COMPOSITE ARCHITECTURES: Engineering Complex Fiber Placed Structural Membranes for Sustainable Building Applications
BSA Research Report:

COMPOSITE ARCHITECTURES: Engineering Complex Fiber Placed Structural Membranes for Sustainable Building Applications

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A. EXECUTIVE SUMMARY:

In the Beginning of the 20th century two materials: reinforced concrete and carbon steel, effected widespread transformations in the structure, form and production of built space. Long-span systems and lightweight supporting frames replaced the heavy, telluric massing of the Beaux-Arts with an ethereal, gravity defying modernism. Today, however these ‘modern’ materials have become voracious consumers of energy, structurally inefficient, overweight, and ubiquitous. Our research sought to challenge the predominance of frame and non-load bearing “skins” at a time when material resources have become increasingly scarce and where the search for sustainable alternatives has defined the economic core of a technologically grounded marketplace. The principle aim of our investigation was to develop a new construction paradigm aimed at developing innovative modes of production though sustainable approaches to architecture and engineering. By creating high strength, ultra-light, multi-functional, structural membranes for affordable and environmentally responsive building applications, architecture can respond to pressing contemporary demands by seeking better ways to solve the practical problems of shelter, structure and use. To meet these challenges our BSA funded work explored the production of ultra-sustainable, structural building membranes made from recycled and biodegradable ‘green’ composites fabricated on a multi-axis, CNC fiber placement robot.

Figure 1: “Frame and panel” systems have determined built forms for more than a century. Despite dramatic variations in design, from masonry veneer to cable and mast-supported membranes, architecture continues to embody the opposition between skin and bones, structure and infill.
Figure 2: Mandrel production process for Ver 1. and Ver. 2 in foam and graphite. The tooling was produced on a small scale CNC mill.
B. RESEARCH METHODS:

I. Project Description

Composite structures consist of high strength fibers held together in a matrix of thermoset or thermoplastic resin. A panel made from these materials is typically 1.5 times stronger and 7 times lighter than the same panel made of steel. Composite structures may also be made using a combination of transparent and translucent materials that control privacy and views. Both simple and highly contoured shapes possessing extreme strength can be produced using a computer controlled fiber placement machine. These incredibly thin membranes require little or no supplemental support to manage loads and enclose space. The computer’s ability to determine the precise location of each fiber strand in a composite part also facilitates unprecedented control of its aesthetic and functional properties. By manipulating fiber types, patterns, layering and orientation, designers can create new ways of managing natural light, structural forces, function and thermal comfort.

Computer Automated Fiber Placement technology (AFP) is a relatively new fabrication process that is necessitating fundamental changes in the way we think about space, structure and program. Fiber placement machines employ a robotically controlled taping head to lay down fiber reinforced plastic strips on a reusable mold or “mandrel”. Because the forms AFP creates are incredibly strong, rigid, and corrosion resistant, they are also able to handle dynamic mechanical loads without the need for an independent structural armature. “For its size, the Premier 1 [business jet] is very light and features a composite fuselage for superior strength. The fuselage is built without an internal frame.” (1)

The primary aim of this investigation was to design, test and prefabricate high-strength, structural membranes assembled from easy to install parts that integrate multiple functions in a single production process. This ultra-light engineered composite building system was designed to provide for shelter against the elements. The prototype was to be affordable, strong and environmentally responsive. Our research also focused on the production of complex, curvilinear surfaces using a single, reconfigurable mold shaped to form walls, floors, ceilings, and windows. By collapsing conventional “skin and bones” construction into a single “frameless” assembly an enormous amount of time, energy, and natural resources will be conserved. Proprietary software, developed at each stage of the project, was written to help visualize, fabricate and analyze optimized designs. BSA funds helped us produce a marketable prototype for future use in real world projects.

II. Work Accomplished

With the budget given by BSA and Cornell we were able to realize a sizable amount of work. The following list describes the basic stages of our research and its resulting products:

1. **Models:** Our Team fabricated over 40 CNC milled butter board study models of a long-span truss that incorporates light transmitting surfaces and enclosed spaces for potential inhabitation and privacy. (Two 1/10” scale Last-A-Foam test molds were milled out at Cornell University. These were used to evaluate tolerances and to check for problems in the mold designs before they entered the final stages of production.)

2. **Software:** Our programmers wrote over 600 lines of code for visualizing complex composite taping patterns on curvilinear molds. (The code also produces machine commands for the fiber placement robots at Automated Dynamics.)

3. **Simulations:** Finite Elements Analysis (FEA) models of the structural performance of our design were produced in order to evaluate their efficiency.

4. **Fabrication:** Automated Dynamics and Cornell constructed a 1/10 scale, fiber placed truss using S-glass tape laid down on a graphite mandrel. The mandrel was milled at the College of Architecture, Art and Planning. (We also fabricated a Hydrocal mandrel using silicon rubber molds. The Hydrocal
parts were made to evaluate various casting techniques intended for the production of low cost tooling. Water jet cut aluminum fittings and connections were produced by INCODEMA Inc., in Ithaca New York.)

5. Specifications: Specifications were written for our full-scale truss that incorporates biodegradable composites that can be returned to the earth as nutrients. Augmenting these specs is a series of design strategies that expand the potential sustainability of the prototype beyond material use alone.

6. Pedagogy: In the course of conducting this research a graduate level studio was convened in the College of Architecture, Art and Planning at Cornell University. (AAP) In the class students explored a wide array of applications for robotically placed composites. Office towers, long-span structures for athletic events, prefabricated housing and museums were some of the building types developed and re-imagined through the use of this new material processing technology. (An independent study group working together at the AAP assisted the production of the final prototype.)

III. Sustainability Targets

Our research attempted to find replacements for some of the most widely applied and ecologically detrimental construction practices in use today. As one of the world’s leading material consumers, architecture needs to tackle the problem of sustainability in at least four major areas: (A) through the reduction of the total embodied energy of its building materials, (B) through improvements in the thermodynamic efficiency of space enclosing membranes, (C) through an overall reduction in pollution caused by construction, and (D) though the conservation of resources, manpower and capital. With the use of fiber reinforced composites many of these challenges were successfully met. Our work targeted specific material applications and fabrication methodologies by developing practical replacements for conventional building systems employing steel, concrete and masonry. The following categories were used to substantiate the claim that sustainable applications for advanced composites in architecture can be engineered for the benefit of clients, the public and the world as a whole. To achieve these goals we reinvented the way building membranes and structures are deployed in the built environment. Our primary achievement has been the development of a curvilinear, long-span fiber placed structural membrane that incorporates multiple functions and spaces in a single CNC fabricated component. The design responds to the need for energy and recourse efficiency in the following ways:

Figure 3: Preliminary Mandrel designs for s-glass fiber placed truss with support spaces. The complex transition between the center span and the ends of the truss allow for a smooth transition between different functions.
Figure 4: Deflection maps from finite elements analysis software of room to long-span fiber placed structural membrane.
A. Embodied Energy: The ability to span longer distances with less material and weight helps reduce waste and the total amount of energy used in construction. With our fiber placement truss, different functional requirements were met through the computer controlled, mass customization of intricate taping patterns laid down on a single, reusable mold or ‘mandrel’. Because this ultra-light composite system contains all of the elements of a typical building structure and its associated non-structural skin, the number of elements delivered to a job site is greatly reduced. With low weight components, fuel consumption and shipping costs also decrease.

B. Thermal Performance: Improvements in the thermal performance of fiber placed composite membranes can be achieved by laying down different kinds of materials between multiple, fiber plies. These include, soy based foam, insulated Nomex sheets and even Aerogel, a low-density solid consisting mostly of air. While we did not actually use these materials in our prototype the drawings included in this report clearly show how they can be incorporated into the process.

C. Material Sustainability: Environment friendly replacements for toxic, fiber binding agents are now being developed. Many of these plant-based plastics (polylactic acid, modified starch and soy-based resins, etc.) are ideal for interior applications and can be returned to the earth as nutrients after demolition. Co-PI Prof. Netravali, our matrix expert, is one of the leading engineers of ‘Green Composites’. His work includes research into biodegradable fibers as well as nano-engineered resins and composites. Prof. Netravali produced the necessary specification for a large-scale fiber placed building component made with soy-based plastics and natural fibers. (See Addenda.) Again, while we did not incorporate these materials in our physical prototype their actual deployment would be a matter of switching one spool of material on the robot to another. (Note: Depending on the application a typical reinforced thermoplastic composite consists of 40-50% matrix and 50-60% fiber. This fact alone limits the application of petroleum-based resins used for exterior applications to a bare minimum. Introduction of S-glass (or S2-glass) fiber promises a competitive strength advantage over steel, while avoiding the need to exploit limited oil reserves. (S2-glass fibers themselves have a delivered strength of almost 600 ksi in tension. Matrix volume fraction and safety factors for size effects and stress-rupture mechanisms more than double the 50 ksi useable strength of steel. The resulting composite structure is four times lighter.) It is also possible to use natural or regenerated cellulose fibers that have excellent mechanical properties. For example ramie fibers have been shown to have a stiffness of 128 GPa, comparable to Kevlar®. Liquid crystalline cellulose fibers can have a higher toughness than Kevlar® and graphite. Carbon neutral resins that are able to resist weathering are also being developed as part of Cornell’s research into green materials.

D. Cost Savings: Multifunctional structural membranes combine different building systems normally produced and assembled by different trades and production techniques. Bringing these systems together on a job site for assembly normally consumes a vast amount of money, time, energy and natural resources. Using fiber placement technology to construct a fully integrated, structural membrane, complete with windows, closed wall areas, insulation and load bearing supports, vastly reduces the amount of materials needed to construct a fully functional building. While a composite beam might be more expensive to manufacture than a steel one, multifunctional, fiber reinforced thermoplastic membranes, cost far less than

Figure 5: Green building construction and life-cycle diagram showing 10% S-glass recycled after demolition with 90% biodegradable soy plastic and ramie fiber reinforcements returned to the earth as nutrients.
Figure 6: Final CNC milled graphite mandrel components for Ver. 1 prototype. The image shows curved surfaces, slots for post tensioning rots and central rotation shaft.
conventional space making systems with their heavy and difficult to transport parts and sub assemblies. In other words a typical frame and panel building contains steel, concrete, glass, insulating materials, silicon caulking and nonferrous metals. With a fiber placed structural membrane the total number of materials used during construction can be cut in half. (Decreases in the weight of a building’s superstructure also permit significant reductions in the cost, size and complexity of its supporting foundations.)

Figure 7: Diagram of a multifunctional composite membrane: a. mullion, b. plastic window with two mullions, c. mullion, with a window and a partition, d. porous screen and c. a composite wall. In b. and c. the window exists as an extension of structure.

C. KEY FINDINGS:

Our BSA funded research began as the extension of an earlier collaboration between Automated Dynamics, Raphael Vinoly Architects, PC and Pratt Institute. In an attempt to go beyond the simple, extruded truss prototype we built for Vinoly this phase of the research pursued the creation of double curvatures. The importance of achieving complex and fluid surface transitions between functionally distinct areas of a designed component cannot be over estimated. Complex surfaces allow for the facile integration of multiple and sometimes-contradictory space requirements into a single fabrication process. This allows the material and associated methods of production to achieve “much more with much less”. Through the efficient, resource conserving process of robotic fiber placement we were able to introduce closed voids and minimal volumes each suited to a specific function i.e. square rooms for inhabitation and minimal triangulated surfaces for spanning long distances. All of this was achieved with extremely light weight and strong materials that were deployed to solve multiple functions without the need to introduce extraneous building systems or material production processes.

Figure 8. Left: Three roof designs: Renzo Piano’s Menil Museum in Houston Texas, Louis I. Kahn’s Kimbell Museum in Fort Worth Texas and our design for an S-glass fiber placed truss system. Piano uses three discrete systems to create shelter, hold up the building and modulate light. Kahn reduces these systems to a curved concrete beam and a metal light reflector. Our truss integrates theses function into one, ultra light fiber placed component. Above Right: Drawing showing how materials can be conserved by integrating multiple building systems into a single composite envelope.
Figure 9: Mandrel assembly and preparation sequence showing central shaft and milled graphite components.
D. CONCLUSIONS:

Our multidisciplinary research team constituted a unique integration of industry and academia. Faculty form different parts of the University, engineers, practitioners and industry collaborators worked closely with students at each stage of the process. This support team included experts in composite structures and analysis, software programming, modeling/simulation, sustainable technologies, materials science, and architecture. Through this unique synergy of experts we developed a comprehensive and sustainable method of building construction that responds to the aesthetic/functional challenges associated with the creation of a new kind of architecture. The system will have a long-term impact on our ‘national’ building infrastructure and material ‘needs’ by providing a sustainable alternative to the following construction systems:

a. Load bearing façade retrofits,
b. Long-span steel and/or reinforced concrete structures,
c. Laminated timber structures,
d. Traditional balloon frame construction,
e. Prefabricated housing.

E. ADDENDA: (Prof. Anil Netravali)

Fiber reinforced composites are made from fibers such as graphite, Kevlar®, glass and resins such as epoxies, vinyl esters, etc. They have excellent mechanical properties and low density. As a result, they have very high specific mechanical properties. They have been steadily replacing traditional metals in many applications. They have two serious shortcomings; 1) most of the fibers and resins are made from petroleum as feedstock, non-sustainable resource and 2) because they cannot be easily recycled or reused, over 90% of them end up in landfills at the end of their life. Fully sustainable ‘Green’ composites, on the other hand, are made using yearly renewable, plant-based, fibers (cellulose) and resins (modified soy protein, starches, etc.) and can be easily disposed of or composted at the end of their life. These fibers and resins are also carbon neutral. Green composites can be made using natural fibers in various forms; fibers, yarns, nonwoven, woven and knitted fabrics. While unidirectional yarn based composites could be made with strength in the range of up to 340 MPa for structural applications, nonwovens/fabric based
composites could be used as replacement for plywood, MDF and particle board. Netravali group has made unidirectional ‘Advanced Green Composites’ with strength of over 600 MPa using liquid crystalline cellulose fibers. These fibers open the possibility of fabricating unidirectional composites of strengths close to 1 GPa when fiber content is increased to 60% as in the case conventional composites. With densities of about 1.4 g/cc, these green composites are as strong as high strength steel but have less than 1/6 the weight of steel and hence can be used in primary structural applications such as beams and trusses. In other words these advanced green composites, are more than 6 times stronger than the strongest steel on a ‘per pound basis’.

While the mechanical properties of green composites are excellent, their use of hydrophilic fibers and resins makes them susceptible to moisture absorption and associated swelling and mechanical property loss, when exposed to wet or high humidity conditions. However, this can be mitigated to a great extent by mixing hydrophobic additives into the resin. The additives could be natural oil based compounds and/or nanoclays (e.g. Montmorillonite, cloisite®, etc.) or nanotubes (e.g. Halloysite). Addition of nanoclays and nanotubes has also been shown to improve the thermal stability of green resins and hence of the composites. Another simple and practical solution would be to protect green composites from moisture. This can be easily achieved by using a sheath/core structured composite where the core (over 90% of the total wt) would be of green composite that is protected by a hydrophobic sheath consisting of S-glass/epoxy or S-glass/vinyl ester composite. This sheath/core structure can extend the life of the green composite indefinitely while also providing additional strength and integrity. At the end of their life, the ‘green’ composites can be composted where they degrade into organic soil within 3 to 6 months. In the case of sheath/core structure, the sheath could be easily removed separated from the core by enzymatic action and composted.

Another technique used by Netravali group to improve the mechanical property, particularly the toughness and strength of the soy protein based resin, is through the use of micro-fibrillated- and nano-fibrillated-cellulose (MFC/NFC). Both MFC and NFC are obtained from plant cellulose by shearing and separating into micro- and nano-fibrils. MFC and NFC have been shown to have high molecular orientation and crystallinity. As a result, their strength is estimated to be in the range of 2 to 10 GPa (average of 6 GPa), much stronger than Kevlar® (3.5 GPa) and the modulus (stiffness) is about 140 GPa, compared to 125 GPa for Kevlar® 49. Addition of MFC and NFC increases the strength and toughness of the soy protein based resin significantly. The properties of the modified soy resins are comparable or better than the most commonly used epoxy resins.

![Diagram](image-url)

Figure 11: Section through demountable mandrel version 2 showing steel shaft and tape wrapping blocks with post tensioned re bars.
The soy protein comes in three categories; defatted soy flour (SF, $0.30/lb), soy protein concentrate (SPC, $1.50/lb) and soy protein isolate (SPI, $2.25/lb). While SPC is commonly used in green composites, it is possible to use SF after increasing the protein content by insolubilizing the protein and solubilizing the carbohydrates and filtering them out. This process raises the cost of the SF to about $0.55/lb which is significantly lower than the commonly used epoxy resins ($1.60 – 3.00/lb). The natural fibers are also significantly cheaper than the S-glass, Kevlar® or graphite fibers. As a result, the green composites could be very inexpensive compared to the conventional composites. Fabricating of green composites is simple and involves preparing the procured resin, dipping the fibers in the procured resin, orienting them in the preferred direction and hot pressing in to desired shape. The curing temperatures are around 120°C, compared to much higher temperatures used for conventional composites (e.g. epoxies may be cured at temperatures of 150°C or higher). The curing process itself saves significant amount of energy used for fabrication.

In summary, fully sustainable and carbon neutral green composites may be fabricated to obtain desired properties but at significantly lower cost compared to conventional composites. They may be used as structural element or as replacement for plywood, MDF, particle board, etc. At the end of their life they can be easily disposed of or composted rather than putting in to the landfills, thus helping the nature.

Notes:
Figure 14: Photographs showing tool mounting, machine motion tests and final fiber placement of Version 1 composite prototype.
Figure 15: Version 1 composite prototype finished part.

Figure 16: View of the finished prototype.
Figure 17: Interior views of s-glass fiber placed structure showing transitional space between inhabitable space and long-span beam.

Figure 18: First layer of four separate spiral S-glass strips forming a truss to volume transition on our Version 1 prototype.
Figure 19: Screen shots of 'Fibershop' script calculating fiber winding paths on complex shape in full 3D.

FIBERSHOP VER. 1.0 Beta Code Extract: (Option Explicit)

'Create Layers
'Rhino.AddLayer("Points")
'Rhino.LayerColor "Points", RGB(100, 0, 100)
'Rhino.AddLayer("Helix")
'Rhino.LayerColor "Helix", RGB(0, 0, 250)
'Rhino.AddLayer("Tape")
'Rhino.LayerColor "Tape", RGB(250, 0, 0)
'Rhino.AddLayer("TapePts")
'Rhino.LayerColor "TapePts", RGB(100, 150, 100)
Call Main()
Sub Main()
Dim dblMin, dblMax, intDeg
Dim arrRails, arrNormal, arrDir, arrPts, arrLines, arrLines1, arrLines2, arrJoin1, arrJoin2, arrRailsO
Dim width
Dim intDens
Dim strMan, strB, strA, strAns, strE, strK1, strK2
Dim strLayerName, intTapeLayerCnt
Dim arrObjects, strChild
'strMan = Rhino.GetObject("Select the mandrel surface.", 8, , True)
arrObjects = Rhino.ObjectsByLayer("Mandrel")
strMan = arrObjects(0)
arrRails = Rhino.ObjectsByLayer("Rails") ' Rails prepared external
'strA = Rhino.GetObject("Select central axis", 4)
arrObjects = Rhino.ObjectsByLayer("Axis")
strA = arrObjects(0)
'strB = Rhino.GetObject("Select base curve", 4)
arrObjects = Rhino.ObjectsByLayer("Start")
strB = arrObjects(0)
'strE = Rhino.GetObject("Select middle section curve", 4)
arrObjects = Rhino.ObjectsByLayer("End")
strE = arrObjects(0)
If Not Rhino.IsCurvePlanar(strB) Then
Rhino.Print "The base curve must be planar! Script cancelled."
Exit
F. AFTERWORDS:

Working directly with the staff at Automated Dynamics it was possible to gain direct, hands on experience of new computer automated composite manufacturing systems. Through this collaborative exchange we were able to produce a better understanding of how composites can be used to make buildings. Instead of generating forms that are post-rationalized for structure and/or material ascription, architectural components in our research were produced as an expression of the nature of materials and the processes that shape them. While this approach might seem to privilege matter, process and structure over architecture, the creative subjectivity of the designer, once engaged with these techniques, can open up unforeseeable formal possibilities that exceed the demands of “firmness” and “commodity”. In other words, new insights into architecture’s formal transformation can be stimulated through a deep understanding of advanced techniques. Here neither structure nor aesthetics is privileged as the driving force behind the art of design. It is my hope that the next phase of our research will produce a more compressive, fully dressed manifestation of these ideas in a rigorous and well-developed architecture.

G. ACKNOWLEDGMENTS:

I would like to personally thank the engineers, programmers, craftsmen and technicians at Automated Dynamics for their generous support of this project. I’d especially like to extend a note of gratitude to ADC President Robert Langone for his extraordinary contributions of staff time, materials and engineering insight. It takes a lot of courage to invest company time on risky design experiments that can easily founedered or worse reach an expensive dead end. Thankfully, neither of these fates came to pass. The production of this prototype composite part could not have been realized without the patient guidance of Anne Roberts. To her I extend my deepest thanks and appreciation. Our computer programmers and Engineers Chipp Jansen, Nikolaus Stahl, David Hauber and Mike Pasanen deserve the highest praise for their heroic efforts and the time they spent getting our code to work on ADC’s machines. Finally, I’d like to thank Frank Parish, the Boston Society of Architecture, my independent study students, Anil Netravali and the administration of the AAP at Cornell University for keeping the project running at a busy time during the semester. Their patience and help is greatly appreciated.

-Mike Silver