Laminar Folds: Fabric Structure Molds to Jigs

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DEMONSTRATION ARCHITECTURE

The history of modern architecture contains a rich legacy of demonstration projects - structures that are designed and built to illustrate the potentials of a new material, an innovative construction system, or provocative formal capabilities. These projects typically have no clients in the traditional sense, and instead are sponsored by corporations, manufacturers' associations, fairs and expos, magazines, theme parks, or art museums. The Museum of Modern Art's "House in the Museum Garden" by Marcel Breuer and Gregory Ain's "Exhibition House" offered alternative schemes for suburban living in the mid-twentieth century, and they inspired an updated series of temporary structures by Oskar Leo Kauffmann, Horden Cherry Lee, and Kieran Timberlake.[1] Some architects, like George Fred Keck, have presented futuristic visions of architecture to massive crowds at national expositions.[2] Other designers have achieved modest notoriety for work on manufacturer-driven projects such as the Westinghouse All-Electric homes (A. Quincy Jones)[3] and the Douglas Fir Plywood Association Vacation Cabin (George Matsumoto).[4] Perhaps the most well-known demonstration project resulted from a partnership between Disneyland and the Monsanto Corporation: the infamous "House of the Future." Schools of architecture—the AA in London and Denmark's Aarhus, for instance—have lately supported small temporary pavilions constructed to exhibit digital fabrication techniques, or clever uses for recycled materials. Although these demonstration projects have each set out to prove various ideas in provocative ways, their impermanence affords them optimism and experimental license. They provide opportunities to challenge norms and amplify particular design aspects through focused investigation.

The research presented in this paper illustrates a pavilion fabrication process that resulted from an invitation to design a fiberglass composite structure for exhibition in Buffalo's Erie Canal Central Wharf Park in fall 2011. The project is part of the Fluid Culture Exhibition, and it examines fiberglass composite material qualities, digital and handcraft fabrication methods, and the pavilion's ecological performance characteristics.

TEXTILE COMPOSITES

Textile composite materials offer promising possibilities for architecture, particularly in mass-produced, panelized applications. They are versatile materials with high strength-to-weight ratios that are suitable for structural applications, and their lightness significantly reduces shipping costs and accelerates on-site construction. Textile composites can also be used to produce panels that conflate structure and enclosure with finished skin/surface, and they offer a versatile material that can be formed to mitigate or enhance local climate conditions. This project examines the potentials for woven textile composites in rapidly deployed building systems. In specific, the project researches panel forming materials and techniques, and produces a series of full-scale panel prototypes for testing and analysis, and installation. The research team developed prototypes that capture the material's exuberant formal capabilities and utilize these qualities in efficient, eco-performative structures. Through a series of prototypes, the team varied surface formations to impart depth and texture across glass-fiber fabrics that could then be thermoset with resin.

STRATEGIES FOR MAKING

The research and design intertwines digital and handcraft methods in an iterative and reciprocal process that questions the distinction between virtual modeling and manual assembly. While we were searching for efficient routes from the digital models to fabrication, we engaged in a process that revealed shortcomings in the digital-to-material translations. The line between modeling and post-processing lost distinction.

In a recent lecture entitled "Digital Kraftwerk" at the Glasgow School of Art, Frank Barkow (Barkow Leibinger Architekten) described a pervasive design approach that flows in order from **form** (modeled with software) to **material** to the **tools** of construction. In contrast, Barkow illustrates a significant shift in how his firm utilizes digital media in the design process by reorganizing the operational model into a sequence that promotes materiality:

Material > Tool (Software) > Form[5]

In this format, material attributes and the tools (software and hardware) that manipulate them determine formal possibilities and outcomes. Design processes commonly prioritize software's ability to produce and examine ideas through representational means such as renderings and form generation models. Consequently, visual attributes supersede more tangible material qualities, and the computer becomes a tool for modeling the un-makeable.

Our strategy for making attempts to bridge the digital/material divide, and it is predicated on an understanding of specific material capabilities. The material drives the software exploration, and in turn, the software provides a means to explore material manipulation and panel component assembly. Material constraints provide critical pushback for the digital model.

PROTOTYPE DESIGN AND PRODUCTION

The design team researched and analyzed several panel-making options, and tested various conventional techniques to arrive at the most suitable fabrication methods. Through both analog and digital modeling processes, the team established design parameters for subsequent full-scale mock-ups. Throughout this process, the team categorized the prototype panels by form-giving method and mold type: static molds, tension-line jigs, and non-periodic fabric folding and stretching. These three techniques formed a basis for comparison of working methods, resultant panel form, efficiency, strength and environmental performance.

PROTOTYPE 1 PRODUCTION: STATIC MOLDS

The most conventional method of forming textile composite materials is by first constructing re-usable molds, often referred to as tools. Using the consistent pressure of vacuum bags, this method forms panels through primarily compressive means, while the two other forming procedures (Prototypes 2 and 3) rely more on tensile suspension.

The team prepared and tested several preliminary molds [Fig. 1] out of inexpensive rigid blue foam before milling the final forms out of more costly and durable Renshape foam. The team was interested in forms that could produce self-supporting panels that would also channel rainwater strategically along the surface. The grooves and undulations would serve a dual purpose: they would create folds for structural integrity while directing water away from openings to collection points at the panel base.

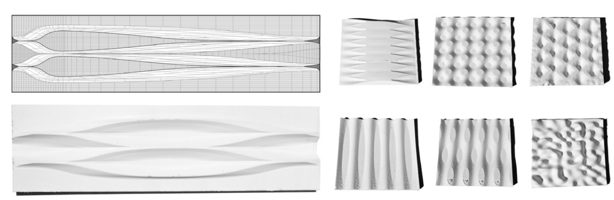

Figure 1. Preliminary molds

To arrive at final mold forms and eventual mock-ups, the research team followed an iterative design process that included:

- Digital models – produced with surface modeling N.U.R.B.S. and scripting software (Rhino and Grasshopper).
- Rapid prototyping – digital models were translated into stereo lithography files and printed on 3D plastics printers.

- CNC form studies and assessment – the team produced multiple full-scale form mockups using rigid blue foam insulation.

- Form refinement – after analyzing the rigid foam forms, the team refined the designs using Rhino software.

- Fiberglass and carbon fiber panel test-runs – using the rigid blue foam molds, the team produced test panels. These shallow-draw panels were produced without vacuum bagging the mold and lay-up materials. We used this method to test the tool's effectiveness and the resin-coated fiberglass' natural draping abilities. This was a cost-saving approach that conserved our vacuum bagging materials for later, more refined mock-ups. In this phase, we also wove rubber tubing into the fiberglass cloth to test it as a possible conduit for water. Once set and cured in resin, the conduit would become permanently integrated in the fiberglass panel.

- Mold (tool) production – using the lessons learned from the test-runs, the team refined the Rhino digital models and translated them into CAD/CAM files. These were instrumental in helping the team produce CNC tool paths that would rout the final molds out of Renshape.

- Final mock-up production – the team seasoned the molds with several layers of form release compound and spray-on poly-vinyl alcohol (PVA), a water-soluble release agent. The team then assembled a custom vacuum bag and proceeded to lay up layers of resin-impregnated sheets of fiberglass (plain and twill weaves). Through testing, the team determined that slow hardener catalyst would work best for the resin in order to give more working time for the lay up process. After running the vacuum for approximately 15 hours, the team could remove the bag, separator sheet, and breather fabric from the finished panel [Fig. 2].

Figure 2. Renshape molds and fiberglass composite panel

PROTOTYPE 2 PRODUCTION: RECONFIGURABLE TENSION-LINE JIGS

The team explored alternatives to conventional static (re-usable) molds for producing textile composite panels. We researched sewing techniques such as darting, pleating, and smocking to determine if they could be used to impart depth, strength, and channels in our panels. We also designed an adjustable frame apparatus that could be strung with tension line (tightly braided monofilament) to hold the fiberglass cloth in suspension. Resin could then be sprayed or brushed on the fabric and left to cure. The result is a deep, cellular panel fabricated from a single sheet of fiberglass. After it is cured, the tension lines are released from the frame, and the frame can be re-strung to form varied panel shapes.

To test this approach, the research team followed a process that included:

- Sewing techniques research – the team determined that smocking the fabric would produce the desired characteristics of depth and strength while also channeling water away from openings.

- Reconfigurable mold design and assembly – using multiple materials (wood, steel and Plexiglas) the team constructed a set of adjustable frames that could we could string with tension lines. The frame is re-usable because it does not come in contact with the resin in the curing process. The frame is capable of accommodating numerous tension stringing patterns, and therefore, the smocked panel can take on varied forms. The Plexiglas plate and threaded rod frame allowed lines to be threaded continuously through a grid of index holes that we laser cut into the Plexiglas. The line is tensioned after the fabric is fully hung from it. The final step is the adjustment of the folds along the line, which in this case runs perpendicular to the folds. The steel frame (4'x4') and the larger wood frame (4'x11') used a method to secure each individual line because in this case the lines run along the folds and determine their path.

- Fiberglass panel production – once the fiberglass was laced into the jig, we made simple adjustments to the fabric to achieve the desired final form. After this, we applied fast-cure resin to the cloth in order to fix its shape. The tension lines could then be snipped to release the cured panel from the frame [Fig. 3].

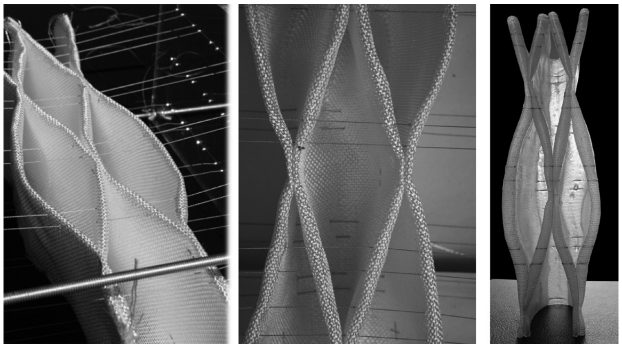

Figure 3. Reconfigurable tension-line jig, cellular fiberglass panel

PROTOTYPE 3 PRODUCTION: FABRIC STRETCHING

The third method is a variation on Prototype 2 that employs similar fabric tensioning to produce form. In this method, the frame becomes integrated with the fabric resulting in a stressed-skin panel. In Prototype 2, the panels are set in resin, and then removed from the jig's frames and plates. Prototype 3 eliminates the need for the monofilament string-lines, but the frame—which defines the panel perimeter—cannot be reused as a jig.

PARK PAVILION – UPLIFT AND DOWNPOUR

The frames come together to form a porous enclosure that formally responds to local wind and precipitation patterns. Lightness is the most salient feature of this structure. The 14'x10'x14'h shelter is sited on an open lawn at the water's edge along the Erie Canal, and the contours of the pavilion and the pattern of folds encourage the prevalent winds to flow over the structure. In addition, the panels leave strategically placed gaps that will allow wind to move through the pavilion wile channeling water away from edges and openings. The walls, which are perforated at different intervals on the leeward and windward sides, merge to become a roof with a large chimney-like opening to release the air.

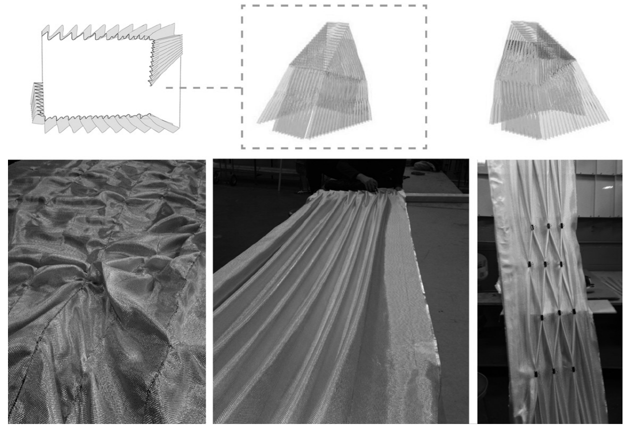

Figure 4. Panel production - pulling strings, smocking edges, panel prepared for resin application

PULLING STRINGS, SMOCKING EDGES, DRAPING SURFACES

A critical step in the process is measuring the fabric and "pulling strings" from the fabric at designated intervals. This is a technique that fiberglass workers use more commonly to gauge straight lines in an otherwise undulating and shifting fabric. In a plain-woven glass fabric, pulling a strand of glass fibers out of the weave leaves behind a clear guideline for cutting accuracy. We have adapted this technique to make visible control lines in the reflective fabric. Spaced every six inches and running parallel to the long edge dimension of the fabric, these control lines mark attachment points for accurate placement on the frame, and they indicate the eventual ridge and valley lines in the panels. The inscribed lines also provide a clear path for laminating and stitching extra layers of fabric to build a thicker, and therefore, more robust panel. The process is comparable to making a fiber "mat," but it is coupled with the pre-tensioning lines in the fabric. In this case, we have laminated two layers of six-ounce fabric using this method, and sewing along the control lines allows the two sheets to move in concert. Done by hand, this has proven to be a tedious, but necessary process that could be automated by programmable looms and industrial sewing machines in subsequent applications.

Once the fabric is stretched on the frame, the control lines indicate the primary path of tension, and they illustrate the forces that give the cloth its shape. The control lines are drawn taught to create ridgelines, and gravity pulls the fabric between them into catenary drapes [Fig. 4]. The distance between the ridge lines defines the depth of the centenary drapes: placed every six inches, it makes a flat surface, and at a standard of three inches, they define a gentle repeated module. Skipped lines give added depth to the surface.

The drape is designed to accommodate the flow of water on the surface of the structure. Around the base, the loops of the drape are partially closed to collect water and allow it to be gradually released into the adjacent landscape. The translucent structure will be tested under extreme wind and snow loads during the coming winter. This type of precipitation will collect on the surface closing off the smaller openings and adding weight to the overall structure. The pavilion is expected to transform into a more solid and insulated skin as the weather becomes colder.

MONOCOQUE vs. FRAMED PANELS

Fiberglass is well known as a material that can be used to produce monocoques, where skin is both durable and strong enough to afford structuring capabilities. Matti Suuronen's pod-like Futuro House of 1968 was an ellipsoid formed by a polar array of butt-jointed fiberglass reinforced polyester plastic panels. Except for a metal base frame that holds the capsule above ground, the Futuro House has no other frame structure. Suuronen's example calls into question our decision to create a frame support for our pavilion. A close inspection of the Futuro panels reveals that they have turndowns running along edges that act as ribs to help stiffen them and to provide panel-to-panel connection surfaces. Once attached, the panel tabs approximate a gridded frame. Our early panel prototypes revealed that thin fiberglass panels without edge tabs tend to twist too easily and cannot be attached to each other. Our edge folds and smocking prevented significant twisting, but inhibited edge fold-downs, especially along edges running perpendicular to the fold ridges. In lieu of edge tabs, we constructed a series of frames by wrapping rigid foam in fiberglass tape. These frames form the outline of the pavilion's faceted planes, but more importantly, the fiberglass "wire-frame" becomes a jig for stretching and forming the fabric before applying resin. The resulting stressed-skin panels eliminate the need for lateral cross bracing. Due to the nature of composites, frame and drape merge and reinforce each other. When they lay flat at the top and bottom of the frame, the pleats bond to the prior layer of fiber. Alternatively, when the panel fabric only bonds with the frame at intermittent intervals, the folds add depth to the frame. On the vertical members, the fabric wraps the edges of the panel adding a full layer of reinforcement to the frame, while simultaneously affixing the panel to it.

Figure 5. Pavilion details

A major goal of the research is to compare traditional panel production methods (Prototype 1) to alternative methods (Prototype 2). One relies on carved molds and vacuum bagging, while the other utilizes a tension wire strung jig to hold the fabric in shape for resin application and setting. The research team actively analyzed each step in the process to determine best practices and ways to proceed to the next iteration.

Each prototype resulted from labor-intensive processes that produced lightweight, portable, and strong panels, but the fabrication methods yielded varied results in terms of lamination consolidation, surface finish and print-through, and panel depth. The vacuum compression in Prototype 1 diffused the resin evenly through several layers of stacked and molded fabric, and it produced a more consistent surface finish with minor print-through. The depth of the mold-making material limits the panel curvature, and most significantly, the shape has to account for minimum draft angles to ensure that the panel could be removed from the mold.

Prototype 2 allowed us to consider deeper fabric structures using fewer sheets, at times, just one pleated layer. Because the panel is formed without a Renshape mold, we eliminated draft angle as a constraint. The result is a deep cellular surface that could not be achieved with conventional molding processes. This method uses fewer layers, but it does come at the expense of full laminate consolidation and consistent surface finish.

In the end, we settled on a modified version of Prototype 2 for the pavilion. The jig-formed test panels with incongruent edges transform in the pavilion application by using the frame as the jig. The resultant linear-edged panels allow for simple assembly. The frame and panel conflation permits straightforward structural modeling which the fluid, variable, and layered drape defies. The resulting Prototype 3 panels are formed without monofilament tension lines, and they derive depth and form by stretching the fabric from opposite points to create tension ridges. The material qualities and the fabrication methods combine to form variable surface structures that are tuned to the deviations of the frame. By varying the frame attachment points, the panel forms can be adjusted to direct wind and water flow, and the panels' undulations serve a strategic purpose by generating additional surface area that both sheds and collects precipitation. More directly, it augments the rigidity of the ultra light structure. The panels are constructed in two sets: triangulated corner piers, and large center panels. Resin is sprayed on to fix the drape, and subsequently it is brushed on to achieve full saturation. The 14'x10'x14'h structure can be assembled on site in a single day without any lifting equipment. The top and bottom halves are assembled on site, and then the top is lifted in one piece by four people and pushed into place by others standing on a five foot scaffold within the bottom half. The two halves are then bolted together, as the individual frames were before.

The pavilion—constructed of pliant materials—registers the ambient dynamic conditions along the Erie Canal. The structure engages wind, water, and light [Fig. 5], both through its overall form and its drape.

ENDNOTES

1 Each of these architects was commissioned to build a prototype house as part of the 2008 MoMA exhibition, "Home Delivery: Fabricating the Modern Dwelling".

2 George Fred Keck designed the Crystal House for the 1933 Century of Progress Exhibition in Chicago.

3 The Westinghouse Company commissioned architects in several U.S. regions to design plan book houses for the All Electric Gold Medallion Home program in 1958. Jones and Emmons represented the Southwest region.

4 Matsumoto designed a small vacation house in 1958 as part of a joint project between the Douglas Fir Plywood Association and Woman's Day Magazine. Plans for the cabin could be purchased through the magazine.

5 Glasgow School of Art, "Mackintosh School of Architecture Friday Lecture Series", Frank Barkow, Barkow Leibinger Architekten, *Digital Kraftwerk,* 1 Oct 2010, accessed September 18, 2011, http://www.gsaevents.com/architecturefls/pastarch/frankbarkow