Pushing the Boundaries: Lessons from a Tensile Membrane Design-Develop-Build Studio

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1 Curvilinear to Nonlinear

In the face of specious curvilinearity that is in vogue at present, tensile membrane structures present genuine, dynamic and novel architectural possibilities (Koch and Habermann 2004; Koch 2004b; Drew 1976; Nerdinger 2005). Tensile membrane structures are more than curvilinear: they are nonlinear in every sense of the word. And the nonlinearity permeates pedagogical issues as well as technical issues.

The dynamic formal and functional possibilities offered by TMSs have been largely ignored by North American circles compared to the European and Asian professional communities (Senagala, 2006). Of dozens of design-build studios taught in the US, not even a handful are dedicated to the exploration or integration of these advanced systems. Moreover, many myths and misunderstanding about TMSs plague even seasoned professionals and professors.

There are, sadly, no documented precedents that deal with the pedagogy of teaching a tensile membrane design-build studio in North America. Pedagogy must be closely aligned with the nature of materials, structures, and fabrication processes. This paper clarifies some common misunderstandings, and identifies the peculiarities of working with tensile membrane systems in an academic design-build situation. The paper presents the lessons learned from a tensile membrane structure design-develop-build studio conducted in partnership with twenty-four trade and professional organizations, including four engineers. The projects were collectively named *UTenSAils*.

There is one more level of argument that the author wishes to overlay in this paper. That is to do with the notion of boundaries. Boundaries of four kinds: formal, functional, pedagogical, and disciplinary. As the paper will try to show, some of the boundaries that we, working within architectural discipline, normally accept either by choice or by imposition, are questioned when new technologies are brought to bear. This has been proven true in the cases of digital fabrication techniques and parametric modeling in contemporary architecture. New alliances, contracting structures, new types of consultants (such as software), and changing ownership of the know-how could be noticed in projects by Frank Gehry and others. TMSs demand pushing the conventional boundaries further and fostering new collaborations, modes of thinking and working beyond the aforementioned transformations that we have been seeing of late.

One important aspect of these particular projects (UTenSAils) should be kept in mind: we were our own developers in addition to being the designers and builders. This crucial distinction has enabled us to gain more control, along with more risk, over the project and process, and taught us the rewards of entrepreneurial approaches to architecture. But that is a subject for a different paper.

Figure 1: UTenSAils detail.

2 A STRETCH OF IMAGINATION

Students, and even seasoned professionals, enter the world of tensile and membrane structures with many misconceptions. The first step of teaching a studio with this focus was to devise exercises and lectures that dispelled these misconceptions through knowledge-building as well as experiential learning. Conventional pedagogy in architectural schools focuses predominantly on frame and load-bearing structures (stick-built). Such techniques as solid-void studies are typically used. Tensile membrane systems demand different kinds of imagination, processes and methods. TMSs have proven to be a definite challenge to even the most advanced students entering the studio. If stick-built thinking could be likened to the forgiving artistic media of oil painting, TMS thinking could be likened to water color media.

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 TMS 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 membrane 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 membrane is no more than 0.02%.

These material challenges make the modeling and form-finding of the TMSs very interesting. 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 membrane 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.

TMSs are technologically advanced and demanding structures in terms of employing computational tools. Conventional design approaches and methods have proven to be quite useless in the case of TMSs. In the UTenSAils studio, 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 nonlinear forces. Until physical models were used in combination with computational tools, the students were at sea in the TMS design process. The fact that every detail in a TMS project had to perform "structurally" under pre-stress conditions as well as dynamic loading conditions made it all the more challenging. Compared to stick-built structures, there is lesser room for error, and more demands on accuracy, coordination, and construction timeline.

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 membrane systems.

3 WORKFLOW OF TMS DESIGN AND FABRICATION PROCESS

It is important to understand some of the material, procedural, and structural peculiarities of TMSs in order to understand why they require different pedagogical and architectural strategies. Design, fabrication, and erection of TMSs involve the steps shown in the table below.

Design	1	Form-finding
	2	Stressing
	3	Compensating
Fabrication	4	Paneling
	5	Stamping
	6	Cutting
	7	Sewing and Welding
	8	Rigging
Erection	9	Anchoring
	10	Erecting

Table 1: TMS Workflow.

3.1 Form-giving to 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 TMSs. 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. Moreover, the stress distribution changes nonlinearly with any changes in any of the parameters such as catenary curvature, surface curvature, prestress, wind loads, membrane materiality, cable systems, and so on. This process demands discipline. Form-finding, in the case of TMSs, 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 of minimal surfaces, the final models were made out of non-stretch cloth 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 membrane structures.

Typically, 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 membrane 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.

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

3.2 *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 membrane to be held in place without any other mechanical means. Shown here is a sail cutter in The Chism Company that we used to CNC cut the panels.

Figure 2: Membrane Cut to Pattern.

3.3 *Microwave Cooking*

As unbelievable as it might sound, certain industrial fabrics used in the tensile membrane industry can be “welded” instead of being sewn. Whereas sewing actually weakens the joint a bit and leaves the possibility for tears, welding almost doubles the strength of the joint. Moreover, welding is enormously faster than sewing. PVC-coated membranes can be welded using Radio Frequency (RF), sometimes referred as High Frequency or Dielectric Welding. In this process, two PVC edges are fused together using HF (13-100 MHZ) electromagnetic field. It takes less than ten seconds to weld. Shown in figure 3 is the students working on The Chism Company’s RF Welder.

Figure 3: Radio Frequency Welding of Membrane Panels.

3.4 PROJECT DESIGN PROCESS

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 TMSs, one more challenge is added: to unlearn “broad-based stick-built thinking” and embrace “tensile-structural thinking” with an emphasis on minutest details. In our case, we took on yet another and daunting challenge of raising our own funds for the project. So, we were our own developers. We started the semester with a single dollar as our starting budget and ended with nearly $103,000 worth of sponsorships.

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? 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 such studios, we normally notice that most of the student work looks alike or resembles the work of the teacher. In the “firm” or think tank 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. Research and exploration of the unknown becomes a big part of the studio’s activities. The professor facilitates learning and leadership as a main partner.

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 infatuation with the projects*.

Moreover, the firm was divided up into task-based teams: aluminum team, membrane 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. Ensuing a successful fundraising strategy implementation, we had an overwhelming response from the industry. Donations of materials and services worth nearly $103,000 were received. Of the two structures, one structure was chosen to use PVC-coated polyester membranes. The second large structure was selected to use PTFE fabric, which has a 40% transparency.

In consultation with 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.

Initial models, which did not include the specific material characteristics, gave way to more accurate models that took into account membrane 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 their MPanel software were put to a rigorous test during the design and fabrication process.

3.5 Mockups

One of the lessons in design-build process was *not* to finalize any detail or authorize any final 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. Rigorous mock up process has helped us catch the mistakes early enough.

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. Thus, securing the services of a water-jet cutter was important to be scheduled.

3.6 Pacing the Project

TMS projects have different rhythms through the design, fabrication, and erection process. These rhythms have serious implications to pedagogy and task scheduling in the studio.

First thing is to watch out in TMS 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 TMSs, 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 differed 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.

3.7 Aluminum Fabrication

For longevity, aesthetics, and corrosion resistance, T6061 grade aluminum and 316 grade stainless steel were used instead of regular steel. 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.

3.8 Erection

Although the whole erection process lasted only four hours in duration, much preparation was necessary for weeks. This is also a step where the pedagogy of TMSs differs from that of non-tensile structures. 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. And contributed four construction workers. All the nuts and bolts were 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, or staging a drama, of bringing things together and orchestrating the movements of students and crane operators in the field. To minimize risk of injuries, the whole sequence was rehearsed once.

Figure 4: Finished Structure.

Figure 5: Finished Structure.

3.9 After Word

At a time when the hegemony of specious curvilinearity has taken hold of novice and professional *form-givers'* imagination alike, tensile membrane structures present a different set of opportunities and challenges to push the boundaries. TMSs deserve greater attention and exploration in the North American academic circles of architecture. While the push for stick-built digital fabrication techniques have begun reconfiguring architectural practice and the resurrection of the notion of "master builder", it would be a shame to limit architects and designers to be just master builders. If there is one thing that the UTenSails projects have shown us, it is the importance of pushing the practice boundaries into becoming, in addition, "master developers". TMS thinking enables us to make new connections (pun intended) with industries and professionals that we seldom connect with. Collaborative processes are essential to the success of TMS projects. It also enables us to push the boundaries of many conventional practices in the studio and the design and construction process. A pedagogy based on a deeper understanding of the differences, nuances and logistical peculiarities of tensile membrane structures is important to the education of the next generation of designers.

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Partners and Sponsors

Company	Sponsorship	Location
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