Curvilinear

Pedagogy of Tensile Fabric-ations

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Abstract

This paper outlines the pedagogical issues of design and fabrication of tensile membrane structures. Pedagogy needs to closely follow the nature of structures, materials and fabrication processes. Pedagogy of tensile fabric structures is significantly different from that of the conventional frame and panel (stick-built) structures. To explore the digital design and fabrication of tensile membrane structures, a design/build studio was conducted at the University of Texas at San Antonio. The present paper identifies the peculiarities of this type of project and discusses the pedagogical lessons learned from this design-build studio.

Introduction

Tensile systems in general, and tensile fabric structures (TFSs) in particular, have not been discussed or explored in sufficient depth in architectural circles in North America. In the face of specious curvilinearity that is in vogue at present, tensile fabric structures present genuine, dynamic, and novel architectural possibilities (Koch and Habermann 2004; Koch 2004b; Drew 1976; Nardinger 2005).

There are, sadly, no documented precedents that deal with the pedagogy of teaching a tensile fabric design-build studio on the west side of the Atlantic. On the east side, however, few examples could be found. The Institute for Membrane and Shell Technology (www.ims-institute.org) at Anhalt University has done and written about many TFS projects with student involvement. The Textile Roofs conference routinely features many such examples (Llorens 2002).

Pedagogy has to closely follow the nature of structures, materials and fabrication processes, which is significantly different from that of the conventional stick-built structures. The paper presents the lessons learned from a design/build studio. The projects were named UTenSAils, and the studio was conducted

Figure 1. UTenSAils Detail.

at the University of Texas at San Antonio in spring 2005 (Figure 1). The studio was conducted in partnership with twenty-four organizations and industry members.

A STRETCH OF IMAGINATION

Students, and often the professionals, enter the world of tensile and fabric structures with many misconceptions. The first step of teaching a studio with this focus is to devise exercises and lectures that dispel these misconceptions through knowledge-building as well as experiential learning. Conventional pedagogy in architectural schools focuses predominantly on frame and load-bearing structures. Such techniques as solid-void studies are typically used. Tensile systems demand different kinds of imagination, processes and methods. TFSs have proven to be a definite challenge to even the most advanced students entering the studio.

Contrary to the common misconception, tensile membranes are not stretched like Lycra® or rubber. While it is possible to use Lycra-like fabrics, such fabrics are not meant for either outdoor use or for any durable and performative structural situations. The stretchability of some of the common tensile fabrics is limited to mere inches over hundreds of feet of length.

Unlike other curvilinear frame structures, understanding the materiality of the membranes to be used in a TFS project is absolutely essential to the modeling and design of the minimal surface structures. For instance, such varied fabrics as Teflon®-coated PolyTetraFluoroEthylene (PTFE), PolyVinylChloride (PVC) coated polyester and Silicon-coated glass fabrics are used to suit different structural, spatial and durability requirements. Each of these materials has different levels of stretchability, brittleness and foldability requirements. For instance, PVC fabrics, which are rated for 10-20 years of durability, have the most stretch and moderate foldability. With PVC fabrics becoming recyclable through such innovations as Ferrari Textiles' Texiloop® technology, PVC is becoming the first choice tensile fabric for many projects. PTFE fabrics such as Gore Tenara® have less stretch and high foldability tolerance. Teflon® coated or Silicon coated glass fabrics are highly fragile and need to be designed with least amount of stretch or fold or error tolerance. The famous Haj terminal in Saudi Arabia has used glass fabrics, where the structures needed to be very carefully and very slowly hoisted into place in a coordinated manner to minimize cracking and structural failure. In any event, the stretch factor of a PVC-coated or PTFE tensile fabric is no more than 0.02%.

These material challenges make the modeling and form-finding of the TFS very interesting. Similar to the design and fabrication methods that Gehry Partners LLP employ in the design of complexly curving glass surfaces where the material characteristics of glass had to be taken into account at every stage of the design, fabrication and construction process, the nature of a tensile membrane needs to be accounted in tempering the minimal surfaces evolved in the form-finding process. Most of the tensile membranes are woven fabrics. The process of weaving makes it difficult to provide the same tensile characteristics in warp and weft directions. As a result, warp direction of the fabric has higher tensile strength than the weft (or fill) direction. The weft-to-warp tensile ratio is one of the essential parameters to be used in finding viable, fabricable and buildable structures.

Tensile fabric structures cannot be reliably designed and built without the aid of computational tools, which are only becoming available now. Before the advent of computational tools, fabrication of TFS was a laborious geodesic process of translating the double curvature of the minimal surfaces into two-dimensional patterns. From these patterns of flat fabric a three dimensional structure can be formed. But without a truly experiential understanding of how the forces can be transmitted elegantly through the slender structural systems, computational tools have proven to be of little use in and of themselves. Those students who began aggressively sketching or "mesh-modeling" in form*Z soon discovered the futility of such processes. Stretchable nylon and Lycra physical models with "structurally working" supports were essential to experientially understand how to resolve dynamic and non-linear forces. A powerful and expensive software tool called MPanel was introduced simultaneously. This combination proved to be right on target. The students began realizing the "language" of tensile fabric structures and the fact that every detail in the project had to work "structurally" under pre-stress conditions as well as dynamic loading conditions.

Chip-board models, sketching, surface and solid modeling in Sketchup or form*Z are the typical mainstays of an architecture student's design process from conceptual to design development stages these days. Unfortunately, these tools, skills and abilities are inadequate when it comes to TFSs. In over four semesters of teaching studios with this emphasis, the author has found that it takes at least three to four weeks to "unlearn" the misconceptions and develop an informed and systematic process of working with tensile fabric systems. It was important to provide a "real site" on hand so that the structural characteristics of the soil, existing surroundings and micro-climatic characteristics could be engaged.

WORKFLOW OF TFS DESIGN AND FABRICATION PROCESS

A trip to the local fabric fabrication shop was a necessary eye-opener for all the students. The workflow and process of patterning, cutting, welding, finishing and rigging these structures was seen firsthand. TFSs are always collaborative works between engineers, architects, fabricators and erectors.

The necessity of close collaboration was stressed right from the beginning through tele-conferences with practicing engineers. Tensile membrane structures involve the steps shown below in Figure 2.

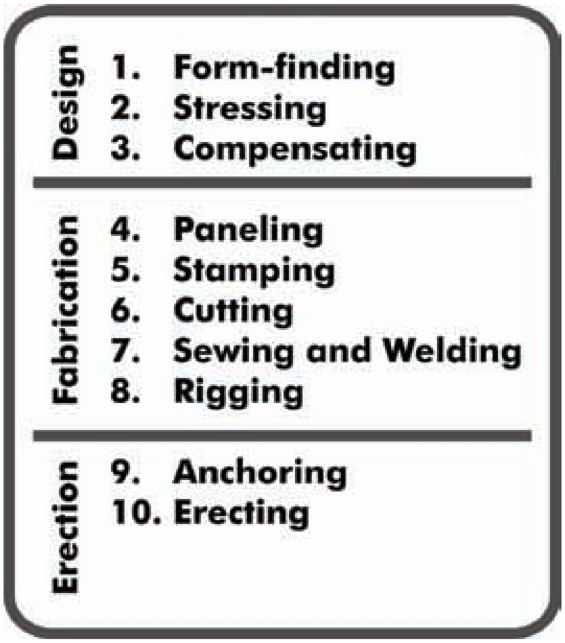

Figure 2. TFS Workflow.

Figure 3. Stretch Model by Andrew Wit.

Figure 4. Non-Stretch Canvas Model Detail.

Form-finding

Conventional studio projects and processes often (mis)lead the students down the lane of "form-giving." In form-giving, there is a shade of arrogance and presumptuousness that goes with the notion that the architect "gives" the form. This kind of approach and attitude are counter-productive when it comes to TFSs. The designer has to respect the material, forces, micro conditions, schedules, budgets and other parameters that impact the project from day one. It is similar to working on a parametric design model with one exception: this one is a live project in physical space. If one factor changes in the matrix, everything changes. The students were encouraged to play with and discover the formal possibilities through "form-finding" process. Any willful manipulation of the surface without paying attention to the force propagation would result in wrinkles, overstressed anchors and disfigured form. This process demands a certain discipline, which the tyros often lack. Form-finding involves working with high and low points of the structure, determining the catenary curves, determining the allowances that must be considered for optimal surface curvature, positioning the masts, and anchoring the guy cables.

Although the students began with nylon "stretch" models to explore the form and force, the final models were made out of non-stretch canvas that needed to be patterned, cut and sewn to form the curvilinear surfaces. This particular step was important as it teaches the students the economy of patterning and labor involved in the actual process. This step would be analogous to the actual design and fabrication of full-scale tensile fabric structures (Figures 3 and 4).

In addition to form-finding, given below are some of the processes and issues that the students found challenging. Even in the study models, the following steps were required to be followed.

Stressing and Paneling

After estimating the stresses on the fabric, the masts, and the catenaries, the surface curvature is determined and meshes are panelized. These patterns are then compensated for the manufacturer's specification of nominal fabric stretch. Simple panel polygons are then given seam allowance for stitch or weld overlap. This overlap should usually exceed 1.5" for sufficient surface area of bonding.

Stamping

The panels need to be stamped for fabrication. Stamping involves delineating points for fabric alignment and orientation. The CAD files contain both the cut layers and draw layers. Draw layers can be drawn on the final fabric using the same cutting machine to provide assembly instructions (Figure 5). Cut layer can be used to direct the cutter to execute the knife to cut along the given outer edge.

A Very large Plotter

Sail cutters, which can accommodate nearly 6'x44' of cutting surface, are used for high-speed cutting. Cutting surfaces employ perforated plates that allow for vacuum suction. Vacuum suction enables the fabric to be held in place without any other mechanical means (Figure 6).

Figure 5. Stamping and Preparation of Sail Cutting Machine.

Figure 6. Fabric Cut to Pattern.

Microwave Cooking

As unbelievable as it might sound, certain industrial fabrics used in the tensile membrane industry can be "welded" instead of being sewn. PVC-coated membranes can be welded using Radio Frequency, sometimes referred as High Frequency or Dielectric Welding. In this process, two PVC edges are fused together using HF (13-100 MHZ) electromagnetic field. The alternating electromagnetic field causes the dipoles of the plastic molecules to oscillate and produce heat. This heat then bonds the two edges together, which is often stronger than sewing. However,

Figure 7: Radio Frequency Welding of Fabric Panels.

this strength is generally useful in shear direction. Fabric edges are fed in between the top and bottom plates twelve inches (30.5 centimeters) of length or less at a time. It takes less than ten seconds to weld (Figure 7).

Welding could also be accomplished using special hand-held plastic welding heat guns such as Leister Varimat. The advantage of hand-held guns is their usability in the field. However, the studio's experiments with heat guns have ended in spectacularly scorched and wrinkled welds.

PROJECT DESIGN PROCESS

With these steps understood, the studio had set out to tackle the main design-build project(s). Any design-build studio has a two-fold challenge: to learn as well as to apply the learning to actually build full scale structures to a set schedule. In case of TFSs, one more challenge is added: to unlearn "broad-based stick-built thinking" and embrace "tensile-structural thinking" with an emphasis on minutest details.

Pedagogically, how can one make the entire studio choose one or two projects and make them their own? How can one make all the students take ownership of the project with equal fervor? With no single shop on the university premises, how can tasks strewn all over the town in professional workshops be coordinated? How does one make sure that the details actually fit and pass the structural requirements? These were all burning questions to which we had to come up with interesting solutions.

Typically, in an architectural studio, students competitively respond to a design challenge individually. The professor usually serves as the master, the almighty from whom the students are supposed to learn. I would wittily call this the "Howard Roark model" of teaching. Even in the case of many design-build studios, this master-centric model is prevalent. In the "firm" model, the professor, the students, the professionals, the suppliers and the fabricators form a collaborative and entrepreneurial collective where all parties learn and benefit from the partnerships. The professor facilitates learning and leadership as a main partner. This model of teaching has been successfully implemented in many design-build studios around the world.

The students were asked to form a hypothetical architectural firm. An administrative layer of positions was created to run the firm: office director, graphic designers, PR specialists, transportation associates and others were created. The students were invited to apply for the positions and hypothetically hired based on their resumes and interest. The students came up with a name for the firm. A web-based collaborative forum and discussion group was used to establish a communication network with our partners during and outside of the studio hours. On top of the administrative layer, a professional layer of positions was created where the students took on different roles to accomplish different project-specific tasks. These layers had enabled a sense of responsibility and a professional relationship with each other.

As it was proven later on in the project process, this step of "forming and formulating the studio as a different kind of institution" was absolutely and fundamentally essential.

The hypothetical employees were asked to form teams of three members each and propose different projects around the school of architecture building. The students were given five days to develop models of the project. A jury consisting of the students, the professor, the dean, university facilities manager, and a practicing engineer was formed to rank the projects. The emphasis was on ranking, not elimination. Projects were thus prioritized for resource allocation and scheduling. It was important that this step was of a very short duration (no more than a week) so as to prevent any excessive attachment to the projects.

Moreover, the firm was divided up into task-based teams: aluminum team, fabric team, detailing team, foundation team and transportation team. The whole firm was brought together every day to discuss design development and detailing.

Two structures of approximately 600 square feet (56 square meters) each were prioritized as main design-build projects to mark the two main entrances to the school of architecture building. With an overwhelming response from industry donors, materials and services worth nearly $103,000 were received. Of the two structures, one structure was chosen to use PVC-coated polyester membranes supplied by Hiraoka Company of Japan and Verseidag of Holland/Germany. The second large structure was selected to use Gore Tenara PTFE fabric, which has a 40% transparency.

In consultation with Wayne Rendely PE, a tensile structures engineer, the larger structures were designed and modeled in both digital as well as physical media. It is extremely important to test the buildability of the digital meshes in physical form and the accuracy of the physical meshes in digital form. The digital and the physical have to go hand-in-hand (Figures 8, 9 and 10).

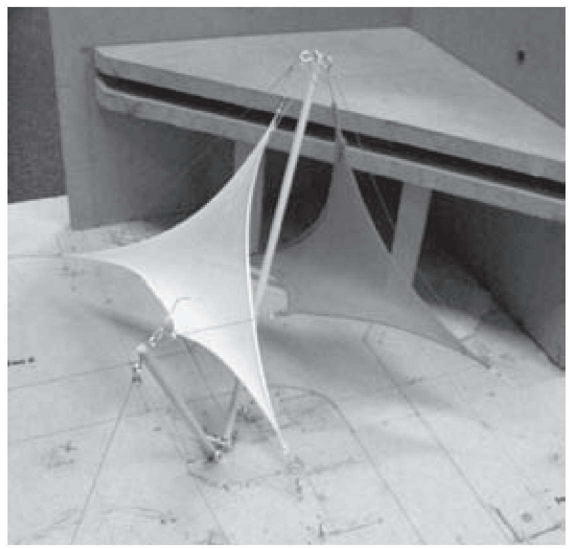

Figure 8. Physical Stretch Model for Exploration.

Figure 9. Physical Patterned and Welded Model for Verification.

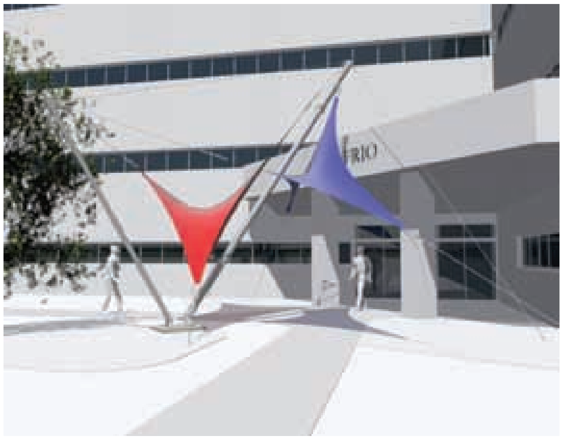

Figure 10. Digital Master Model.

Initial models, which did not include the specific material characteristics, gave way to more accurate models that took into account fabric stretch, rigging details, catenary curves, desirable pre-tension, soil conditions, anchor strength requirements, wind loads, safety factors, and, of course, the spatial requirements.

The digital models were developed in close consultation with Meliar Design Company of UK. The capabilities of the MPanel software were put to a rigorous test during the design and fabrication process.

Mockups

One of the lessons in tensile fabric structure design-build was not to finalize any detail or any fabrication without a full-size mockup. Many inconsistencies and mismatches were discovered, sometimes after fabrication. Most of these were due to mismatches between custom fabricated plating and standard fittings. Midway through the process, it was decided that all the details would be mocked up in wood and PVC piping. All the details went through an approval by a structural engineer (Figure 11).

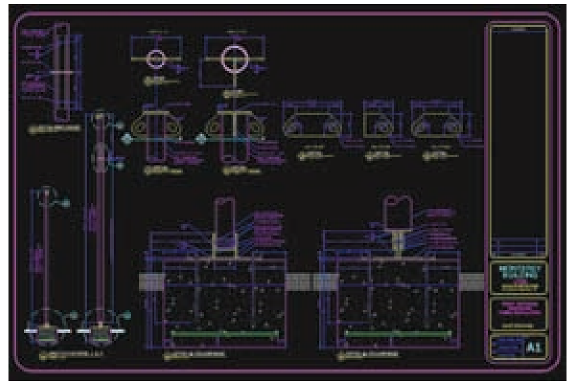

Figure 11. Working Drawings.

Also important was to match fabrication methods to design detailing. For instance, the mast plating needed a cut that is 1/1000th of an inch (0.00254 cm), which could only be achieved by using a water-jet cutter.

RE: LIABILITY

No design-build project can get built without addressing the issues of liability. Different schools have developed different models. As a pilot project, we had chosen to see if liability could be dealt with on a donation basis where certain parties assume the liability. What was different about these projects was that liability was spread in a different manner than stick-built structures. These projects were engineering-intense. One hundred percent of the components of tensile fabric systems are structurally active at all times. This meant that it was the engineer who had to seal the drawings per university's requirements. However, it was not easy to find an engineer who was either competent or interested in tensile and fabric structures. We had to resort to teaming up four engineers with different specializations, with one engineer of record assuming a part of the liability equation.

The second part was during the fabrication process. Different shops offered to assume liability of different processes. Most had allowed the students to work under their supervision.

By the time the engineering and liability issues were fully visible, the students had realized that "design" was only a small portion of the process of building a structure.

Timing

One important thing to watch out in TFS design-builds is for student morale with respect to seeing the fruits of their labor. With stick-built or other structures that do not use extensive pre-fabrication, most work goes up in a cumulative fashion of accrual. Everyone gets to see the work gradually going up. With TFSs, all the fabrication and assembly has to be done before the final erection. 95% of time is spent on fabrication, rigging and assembly. The pacing of our projects differs significantly from non-tensile structures. For instance, nearly three months of time was spent on the project with absolutely nothing built above ground on the site. Then on one fine morning everything went up within a span of four hours.

Anchoring

Conventional foundations involve digging and pouring. Tensile fabric structures typically involve little digging as most of the forces are upward acting pull-out forces (Figures 12 and 13).

The only compression foundation was under the masts. All other supports were helical (screw) earth anchors, which

Figure 12. Helical Anchor Installation.

Figure 13. Driving the Anchors to Achieve the Target Torque.

involve special equipment and installation than the "low-tech" digging and pouring.

Once the students determined the angles at which the helical anchors would go down, an engineer who specialized in their design designed them. The angle of the anchors had to match that of the force vectors. A BobCAT was rigged to drive a special anchor installation drive-head. The anchors were screwed down till they achieved the required 20Kips (89 KN or 9 Tons) of resistance as measured by the maximum torque. This process was at once simple, sophisticated and expensive.

This was the single most expensive item in the project.

Aluminum Fabrication

For longevity, aesthetics, and corrosion resistance, T6061 grade aluminum and 316 grade stainless steel were used instead of regular steel (Figure 14). Again, in contrast to conventional frame structures, aluminum masts demand a lot more craft, accuracy, skill and care. Aluminum was cut using a CNC router and welded by an experienced welder. Even in skilled hands, it took two weeks more to ensure absolute precision of mast splice alignment (pipes come in 20' (6 meter) lengths and needed to be spliced to achieve longer mast lengths). Aluminum team had spent days assisting the welder and learning immensely in the process. Aluminum, given its ductility and softness, needed to be handled carefully to prevent deep dents and scratches. The studio spent hours polishing aluminum and sealing it for weather resistance.

Figure 14. Aluminum Fabrication.

Rigging

Another distinguishing feature of TFS is rigging (Figure 15). The cables and fittings need to be run through the fabric pockets to form catenaries. Quite a bit of edge treatment and stitching needs to be done after rigging, which requires much forethought. These are the kinds of things that require non-linear process of working, designing, detailing and fabrication.

Once rigged, the fabric sails need to be carefully handled to prevent lash-back of cables as well as fabric damage. Procedures were put in place for proper and safe handling of the fabric after rigging.

Figure 15. Rigged Fabric Sails.

Erection

Part of the legal liability involved the erection process that needed pre-approved sequencing of lifting, hoisting, assembling and pre-tensioning on site. Although the whole erection process was only four hours in duration, much preparation was necessary. This is also a step where the pedagogy of TFSs differs from that of non-tensile structures (Figures 16, 17, 18, 19, 20 and 21). Enormous amount of organization, thinking, ordering, rehearsals were necessary. The contractor, who had assumed the liability of the erection process, had pre-approved the sequencing and erection. All the nuts and bolts were to be packaged with special coding that referenced their location and sequence number. The packets were then distributed on site to match their location. It was more like a theatrical act of bringing things together and orchestrating the movements of students and crane operators in the field. To prevent injuries, the whole sequence was rehearsed once.

Figure 16. Rear Entry UTenSAil Mast Erection.

Figure 17. Sail Installation.

Figure 18. Front Entry UTenSAil Erection.

Figure 19. Finished Structure.

Figure 20. Finished Structure.

Figure 21. Finished Front Entry UTenSAil.

Conclusions

At a time when the hegemony of specious curvilinearity has taken hold of novice and professional "form-givers'" imagination alike, tensile fabric structures present a different set of opportunities and challenges to design-fabricate-build studios. More importantly, a pedagogy based on a deeper understanding of the differences, nuances and logistical peculiarities of tensile fabric structures is important to the education of the next generation of designers. Forming and formulating the studio as an institution to tackle these challenges is an important first step. It is also important to understand the peculiar pacing of TFS projects, which differs radically from conventional structures that use "gradual accrual" construction process. Collaborative processes are essential to the success of TFS projects. Finally, the most difficult task of all is to help the students unlearn their misconceptions and the inertia of imagination.

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Company	Sponsorship	Location
A. B. Chance	Helical Earth Anchors	Kansas City, MO
American Earth Anchors	Earth Anchors	Franklin, MA
Astrup Company	Ferrari PVC Coated Fabric	Dallas, USA/ France
Bruni The Weldor Inc.	Aluminum Welding	San Antonio
The Chism Company	Fabric Fabrication	San Antonio
Comet Signs	Aluminum Cutting	San Antonio
Constructors and Associates, Inc.	General Contractor	New York/ San Antonio
Dazian LLC.	Lycra IFR Fabric	New Jersey, NJ
Delta Prime Specialties	Anchor Installation	Corpus Christie
Fiesta Bolt Co., Inc.	Stainless Steel Hardware	San Antonio
Garces Metal Specialty, Inc. SS	Welding, Stamping, Water Jet	San Antonio
Hayn Enterprises LLC.	Back Entry SS Rigging	Rocky Hill, CT
Hendee Enterprises Inc.	Aluminum Donation	Houston
Hiraoka and Co., Ltd.	Red PVC Coated Fabric	Japan
Home Depot	Misc. Hardware	San Antonio
Lawrence Calvetti, PE	Foundation Engineering	San Antonio
Lowe's	Misc. Hardware	San Antonio
Meliar Design	Membrane Structures Software	London, UK
Rich Thorsten, PE	Helical Anchor Engineering	Houston
Robert Harper, AIA,	PE Engineer of Record	San Antonio
Ronstan International Inc.	Front Entry SS Rigging	Miami, FL

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Table 1. Partners and Sponsors

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