TECTONIC FORM MAKING

Search for a New Approach into the Investigation of Fabric Structures

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INTRODUCTION

Today architectural fabrics are used for a variety of applications including amphitheaters, sports venues, retail malls, auditoriums, museums, hotels, transportation terminals and commercial buildings. Perhaps the most famous of these is the Millennium Dome (Figure 1), in Greenwich, England.

Despite the wide use of these materials, inadequate structural modeling tools create engineering and design limitations. It is anticipated that with a proper understanding of the behavior of these materials, their use would likely increase 10 fold, to a market value of over $20 billion, internationally.

Figure 1. Millennium Dome in Greenwich, England.

Currently structural analysis is performed on a rudimentary level, and much emphasis is placed on experiential knowledge. The objective of this research is to enable optimization of architectural fabric design by developing the necessary structural analysis models in general. In particular, the objective is to develop an understanding of the mechanical behavior of nonlinear anisotropic fabrics under tension and create a spatial vocabulary and grammar for architectural structures.

To accomplish this goal, various fabric configurations were designed, modeled, visualized and fabricate. The structures involved in this study focused on knitted fabrics with high extensibility in all directions. Knitted fabrics were chosen for two reasons: the use of these highly extensible materials allow design of complex, organic forms that cannot be realized with traditional glass/Teflon fabrics, and the modeling of such materials is vastly more challenging.

To this end, four different experimental structures were assembled, digitized, and visualized, providing both physical and digital models of the systems. The structures combined different architectural configurations as well as different fabrics with different mechanical response. Apparati were designed and fabricated which allow quantitatively variable tension parameters in a consistent manner allowing equitable comparison amongst different fabric structures. Visualization was performed using photographic techniques as well as 3D rendering software in order to develop an understanding of the mechanical behavior of nonlinear anisotropic fabrics under tension and create a spatial vocabulary and grammar for architectural structures.

At present, the researchers have attempted to characterize a new family of fabrics for potential application in architectural structures and the development of a new type of fabric structure configuration were realized. The new fabrics have been tested for overall suitability and further environmental capabilities will be investigated in the coming year. The new architectural module provides an interesting alternative to the traditional approach of rectangular parallelepipeds defining space.

STATE OF THE ART

The Millennium Dome (Figure 1) represents the highest level of structural demand on a fabric to date. This 320-m diameter dome is the largest fabric structure ever built, constructed by a team of the world's leaders in structural design, fabric architecture, and fabric manufacturing (Buro-Happold, ChemFab, et al.).

Although state- of-the-art, the computer modeling used for the Millennium Dome is still limited in its capabilities, and has led to dramatic errors in the size of the entry ways, resulting in costly scrap fabric and even more expensive delays in construction. These errors were related to the inadequate modeling of the anisotropic behavior of the PTFE/Glass woven fabrics. It was determined by Buro-Happold that a change in cutting angles on the woven fabric resulted in the structural errors.

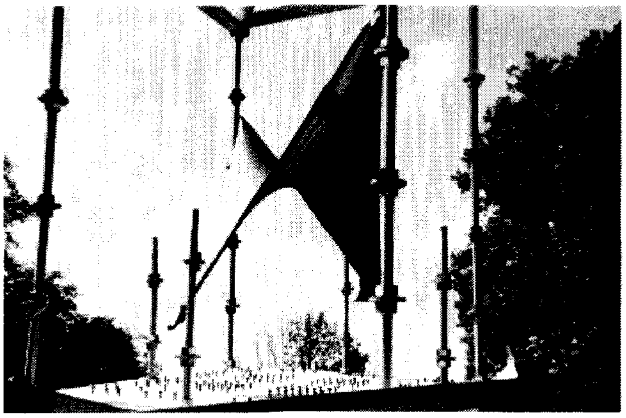


Figure 2. Apparatus and knitted 2/2 configuration fabric.

A review of cutting edge software for the fabric structures industry (*Fabrics and Architectures*, Sept./Oct. 1998) reveals a lack of theoretical rigor in the state of the art. Most of the software used in based on simple models of homogeneous materials that do not correctly account for fabric properties. This is not surprising as the developments in form finding software have their roots in finite element methods, which find their solutions through strain continuity conditions at the boundaries, and require that material properties be expressed in terms of positive definite material matrices.

In reality, fabrics are non-linear, fully anisotropic, membrane systems. Further, the degree of anisotropy depends on the loading conditions. Thus stretched fabric structures will have varying elastic properties and degrees of anisotropy throughout their surface. Even more challenging to accurate modeling is the fact that for fabrics, shear modulus is independent of tensile modulus, and bending stiffness cannot be predicted as EI. Both of these features of textiles, while making them useful materials result in a material response which cannot be modeled using a positive definite material matrix. Correct modeling of these materials will require appropriate software to account for these seeming anomalies.

A significant amount of research into the response and analysis of membranes has developed from work carried out by Adkins and Rivlin[1] and successors. One of the more interesting approaches to this problem would be the application of Cosserat mechanics to the fabric structure. It is possible to use such an approach to address the independence of tensile and shear modulus, but current modeling techniques are not able to handle such material response descriptions.

For experimental measurements, membrane structures require non-invasive, non-contract methods. The grid and Moiré methods have been used with some success (Chiang et al.[2]).

THE ARGUMENT: THE NEED FOR A NEW DIRECTION

The Master Mason during the Gothic period was well educated in mathematics, geometry and philosophy. He approached stone using these skills and tried to maximize the ability of what the stone could do as an architectural element. He could look at the stone, see the vein, grain, and postulate how to cut the stone, and what its structural function would be within the building. Michelangelo could look at a piece of marble and seemingly defy gravity in work that reveals the inner beauty and maximizes the function of the stone as a sculptural element.

As technology developed, people looked for ways to mass-produce building elements and created man-made objects, such as bricks and tiles. These synthetic stones were intended to optimize the use of the material to create structures greater than were conceived before using irregular, natural materials. This was allowed because the level of understanding of the material properties was increased, and the uniformity and consistency of the materials allowed constructors with less intimate knowledge of materials create satisfactory results.

In the 19th Century, Inspired by Gothic cathedrals, Gaudi used tiles to create composite structures. The way he modeled curvature as well as the overall behavior of structures was to stretch fabrics and observe their behavior to model stress flow.

At the turn of the 20th Century, using the technologies developed by Gaudi, the Castovino Dome system of laminated composite tiles was first applied in Philadelphia, resulting in the first example in the world with nested domes – one dome serving as the flooring for the rotunda contained within the outer dome.

For at least 5,000 years humans have been using membrane structures (skins or fabrics) to define space and create shelter. However membrane structures were not maximized for their performance. This was partly due to the fact that skins are inherently small, and that the materials available to them were not of high tensile strength. Fabrics were primarily used to an outer skin that drapes over a skeleton structure. The skeleton provides most of the structural performance.

The science of tensioned fabric structures was documented and pioneered by Frei Otto[3] starting in 1957. Tension structures use fabrics as the primarily structural element. There is no draping over skeletons, rather the tension built up in the fabric membrane surface defines the space while providing shelter and other structural aspects. The guiding principle behind these structures is the minimal surface principle, such as that displayed by hyperbolic paraboloids (so called "monkey saddle") observed in materials such as soap bubbles and other minimal surface materials.

The study of soap bubbles[4] (Figure 3) led to the understanding

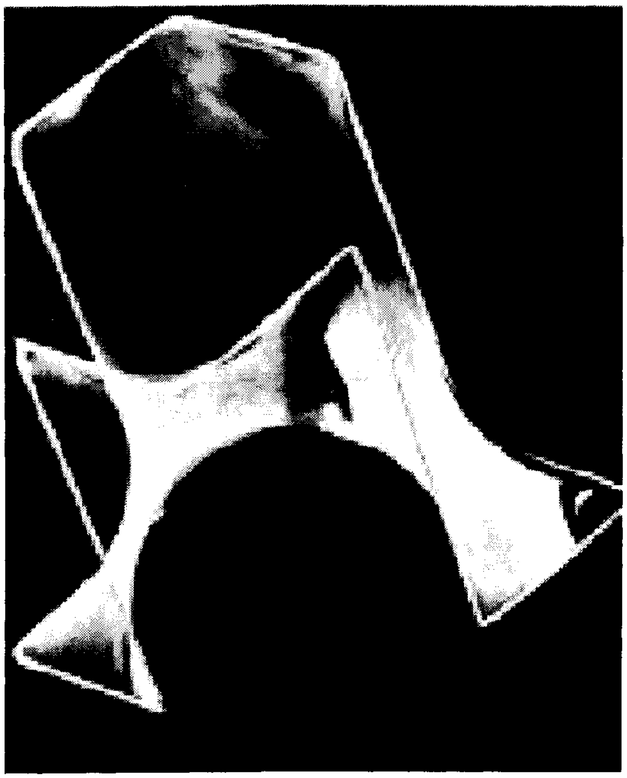


Figure 3. Experimentation with soap bubble membranes.

of the behavior of hyperbolic parabaloids as spatial hexagons. This led to applications using composite materials. Robert LeRicolais[5] developed similar ideas using steel meshes, using the term "monkey saddle" to describe these forms. Much tension structure follows this metaphor. A limitation of this approach is the inherent assumption that the membrane material is isotropic. Fabrics are not. The result of this is that much of the modeling of complex tension structures is wrong, as demonstrated in dramatic examples such as the Millennium Dome in London, wherein much effort was spent correcting mistakes from analytical models.

To date, modeling in the industry is based on the assumption of isotropic, linear elastic materials. To exploit the potentials of tension structures, it is essential to develop more rigorous and correct models of fabric behavior. Such models allow a comprehensive investigation of the opportunities available. With such models, fabrics can be optimized for particular uses and new architectural forms can be generated.

Even acknowledged fabric architecture experts, such as Horst Berger[6] can only describe fabric architectural structures as mimicking the behavior of **isotropic**, **weightless** membranes. Clearly these assumptions are incorrect for real materials (which have mass), and particularly textiles, which are generally orthotropic, and can express anisotropic behavior when subject to non-uniform displacement or shear, such as that experienced in the construction of fabric architectural systems.

The unfortunate result of this lack of rigorous understanding of fabric behavior is that the actual forms generated by modeling do not match the form that the particular fabric will or can generate. The result of this is either wrinkling, failure, need for modification on-site to compensate for the miscalculations, and, even more distressing, the degeneration to simplified, common forms not expressing the opportunities for creativity that fabric structures offer.

To explore the response of anisotropic materials in tensile structures, different fabrics of similar areal densities but different degrees of anisotropy were evaluated and formed in structures with similar boundary conditions. The resulting forms were markedly different reflecting the response of the anisotropy to the boundary conditions and the volumetric enclosure.

RESEARCH APPROACH

This work is structured in four phases. The initial phase addressed characterization of material, generation of basic forms, and characterization and visualization techniques for these forms. The second phase addresses the development of new fabric materials that have unique characteristics suitable for the design of high efficiency tension structures. The third phase was the initiation of a new vocabulary and grammar for a modular tension structure that can be varied in many ways to define space. This is accompanied with visualization techniques to evaluate the forms and fabrics. The fourth phase is the construction of a prototype for long-term testing.

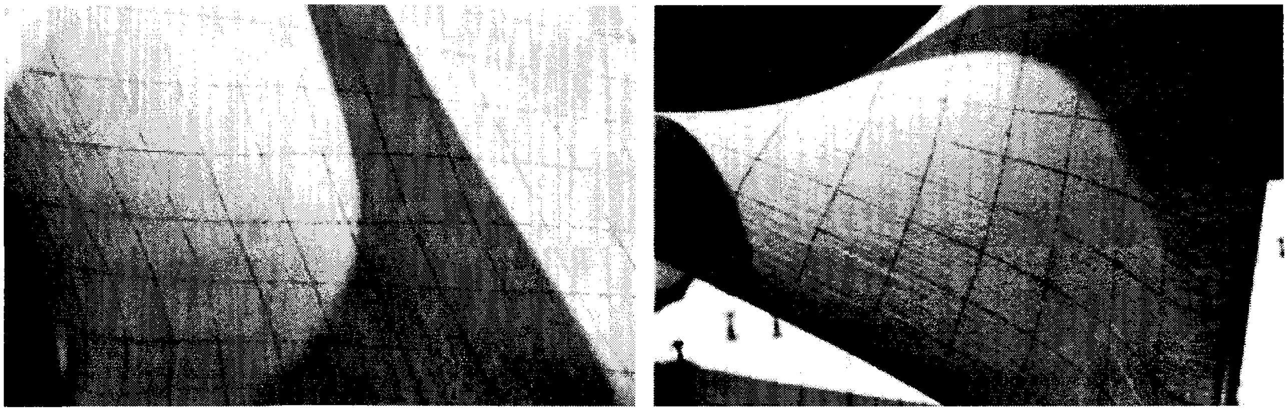
PHASE I: FABRIC CHARACTERIZATION

The first phase of this research involved the characterization of fabrics both in terms of mechanical properties and form finding properties. The forms were digitized to capture geometry, and this geometry was visualized to evaluate the resulting enclosed space.

In characterization, an evaluation of fabrics used currently for architectural structures (woven PET, WIWK PET, woven fiberglass, woven ePTFE, woven PVDT, "stretch" fabric) as well as novel fabrics developed in this research activity, including specially designed weft knitted structures was performed. These fabrics were characterized in terms of basic mechanical response (tensile, shear, bending, multi-directional stress). These fabrics were also characterized in terms of

Figure 4. Images of polyester jersey knit fabrics stretched in 2/2 configuration.

A new vocabulary of form develops as a result of the experimentation and analysis. It is important to be able to communicate this vocabulary to the wider audience, and to this end, a visualization task has been added to the proposal.



their ability to create new types of architectural forms.

In visualization, the issues of how to share images, designs and ideas for new fabric structures research are explored. Animations are used to assist the layperson in understanding the complex dynamics of how fabrics structures are conceived and built. Multimedia brings these ideas to life by adding color, light, sound and interactivity. Interactivity permits virtual walk-through and geometric parameter variations. The overall benefit of developing these areas in relationship to fabric architectures is to promote ideas, construction techniques, innovative fabric, building concepts and research projects to the larger design and manufacturing community.

Once the fabric models were assembled, a physical three-dimensional digitizer was constructed. This device included a gravity driven planar locator and a vertical rule for determining the z-coordinate. The digitizer was aligned with the grid on the fabric using a penetration probe to ensure proper placement. Using this device the x, y, and z coordinates were recorded for each corresponding intersection mark on the fabric.

Meshwork, a three-dimensional trimesh modeling program for Macintosh was used to transfer the data obtained from each model to a digitized picture. The coordinates obtained from the models were entered into a document file as the vertices or vertex points in three-dimensional space. In order to obtain the edges and faces of the model a computer program was written to calculate the connection between two vertices and further connect three edges to form a triangle. After the output of the computer program and the coordinates were completed the file produced a three-dimensional digitized model in *Meshwork*. This model can now be viewed in several angles as well as rotated and texture mapped to show the original fabric used in the models. Renderings from the digitized data for the beige fabrics are shown in Figure 5.

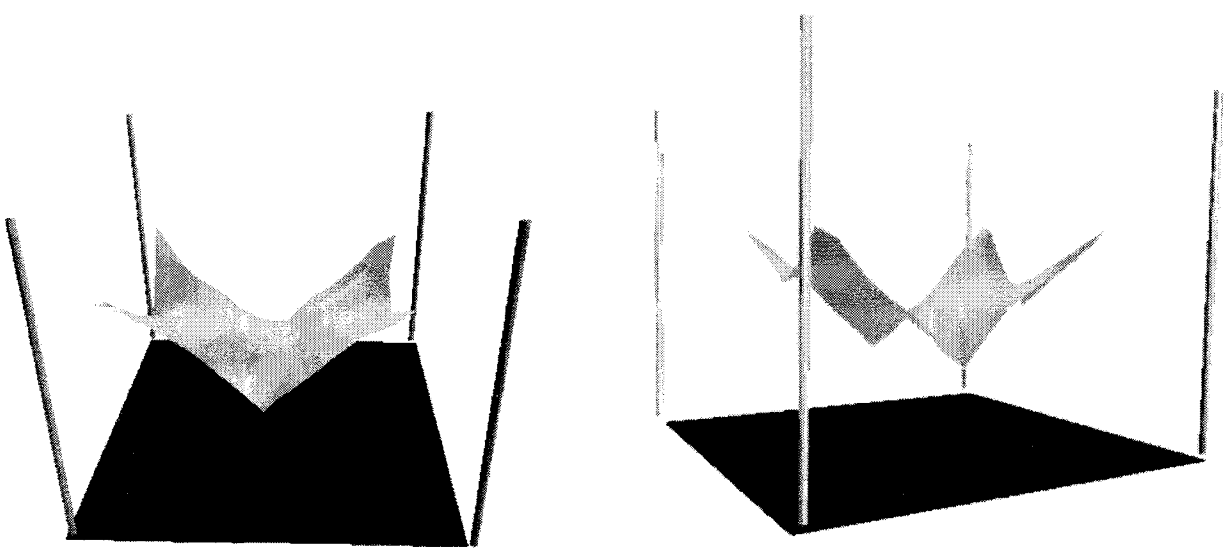


Figure 5. Meshworks visualization of a 4/4 configuration knitted fabric constructed from empirical digitization of the structure.

Initial modeling efforts have been focused on experimental measurements. The techniques described are applicable to any fabrics. Future work will develop predictive models of fabric response to load based on material properties. These predictions will be compared with experimental results such as are described below.

A predictive model of load-deformation response of the fabric subject to external loads will allow visualization of the three dimensional space defined by the tensioned fabric.

The digitized data were used to determine deformations and strains on the fabric. The strains were calculated as

$$e^{w}_{i,j} = \Omega \mathbf{r}_{i,j} - \mathbf{r}_{i,j+1}\Omega / \Omega \mathbf{r}^{\circ}_{i,j} - \mathbf{r}^{\circ}_{i,j+1}\Omega$$

where $e^{w}_{i,j}$ is the strain in the warp direction, $\mathbf{r}_{i,j}$ is the position vector of grid point i,j before deformation, and $\mathbf{r}^{\circ}_{i,j}$ is the position vector of grid point i,j after deformation.

Fill direction strain was calculated in a complementary manner:

$$e^{f}_{i,j} = \Omega \mathbf{r}_{i,j} - \mathbf{r}_{i+1,j}\Omega / \Omega \mathbf{r}^{\circ}_{i,j} - \mathbf{r}^{\circ}_{i+1,j}\Omega$$

The shear deformation angle was determined by considering the corner angles as follows:

$$\cos(g_{i,j}) = (\mathbf{r}_{i+1,j} - \mathbf{r}_{i,j}) \bullet (\mathbf{r}_{i,j+1} - \mathbf{r}_{i,j})$$

where $g_{i,j}$ is the deformation angle at grid point i,j and • is the dot product of the vectors.

For the beige 4/4 construction, the warp strains were calculated as shown below. As can be seen in this figure, there are negative strains apparent near the left edge. Some of the negative value may be caused by Poisson's effect from the fill direction strain, some of this is due to the coarse nature of the digitization, in that curvature of individual grid blocks can appear as contraction, and some of this suggests wrinkling. An observation of the actual structure reveals some small wrinkling in this area, consistent with the calculated strains.

Understanding the creation of three dimensional spaces using tensioned membranes is the objective of this research. Complex forms define these spaces and they are governed by the fundamental nature of the fabric from which they are constructed. Thus specific fabric properties ultimately define a unique 3D form. A model that can translate fabric properties into the potential unique 3D forms inherent to the fabric under consideration provides a strong link between the nature of the material with the creative potential of designers who plan to use these materials.

PHASE II: DEVELOPMENT OF NEW FABRICS

Currently in the industry, woven or warp knitted coated fabrics are being used in membrane structures. The primary requirements for these structures are tensile properties, shear modulus, tear resistance, burst strength, and weather ability. The particular mechanical property requirements vary depending on the actual application. Most of the fabrics in current use are either fiberglass or high tenacity polyester yarn coated with PTFE polytetraflouroethylene). The fabrics formed in this way have adequate performance, but are limited in capability due to the relatively high areal density (from the PTFE coating required for clean appearance over time) and the low shear modulus (also from the PTFE coating).

The fabrics under investigation in this section of the report were designed to be lighter and have lower shear modulus to allow more flexible design of architectural structures. We have chosen to explore knitted fabrics because they are relatively unknown to the industry and thus require further investigation. Knit fabrics are also highly extensible fabrics, with low shear modulus and markedly nonlinear stress-strain response. However, these fabrics are very intriguing for architectural applications because they can be manipulated to create shapes that cannot be reproduced by woven fabrics.

Industrial interactions during this past year have allowed us to expand on our selection of available materials. W.L. Gore has been quite interested in our work and we have bee collaborating with them

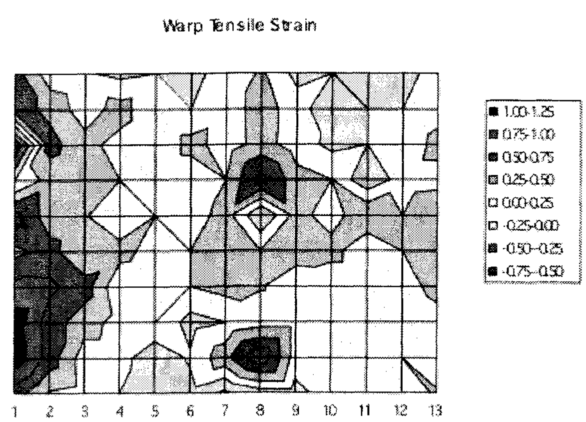


Figure 6. Calculated warp direction tensile strains in beige 4/4 fabric.

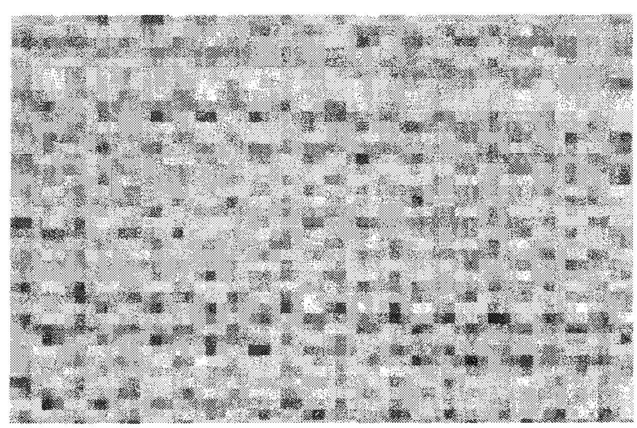


Figure 7. Weft knitted fabric from ePTFE continuous filament yarn

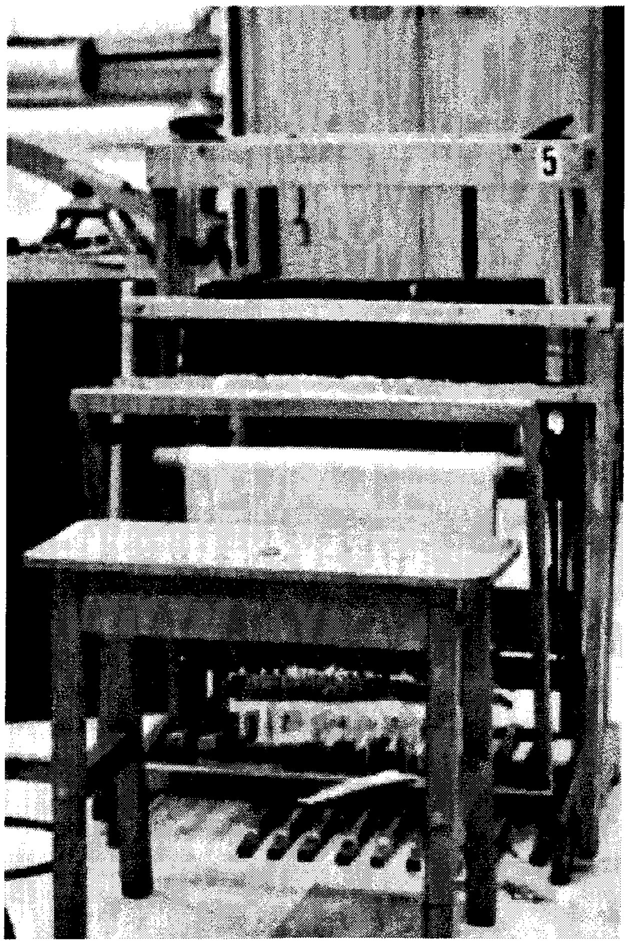


Figure 8. Hand loom used for production of woven ePTFE fabrics

on application of a new fiber/yarn for the architectural industry called Tenara® (ePTFE). Tenara® is an ePTFE fiber than can be formed into a yarn using slit film techniques. Both regular and high tenacity versions are available. Gore has experimented with converting this to woven fabric and has had good response from the community. Compared to other fabrics used in the industry, it offers more textile aesthetics while maintaining the characteristics and longevity of other coated fabrics. They can be utilized in a wide variety of uses including indoor and outdoor structures although up to this date Gore had not knitted the fibers into fabric.

Upon receiving Tenara® yarns, we weft-knitted fabric from them using a Master Sampler Electronic Circular knitting machine. Two types of Tenara® yarn, a high tenacity 400-denier (HT400d) yarn, and the regular 400-denier yarn were converted to knitted fabrics at nominally 26 courses per inch and 40 wales per inch, in a plain jersey configuration. A micrographical image of the fabric is shown in Figure 7.

To provide a baseline comparison, the 400 denier Tenara® yarn was also woven in a plain weave configuration using an 8-harness loom, (Figure 8) formed at nominally 43 ends per inch and 43 picks per inch (Figure 9).

For mechanical characterization, the fabrics were subject to ball burst experimentation. The results shown in Figure 10 indicate that the knitted fabrics have a significantly higher load to burst than the woven. This is not surprising, considering that in a knitted fabric the higher degree of yarn mobility allows multiple yarns to respond to the load, whereas in the woven fabric there is less reorganization to handle load sharing. Also, there were some inconsistent results in the woven fabrics due to slippage of the fabric in the mount. The relatively low burst strength of the high tenacity yarn formed into the knitted fabric requires further investigation. It is possible that the lower strain to failure of this yarn reduced the yarn mobility in the fabric. Currently testing is addressing tensile and shear properties and more will be learned about this behavior.

Preliminary testing to quantify water and air permeability suggests that these fabrics have adequate properties for small tent type structures.

PHASE III: DEVELOPMENT OF NOVEL ARCHITECTURAL STRUCTURES

A three-dimensional fabric module was developed based on the assumption that the module could be used in combination to assemble larger scale complex structures. As an analogy one can look at a brick building where the modular brick unit was used to generate a complex architectural environment. One of the basic requirements for the 3-d module was to create a 3-d complex curvilinear surface that approximates a minimal surface structure (monkey saddle). A computer simulation was produced to model various combinations of the module and also to explore the visual effect of different fabrics.

The module itself is derived from connecting the opposite boundaries of a cube. A surface was created by extending lines from the midpoints on the cube in order to generate a hyperbolic parabolic structure. This allowed the ability to construct a complex curvilinear surface using straight lines that define the boundaries of the curved surface while using the midpoint lines as the major defining elements (Figures 11b, 11c). The module is proposed to be 8' x 8' x 8' to be able to use standard lumber for future construction.

Four prototypical 3-D environments were designed that explored the potential of the basic 3-d module. For this phase, we focused on exploring the potential of a smaller unit composed of 4 modules because this was the one most likely to be built in future phases of the project (see Figure 12). The minimum enclosed environment of this prototype will be approximately 12' x 12' x 12'.

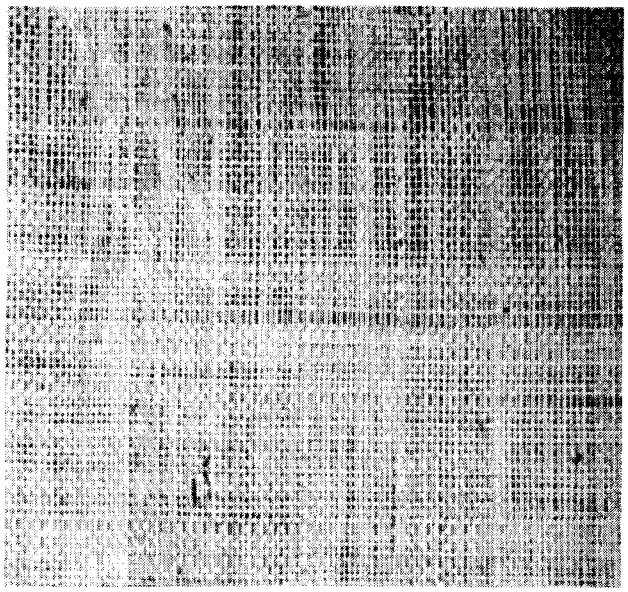


Figure 9. Hand-woven plain weave using ePTFE continuous filament yarn.

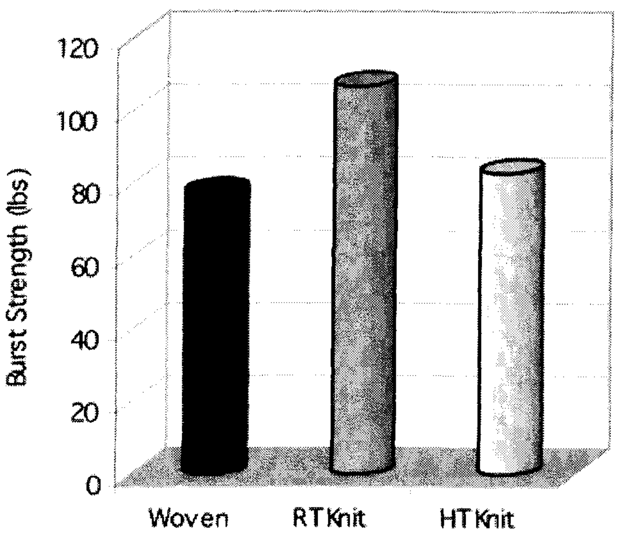


Figure 10. Comparison of ball-burst strengths of the ePTFE fabrics.

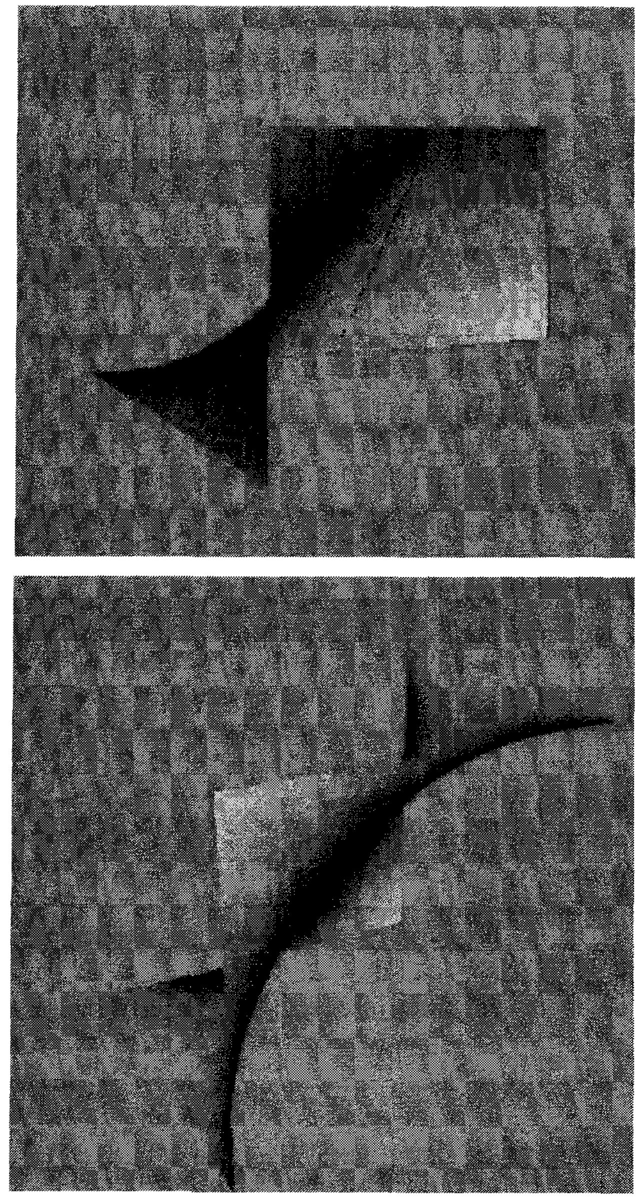


Figure 11a-c. Rendered views of surface of module

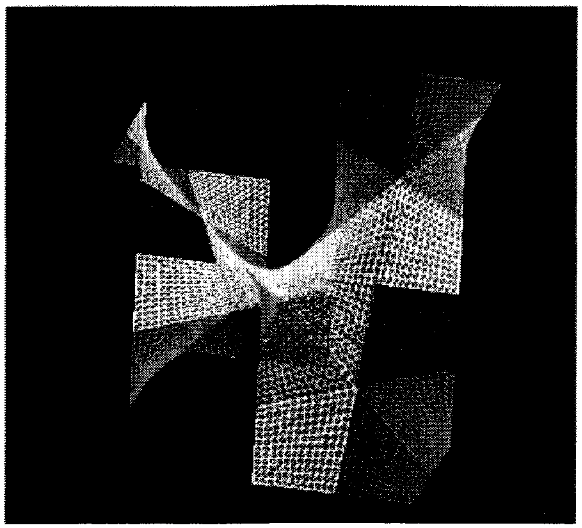
We then assigned different properties to each segment of the module in order to be able to evaluate various types of fabrics (see Figure 13).

This computer model will help us, and others to understand the impact of various fabrics on the environment by manipulating the use of light, color, texture, and transparency values (see Figures 14 & 15)

The computer model will help us to construct a full scale prototype that will evaluate various fabrics in the real environment dealing with elements such as wind, snow, rain, solar radiation, human interaction/perception. The impact of texture, color, shading qualities will also be evaluated and documented. In the future fabric manufacturers will be invited to experience the environment, leading towards test of specific fabrics that possess potential for exterior application.

PHASE IV: CONSTRUCTION OF A PROTOTYPE FOR LONG TERM TESTING

The purpose of this phase is two-fold: to provide a framework for long-term environmental evaluation of fabrics developed in Phase II and to develop an expandable, modulated system that can be evalu-



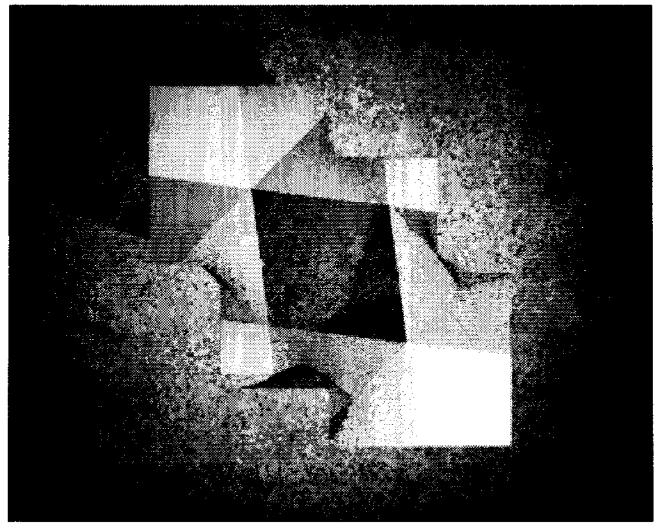


Figure 12. Modular prototype; and Figure 13. Top view of proposed environment w/ artificial lighting

Figure 14 Exterior views

ated for architectural potential based on Phase III. To this end, plans were developed for the construction (Figure 17) and working drawings for building the prototype. Two sites were identified for construction.

The fabric elements of the prototype will vary from panel to panel to allow simultaneous characterization of different fibrous materials identifying both structural performance behavior as well as the three-dimensional form behavior.

CONCLUSIONS

The results of this work demonstrate:

- There is a need to develop better modeling tools to describe the behavior of fabrics in tensile structures allowing greater design flexibility and expanded application of the structures.
- The ability to model tensile structures in modulated form allow exploration of different architectural forms and provide the basis of the development for new architectural vocabulary and grammar.
- The ability to fully understand the response of different fabrics in these structures permits the understanding of the interaction between fabric and enclosed environment, wherein the fabric is a material which addresses other important environmental parameters.

Through this research, the use of fabric structures can be greatly expanded to other architectural applications. Following the brick analogy, there are potential functional uses of modular systems well beyond the original intent. Fabrics can be much more than tents and awnings in architectural applications, and their potential is just beginning to be revealed.

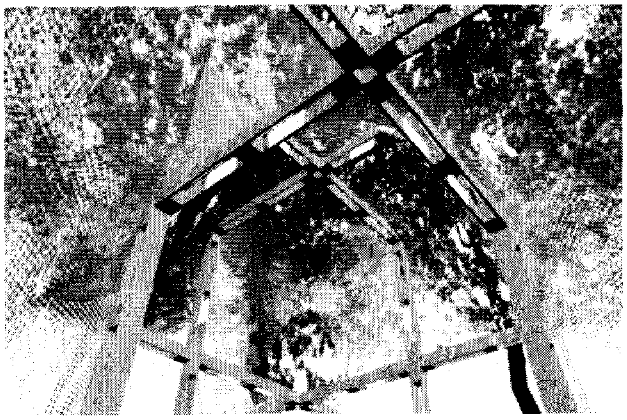


Figure 15. Interior view with different fabrics

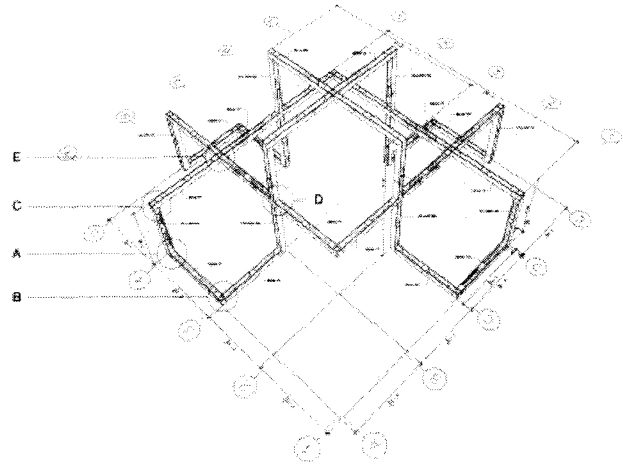


Figure 16. Working drawings for prototype

NOTES

[1]"Large elastic deformations of isotropic materials, Part IX", *Phil. Trans. A* 244, 505, (1952).

[2]"Moire-fringe interpolation and multiplication by fringe shifting", F. P Chiang, V. J. Parks, A.J. Durelli, *Experimental Mechanics*, (1968).

[3]*Finding Forms: Towards an Architecture of the Mininal*, F. Otto & B. Rasch, Deutscher Werkbund Barern, 1995.

[4]*Spatial Arrangement and Polyhedra with Curved Surfaces and Their Architectural Applications*, Michael Burt, Technion, Haifa, 1996.

[5]"Structures et Formes", Robert LeRicolais, *L'Architecture D'Auhourd'hui*, 30 (84) June-July, 1959, pp. 64-68.

[6]*Light Structures, Structure of Light*, Horst Berger, 1996