workflow using VARTM.

4. CONCLUSION

The workflow presented here has evolved over the last year 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, having thus far tested primarily in the object furniture scale. Following the success of the initial prototypes and the established understanding of the material systems, rules, and constraints, I would like to continue by designing a small proto-architecture, with the ultimate goal of designing a full scale house that evolves from this material and construction system.

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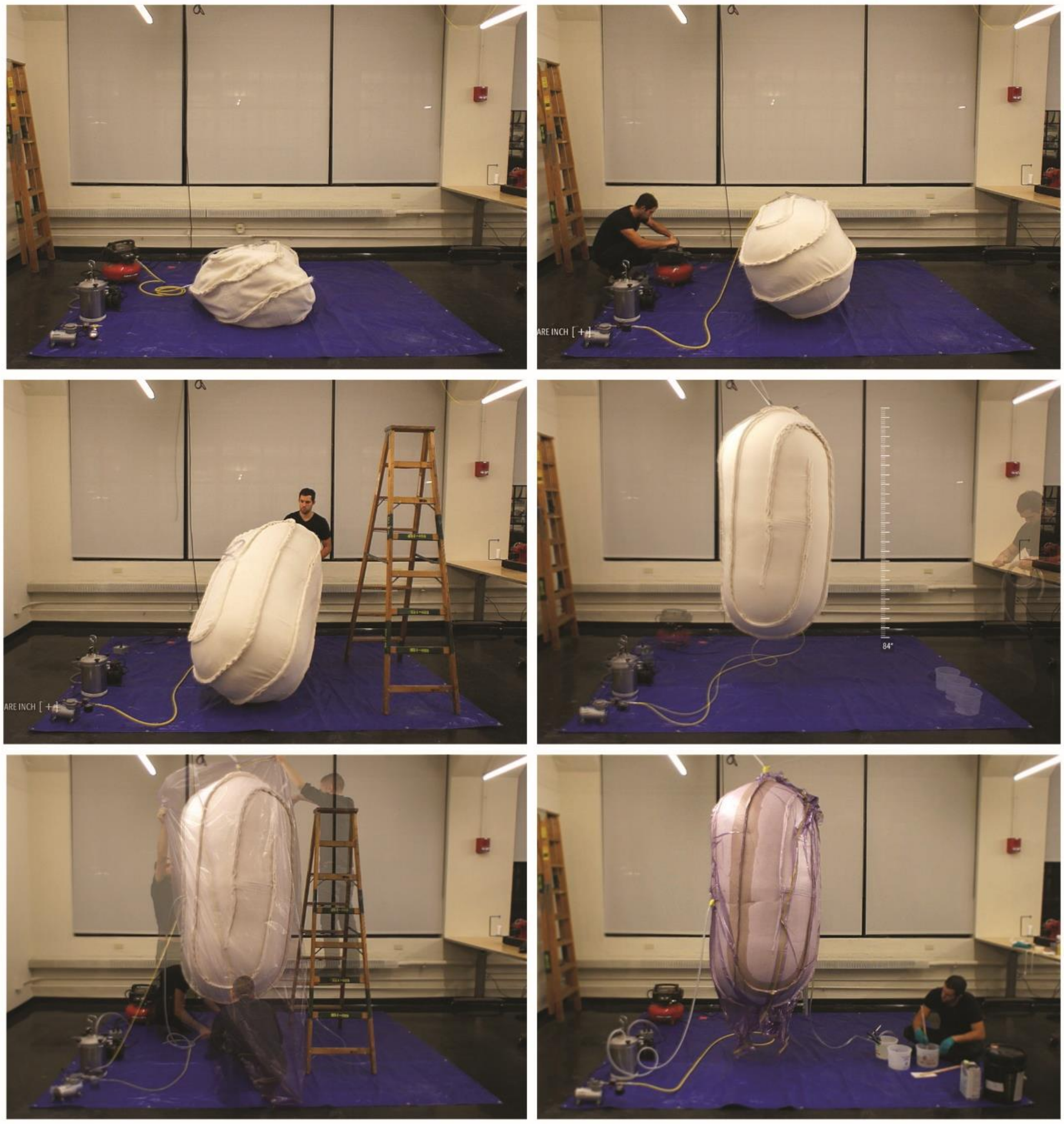

Fig. 9. (a) Workflow for prototype number 16.

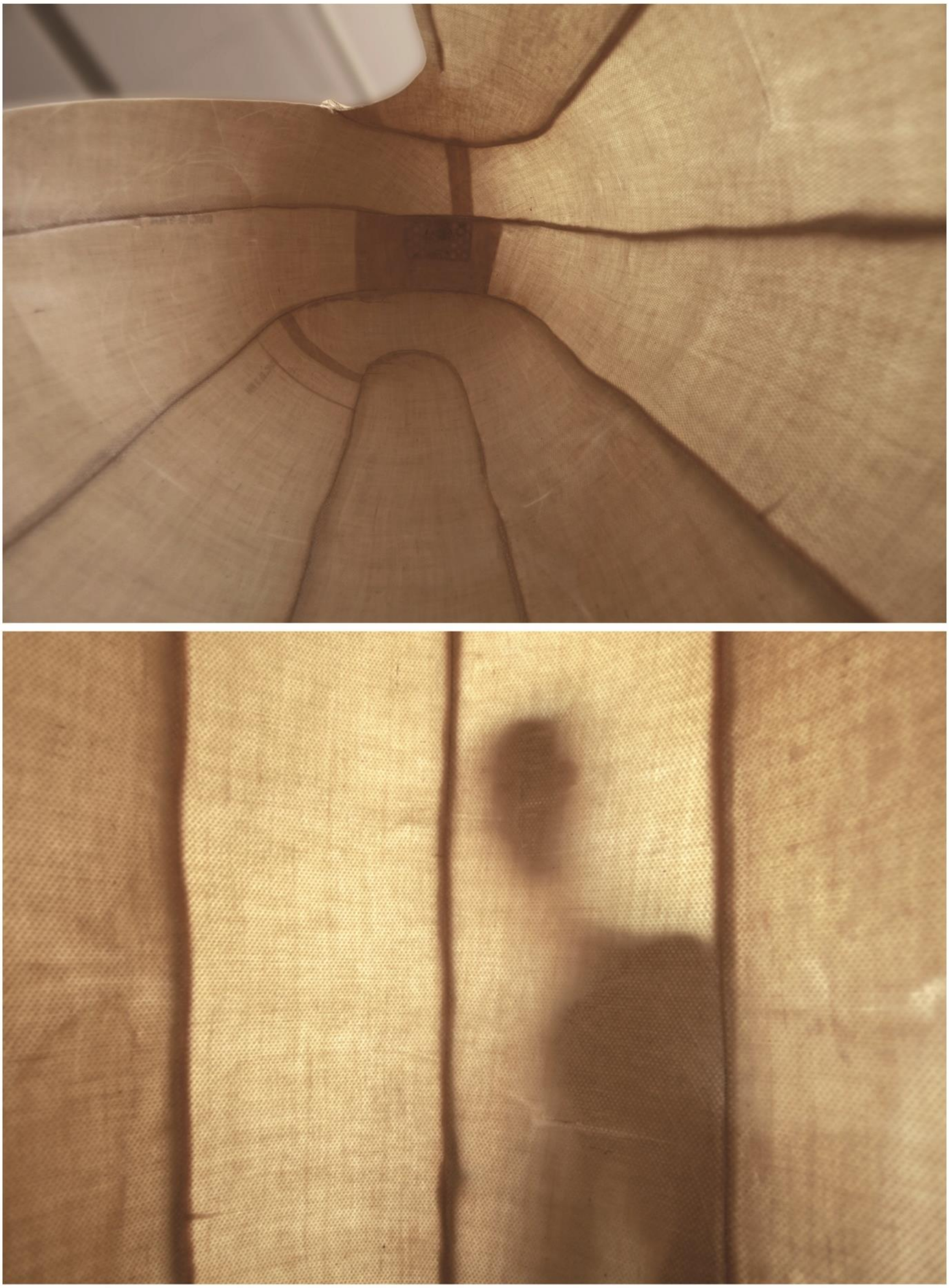

Fig. 10. (a) Final images after infusion.

Fig. 11. (a) Final images after infusion.