Responding With the Drape: Efficiency and Exuberance in Environmentally Responsive Fabric Reinforced Composite Panels

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Over the last two decades, shifting world economies and broader workforces overseas have challenged the U.S. textile industry and research centers to shift their focus away from wearable goods to high tech woven and non-woven fabric applications. Broad-loom textile mills began to decline in the 1990s and the numbers of industry workers[1] has fallen off in even more drastic fashion. Textile engineering programs in major universities have had to reconsider not only their curriculum, but also their basic mission.[2] As a result, this time period has sparked significant partnerships between engineers, manufacturers, entrepreneurs, researchers, and designers who have collaborated to realize significant advances in high-performance textile composite materials in automotive, military, marine, and—to a lesser extent—architectural applications.[3] Potential technology transfers from these fields to architecture is undergoing a renaissance due to concerns about sustainability and construction industry energy consumption, as well as growing interest in fluid forms in many design practices.

Though textile composites present significant economic, ecological, and manufacturing challenges, both synthetic and natural fibers and resins 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[4]. Textile composites can also be used to produce panels that conflate structure and enclosure with finished skin/surface.

We have focused on woven textile composites as an ideal material to produce wall panel systems that are lightweight, waterproof, self-supporting, and rapidly deployable. The panels are designed to channel water, admit natural ventilation, and avoid or permit insolation—depending on climatic conditions—to achieve thermal comfort. To focus our explorations, we established external environmental performance constraints, and we used digital modeling and analysis software, rapid prototyping, and physical mock-ups to develop alternative schemes that could meet our performance requirements. Specifically, we have developed three systems that explore the combined processes of loom-based weaving and textile forming to produce variable panel adaptations [fig.1]. Each iteration that we explored through these methods revealed limitations and new potentials relative to the panel's environmental performance, aggregation, and manufacture. The process has also challenged our understanding of the affordances of the composite shell and its fiber reinforcing matrix.

TEXTILE TRADITIONS IN ARCHITECTURE

In our current material research we bring together Gottfried Semper's discussions of tents, caves, huts, and textiles that speculated on architecture's origins with an interest in the research and development of high-tech composites in the mid-twentieth century driven by modernism's fascination with scientific material experimentation and discovery as described by engineers like Albert Dietz. Textiles' transition from garments to built enclosures has longstanding precedent, from the tent structures of nomadic cultures to textiles that embellish walls and floors of our buildings. The allusion to garments has been both metaphoric and performative. Semper's Romantic Era theories credit textile enclosures as being the first man made tectonic system. More interestingly he proposed the capability of textiles functioning as parts of composite systems that assisted less flexible architectures to attain a thermostable condition:

> "Hanging carpets remained the true walls, the visible boundaries of space. The often solid walls behind them were necessary for reasons that had nothing to do with the creation of space; they were needed for security, for supporting a load, for their permanence, and so on. Whenever the need for these secondary functions did not arise, the carpets remained the original means for separating space. Even when building solid walls became necessary, the latter were only the inner invisible structure hidden behind the true and legitimate representatives of the wall, the colorful woven carpets."[5]

Textiles' role as an adaptable boundary to the elements transcends time and culture. Treated weaves protect from wind and water while their weight and mass responds to desires to cool or warm an enclosure.

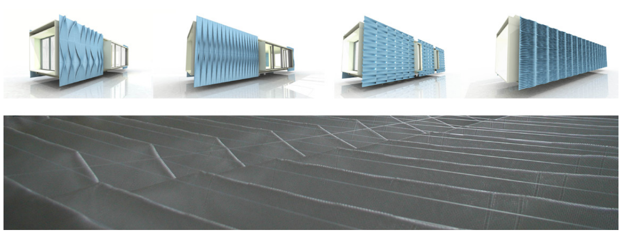

Figure1. Aggregation patterns: Series Two and Three Panels.

Speaking of the transformation of the woven wall to the masonry wall, Semper maintained that " the wall retained its meaning when materials other than the original were used, either for reasons of greater durability, better preservation of the inner wall, economy..."[6] As a flexible material it eludes standardization and quantifiable data that characterize materials like plywood and gypsum board. Textiles' pliability makes them both alluring and problematic for a tradition now rooted in tectonic stability and security, and they are rarely used as more than decorative, temporary, or analogical elements.

Particularly interesting is Semper's reference to the performance of textiles as parts of composite systems where the textile provides the environmentally responsive component of a wall. Here the relation between architecture and garments makes a direct connection: enclosure as comfort-seeking device, the third envelope after skin and clothing in the constant struggle of builders to reach a thermostable condition.[7] However, there is potential in current textile composite developments for coupling environmental performance potentials of fabric structures with durability and security expectations into a single sheet surface through manipulation of its form and composition. Articulating the sheet is for us the means of inserting the environmental performance parameters into a material technology—fiber reinforced composites (FRC)— that has already resolved security and durability problems, and elegantly added benefits of lightness and transportability to the mixture.

FAILURE TO LAUNCH

By the 1940's the invention of fiber reinforced resin matrix materials initiated textiles' new use as part of composites. This opened new formal and structural opportunities where textiles could take on self-structuring shapes. Books like Albert Dietz's *Plastics for Architects and Builders* (1949) and *Composite Materials* (1965), examined the malleability, weathering, durability, and strength of fabric reinforced composites. Dietz presented a variety of exciting experimental constructions like the Monsanto House of the Future (1957) and the Moscow Pavilions (1959) that demonstrated structural potentials of the lightweight materials. However, he also gave clear indication of the problems of pre-assessment and testing that would prevent composites from becoming integrated into the building industry in all but the most stable manners (and even then, these advances were usually the result of another industry's endeavors). While promoting composites for architecture, limits to formal exploration and implications of failure were ingrained in the literature introducing their potentials to the profession. As stated by engineers Adriaan Beukers and Ed van Hinte authors of *Lightness: The Inevitable Renaissance of Minimum*

Energy Structures, composite textiles face a difficult challenge because they are entering a fully "mature" building industry, unlike other materials, such as aluminum, which developed alongside the airline industry that first applied it.[8]

Long before this, *Architectural Graphic Standards* promoted canvas as a roof waterproofing component. Expanding upon this weather sealing technique in the 1930's, Albert Frey[9] experimented with marine grade canvas as an external wrapper in his Experimental Weekend House and Experimental Five Room House. The names imply uncertainty, perhaps in the International Style forms, but more likely in the viability of the primary cladding material: canvas. Frey later collaborated with the Cotton-Textile Institute and designed the Kocher Canvas Weekend House (1934), a diminutive vacation house on stilts that he wrapped in continuous horizontal bands of overlapping cloth. The shingled fabric, delivered in rolls, was both inexpensive and simple to apply. But, unlike his Aluminaire House—a sleek, reflective, industrial structure—the Canvas Weekend House juxtaposed age-old methods of cotton production and looming, and coupled them with modern industrial residential forms and processes. The Weekend House promoted canvas' innovative capabilities, but it revealed the material's structural and weather-shielding shortcomings. Except for the cladding, the house was constructed using standard techniques and materials: 2 x 4 wood studs sheathed with diagonal redwood boards that were coated with lead-based paint before the canvas was applied with copper–headed nails. The fabric formed a porous outer layer that was augmented by three coats of oil-based paint and a finish coat to make it less susceptible to water infiltration.[10] Frey used the textile as an all-weather envelope for the wooden exterior, creating a watertight composite with the assistance of paint. Frey's work with canvas during this time period coincided with material discoveries outside architecture that would eventually produce glass-fiber fabrics more capable of carrying structural loads and providing impervious cladding. Although material conservation issues were not a major concern to pre-war architects, Frey's experimental houses now serve as examples of sustainable construction techniques and novel uses for rapidly renewable material resources. His composite skins (canvas + paint) also prefigure more current attempts to make durable bio-derived composite materials with natural fibers and resins.

Frey's contemporary, Ralph Rapson, experimented with similar composite fiber systems to develop more flexible walls. Prior to designing his Greenbelt House for the California Case Study House Program, Rapson designed a more radical residential fabric structure in 1939. Rapson and David Runnels, submitted their scheme to the New House 194X Competition sponsored by Architectural Forum, and the proposal featured a telescoping aluminum tube structure flexible enough to allow unlimited planning and capable of being configured in multiple arrangements. The supple canvas "Roll-Fab" fabric cladding further accommodated system variation, and it was likewise adaptable to occupants' needs. Rapson, who had learned weaving techniques at Cranbrook and was intrigued by fabric-based, mass-produced housing, devised a pliant sandwich panel that laminated chemically-treated and water-repellent canvas on either side of a one-inch thick insulation. The integrated insulation blanket at once gave the roll cladding additional structural integrity and greater thermal resistance properties. The tent-like house was a Semperian complement to the architects' earlier earth-sheltered Cave House (1938), and though neither a prototype nor a fully functional model was built, the design exploited the limits of textile technology and fabric tectonics. Perhaps more importantly, Rapson questioned textile shelter's supposed temporal nature by suggesting that they could be deployed in more permanent installations without a solid wall to back it up.

These examples focus on "sandwich" systems. However, our interest in the potential of a continuous sheet material with multiple structural and environmental capabilities derived through its composition and form brings attention to the fabric itself. Focusing on the fabric, an understanding of the membrane structures, and the "minimum theory"[11] of German designer Frei Otto redirects our panel design process. Otto is best known for the elegantly detailed tensile cable and fabric structures that he pioneered in the mid- to late- twentieth century. These surface structures, which distribute stresses across a stretched membrane, have influenced present-day textile architecture, and perhaps more importantly, Otto's "minimum theory" of structures provides a framework for current practices whose projects reconcile leading edge material research with ecological sustainability. Otto's thin plates, shells, and membranes achieve an economy that is defined as a ratio of material to space contained, and the material thinness embodies this concept in aesthetic terms: lightness and openness are the chief characteristics of his designs that are suspended in dynamic equilibrium. Lightness is a salient quality of his “minimal structures” that achieve structural performance with the least possible “constructional energy,” or the consumption of material (weight, volume, cost) and labor (person-hours for manufacture and erection). This concept relates to, but precedes the more current term “embodied energy” as a metric for a material’s ecological sensitivity, natural resource depletion, and fossil fuel consumption. As such, economy associates consumption with means, and more importantly, project delivery and subsequent performance. In this construct, light structures that consider minimal transport distances and weight result in “minimum consumption” and optimal performance. Beukers and van Hinte update this theme and elaborate on it in their book. The authors develop a simple, compelling premise: light materials and structures yield light transport loads, which in turn yield light a light environmental footprint. They define lightness as “performance per energy unit [expended]”[12] and explain that “concepts, processes [and] materials” form a “trinity essence”[13] for structures. Furthermore, the authors suggest that textile composites can play an important role in ecologically light structures. Driving our project from its conception was this link between lightness and ease of transportation.

In addition to the lightness of the components, the technological know-how for production of the proposed panels has a small learning curve in most US coastal areas due to local boating industries. Permitting for regional access to unit manufacturing and material sources is available in the proposed region (South and Southeast of the US). Traditional textile manufacturing companies have re-invented themselves to manufacture textiles applicable to the boating and automotive industries in places such as central North Carolina when the majority of the fabric manufacturing business moved outside the US.[14] The focus on the potentially low tech application of this technological material focused our research in this medium. We considered that high tech developments in composite textiles engineered for highly specific needs such as the aerospace industries were outside our scope and focused instead on readily accessible materials.

COURTING FAILURE

Our research and experimentation has grown out of the precedents provided by Frey, Rapson, and Otto. However, our focus is the development of textile-based panels as a single exterior boundary layer rather than the composite systems explored by Frey and Rapson. Material exploration was initiated by applying lightweight composite shells to a disaster relief housing proposal. Our *Series One* panels were intended to be manufactured by filament winding or vacuum molding, and they are composed of multiple laminations of uni-directional and woven fabrics that are layered and oriented to counteract specific structural stresses. A resin matrix is added, and the composite material is molded into rigid, self-structuring, lightweight, hollow and waterproof panels with apertures that allow natural ventilation and views. Lightness, structural stability, ventilation and insulation were main drivers of the design. These characteristics are readily achieved by textile reinforced shell- making techniques used in manufacturing truck bodies and boat hulls.

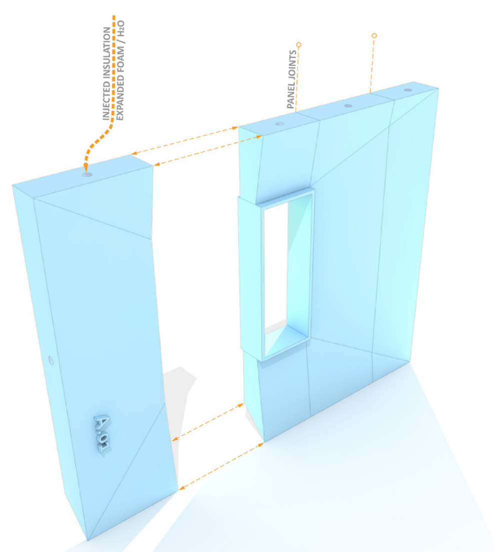

Figure 2. Series One panel.

ASTM D 3878-95c defines composite materials as consisting of “two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents.”[15] Composite materials are typically composed of particulate, flake, laminar, or fibrous reinforcement that is stabilized by a bonding matrix, frequently a thermoplastic or thermoset polymeric resins.

Fiber composites are classified according to four basic reinforcement types including continuous fibers, woven fibers, chopped fibers, and hybrids. Glass fibers—both E-glass and a stronger S-glass—are the most common reinforcements. Recent advances in three-dimensional weaving have also created the ability to incorporate closed-cell foam rods into the reinforcement fabric, resulting in a fabric that synthesizes structure, insulation, and finished surface.[16]

Molding and curing are key processes in producing textile composites, and there are numerous methods of applying resin matrix to woven reinforcements. Hand lay-up and spray-on application are the simplest and most inexpensive procedures, but other techniques such as injection, compression, resin transfer, and preform molding offer alternatives.[17] Prepregs—fabrics that contain a heat-activated resin—are becoming more popular because they eliminate the messiness of wet lay- up procedures.

Critics have identified several drawbacks to textile composites including high material costs, limited availability, and manufacturing processes that rely on petroleum-based production. Indeed, many resins are noxious and not eco-friendly, but researchers have begun focusing on natural fibers and bio-resins as replacements for the more harmful synthetic materials. In spite of their lesser mechanical properties, hemp, sisal, coir, flax, and kenaf are gaining momentum as possible renewable alternatives to glass fibers. Furans—a sugar cane derivative—and other crop-based oils may soon harness the molecular structures of biomass to provide a natural substitute for typical thermoset resins. Bio-composites with optimized fiber blends have already entered the automotive industry as semi-structural components such as interior door panels and cockpit liners, but further research and development is required to achieve tensile strengths and impact resistance that can compete with the petroleum-based materials.[18] Architectural enclosure systems have not participated significantly in this field of study, so there is the potential for a more rapid timeline in the application of bio composites to architecture due to more manageable tensile strength and impact resistance requirements for such applications. Furthermore, while the resistance to weathering, and resistance to extreme thermal conditions of conventional resins make them a viable alternative to other architectural materials they have commonly been allowed restricted application.

PANEL EXPLORATIONS

In spite of the material challenges, our design work explores the potentials of textile composites in architectural applications. Continuing beyond our first series, the *Second* and *Third Series* shifted focus to the composite's underlying woven textile reinforcement. The textile rather than the composite drives both form-finding and environmental interaction strategies. This allowed us to explore the composite's formal, structural and environmental possibilities. We used a series of strategies including faceting, pleating, and patterning, the weave of the fiber reinforcement. Initially these strategies were implemented in pursuit of a self-structuring panel. However, as the project progressed, paralleling garment design, the ability to filter, absorb, or repel heat, air, and water, depending on their beneficial or adverse impact on user comfort, became the focus.

ENVIRONMENTAL RESPONSIVENESS

Series One adapts a textile composite panel system to a *temperate* climate by providing mass and insulation to a material that does not commonly have either. In temperate climate zones, thermal comfort-seeking strategies must accommodate variation in diurnal temperature shifts through boundary layers that insulate, provide thermal mass, and control ventilation and precipitation. We found multiple means of adding the needed insulation either by weaving it into the fabric or by injecting it into the voids created by the pleated fabric. Insulation providing low heat transfer values ensures fewer pollutants are released to the environment because less energy is consumed heating and cooling the housing unit. Through the thermal insulation in the panel fabric and the cavities, the system achieves an R-value well over 19, greatly reducing the energy required to heat and cool the units.

In *Series Two* and *Three* [figure 4 & 5], we established performance parameters for *hot/humid* climates that capitalize on the textile composite's lack of mass and its potential to exploit air flow. In tropical and sub-tropical regions, the temperature is relatively hot, humidity high, and precipitation abundant. The primary means of achieving a thermo-stable—though not altogether comfortable—condition through passive means involves maximizing ventilation and avoiding insolation. While the temperature and relative humidity are not radically reduced, the increased air movement promotes evaporative cooling. In a hot humid environment diurnal temperature variations in the summer, spring, and fall are negligible, making the use of thermal heat sinks as a cooling mechanism inappropriate.[19] Textile composites are beneficial in these zones because they minimize solar radiation absorption. In combination with the water-repelling resins, the textile component of woven fiber-reinforced composites can offer new opportunities by making a membrane that is both watertight and open to air flow. Reflective surface treatments (gel coats) can assist in lowering heat gain as well, and the fold patterns designed to channel water, also self- shade the wall. This provides insulating air pockets within a single membrane that slow heat transfer.

MATERIAL RESPONSIVENESS

Fully aware of the structural constraints of textile composites, we proceeded to subvert them in *Series Two* and *Three* in order to achieve other goals, primarily ventilation and channeling of precipitation. While using textile reinforced composites in the *Series One* cavity wall system, we became intrigued by the aesthetic and performative abilities of the fabric/reinforcement component. The potential of the fiber matrix in relation to these goals challenges some of the pre- established FRC technical optimization constraints. We also realized that a focus on economy of means applied to limiting the fabric used, did not significantly reduce weight, and it prevented thickening the membrane wall as necessary to meet our structural and environmental goals. Instead, we turned to the potentials of what Frank Lloyd Wright described as exuberant redundancy found in nature.[20] While we sought economy in the fabric form arrangement as exemplified by Otto's tensile structures, we coupled it with garment- making techniques that contradicted the ideas of minimal surface and the constraints of FRC structural integrity. This led us to design gravity- based jigs that work with tensile members and sewing techniques to form the panels.

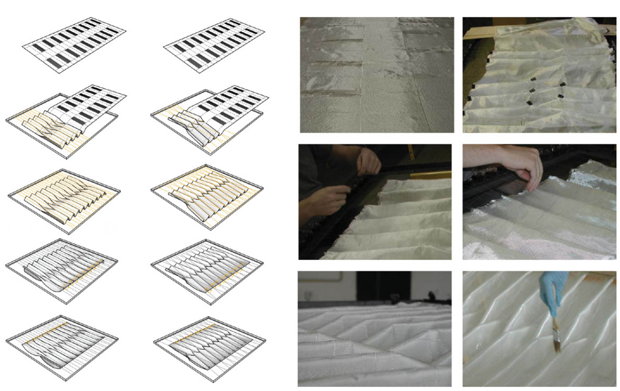

Figure 3. Scoop Series performance parameters and draping patterns

Uniformity is one of this material family's fundamental properties.[21] It is also the property that we exploited in our experiments. Stress is created by the dissolution of the continuous weave. In the event of a break or cut of a fiber in the weave, stress is transferred in shear through the matrix to adjacent fibers, potentially causing failure in the composite matrix.[22] However, in pursuing a surface with continuous ventilation, fibers needed to be interrupted to create larger pores in the surface. This stress-inducing break can be eliminated through computer generated weaving patterns that maintain filament continuity within a variable grid. These pores needed to be protected from rain fall, which lead to a series of pleated forms. In some cases, panel edges were designed to be 1/16" deep despite the 6" panel depth which was achieved through smocking [fig. 3]. The folds necessitated by these techniques cause a break in the stress distribution. However, pleating and smocking were necessary to form water runoff channels, as well as to give greater density to edges that would create a frame for the panel. Consequently, multi-directional layering, which adds strength to the surface, is generated through edge pleating, potentially counteracting the structural failure. This develops one continuous surface- not one continuous structural capability.

SERIES TWO AND *THREE* DEVELOPMENT: SCOOP AND VENT PANEL VARIATIONS

The *Second (Scoop) Series* overlaps traditional sewing and lamination techniques to produce articulated panels. These panels were limited to single plain-woven glass-fiber fabric sheets, and used pleating and smocking to create their form [fig. 4]. By drawing fabric taut and fastening it at specified points along fold lines, the sheet gains depth and contours that channel water away from ventilation and view apertures. The folds also produce lateral stability and the resultant depth allows them to support their own weight. In addition the fold patterns create elliptical forms on the panel's exterior face but its orthogonal edges facilitate panel repetition when constructing an entire wall [Fig. 1].

The *Third (Vent) Series* develops porous panels resulting from the interaction between the weave pattern of the textile and the controlling forces and regulating lines imposed by a jig [Fig. 2]. This series reorganizes the textile's weave, separating threads to create strategic (and programmable) air gaps in the weft.[23] The threads separation creates gaps between the fibers which are augmented once the epoxy is applied and the fibers are fused together. Continuous weave portions create impermeable areas on the same surface [Fig. 5]. A woven pattern of open and closed modules is then arranged on the gravity jig to create a ridge and valley pattern that repel rainwater (full weave) and permit constant airflow (warp only). *Series Two* results in a flexible breathing skin conditioned for hot and humid environments.

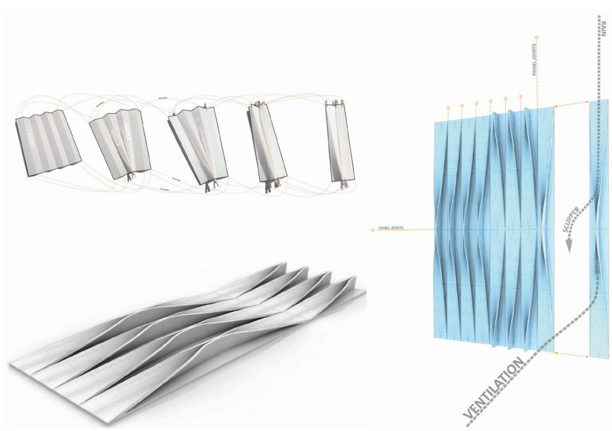

Figure 4. Jig configuration Diagram depicting the pattern of the draped textile and its pleated condition for gravity based panels

The panel forms are designed so that they can be aggregated to enable structural expansion [Fig. 1]. The resulting configurations form larger-scaled surfaces requiring fasteners that are compatible with the panel layout, composite reinforcement type, and material cross-section. Both mechanical and adhesive connection methods are applicable. In a demountable system, mechanical compression fasteners such as rivets draw the panel edges together and a neoprene layer is compressed between the panels to form a watertight seal. In a full unit deployment system, an adhesive joint used in the assembly will join the panels and provide the weather seal simultaneously. The choice is based on the delivery method most appropriate to the situation.

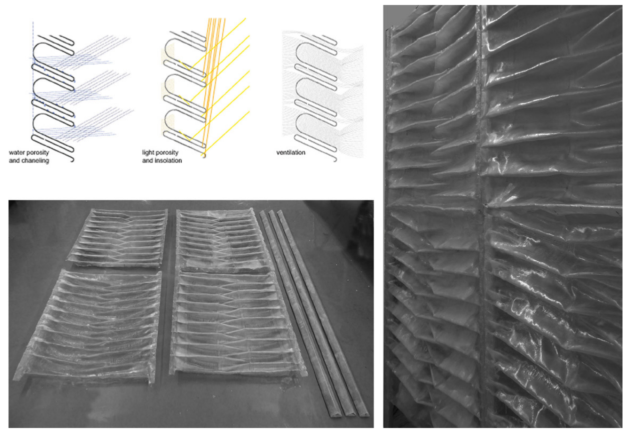

Figure 5. Vent Series performance parameters and composite panel assembly

CONTINUING EXPLORATION

Each new iteration articulated through digital modeling and analysis software, rapid prototyping, and physical mock-ups exposed limitations and revealed new potentials relative to the panel's environmental performance, aggregation, and manufacture. The concurrent mockups that relied on the textile component's structural and tectonic particularities altered the formal and performative development resulting not only in alternative panel designs but also changes in the panel aggregation and the overall structure of the emergency housing units.

Durability is a key attribute of composites that was demonstrated by the failed demolition attempts of the Monsanto House.[24] What, then, has been the impediment to the further implementation of textile reinforced enclosures in the building industries when its use is pervasive in so many other applications? Difficulty in testing and a lack of predictable material behavior characteristics have posed a challenge to more widespread textile composite use in architecture because—unlike materials such as aluminum and steel—composites are not manufactured in standard shapes or extrusions, and therefore engineers cannot easily predict their structural capabilities. Dietz as well as Beukers and van Hinte provide another answer by explaining the difficulty of predetermining the material's behavior along with the inability of alternative techniques to challenge the construction industry's pre-established efficiencies. Perhaps the progressive thinking at led to new material innovations, modularity, and standardization in the war and post-war years (aluminum, steel, and plywood, in particular) has become an impediment to implementing materials such as textile composites whose variability eludes standardization.

Our ongoing research questions these supposed challenges and shortcomings, and it speculates on the possibilities of more broadly implementing textile composites. Through collaboration with textile engineers and fabricators,[25] we hope to further bridge some of the gaps between the design parameters and affordances of the mutable fabric matrix, and the potential of environmentally responsive FRC panels.

ENDNOTES

1 In the 2002 Economic Census, the U.S. Census Bureau shows that the number of Broadwoven Fabric companies in the U.S. fell from 743 in 1997 to 639 in 2002. Similarly, the number of production workers diminished from 115,792 in 1997 to 69,957 in 2002.

2 In 2001, facing lagging enrollment, the oldest textile school in the South at Clemson University merged with the Department of Ceramics. Together, two departments created the more broadly-focused School of Materials Science and Engineering.

3 In 2005, the Cooper Hewitt, National Design Museum displayed innovative high-tech aerospace, medical, automotive, and nautical textiles as part of the exhibition, *Extreme Textiles: Designing for High Performance*.

4 Adriaan Beukers , Ed van Hinte, *Lightness: The Inevitable Renaissance of Minimum Energy Structures.* 4th ed. (Rotterdam, The Netherlands: 010 Publishers, 2005).

5 Gottfried Semper, *The Four Elements Of Architecture And Other Writings* (Cambridge, England: Cambridge University Press, 1989), 103-104.

6 Semper, 104.

7 Gevork Hartoonian, *Ontology of Construction: On Nihilism of Technology in Theories of Modern Architecture* (Cambridge, England: Cambridge University Press,1994), xii.

8 Beukers , van Hinte,79.

9 Albert Frey immigrated to the United States and brought with him an interest in industrial processes that could produce better single-family residences. As Le Corbusier's employee, he was familiar with the prototypical Maison Citrohan, and he translated several of its essential characteristics into the Aluminaire House. The prototypical aluminum-clad house embodied the aspects of machine-architecture that Vers une Architecture touted in the preceding decade, but it overshadowed Frey's groundbreaking experiments with cotton textiles in such projects as the Experimental Five-Room House and the Experimental Weekend Houses. See Joseph Rosa, *Albert Frey, Architect* (New York: Princeton Architectural Press, 1999), 32-34.

10 Joseph Rosa, *Albert Frey, Architect* (New York: Princeton Architectural Press, 1999), 42-47.

11 Conrad Roland, *Frei Otto Tension Structures* (New York: Praeger, 1970), 4.

12 Beukers and van Hinte, 16.

13 Beukers and van Hinte, 22.

14 2002 Economic Census.

15 American Society for Testing and Materials. www.astm.org.

16 North Carolina-based 3Tex is a leading manufacturer of 3-Dimensional fabrics. www.3tex.com

17 For a detailed technical description of composite materials, refer to: Jack R. Vinson and Robert L. Sierakowski, *The Behavior of Structures Composed of Composite Material* (Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002).

18 Caroline Baillie, ed. *Green Composites: Polymer Composites and the Environment* (Cambridge, England, Woodhead Publishing Limited, 2004).

19 Daniel J. Leathers, Michael A. Palecki, David A. Robinson, Kenneth F. Dewey. "Climatology of the daily temperature range annual cycle in the United States", *Journal of Climate Research*, Vol. 9;(1998) 197-211.

20 Frank Lloyd Wright, "Architecture and Nature", *Frank Lloyd Wright: His Living Voice* (Trd), ed., Bruce Brooks Pfeiffer (Chicago: Southern Illinois University Press, 1987), 33-34.

21 Resin-bonded fibers are "structureless" and reside between isotropic membranes and woven fabrics. Isotropic membrane - stressed skin - have equal properties in all directions. Anisotropic membranes-weaves -have do not.

22 Albert Dietz, *Composite Materials* (Baltimore: American Society for Testing and Materials, 1965), 20- 25.

23 In an industrial setting, the weaving pattern would be programmed into the loom but the manipulation was manually done for the experiments.

24 Arthur Quarmby, *Plastics and Architecture* (Washington D.C. : Praeger , 1974).50.

25 We have received material samples and assistance from the North Carolina-based company, 3Tex, which specializes in glass fiber weaving and has been an innovator of three-dimensional weaving processes.