The history of structural engineering can be viewed as a movement towards lighter structures beginning with heavy masonry arches and domes, transitioning in the 19th century with the introduction of steel and iron, and bringing us to the present modern world, where the development of materials and methods continues to improve our ability to create interesting and unique building spaces. In this way, fabric structures represent the forefront of modern structural engineering, the result of centuries of building history and engineering knowledge. In its short history, fabric structures have fascinated architects and engineers alike. Architects appreciate their unusual shapes and forms while engineers delight in their “pure” structural expression. Appearing as sports arenas,
Con-vention halls, or other publicly-exposed buildings, fabric structures have often been regarded as iconic partly due to their specialized nature and partly due to their short history or lack of widespread precedential knowledge. The design and construction of fabric structures requires both the development of new analysis methods and construction procedures as well as an overall transformation in the way that designers work with fabricators.

Fabric structures possess several advantages over conventional structures. Perhaps most importantly, fabric can span large distances without incurring much weight on supporting structure or foundation. They are capable of carrying large applied loads while weighing very little in comparison to steel or concrete structures of the same spans. This reduction in weight and material translates into shorter construction schedules and overall cost savings.

History of Fabric Structure

The following is a brief review of selected structures and their contributions to the (Source: Berger, 2005) advancement of fabric structure design and construction.

(A) J.S. Dortan Arena, Raleigh, North Carolina

Designed by architects William Detrick, Matthew Nowicki, and engineer Fred Severud, the Raleigh Arena is often cited as the first modern, large-scale, cable-net structure. The famous saddle-shaped roof is made from a set of upwardly-curved cables, which intersect with perpendicular downwardly-curved cables. The upward cables span approximately 95 meters between two intersecting and inclined parabolic arches (Vandenberg). The cable-net roof supports a more traditional roof consisting of rigid insulation and corrugated steel sheets, and creates a 30 meter diameter column-free plan.

(B) German Pavilion, Expo, Montreal, Canada

Designed with architect Rudolph Gutbrod, this structure covers a total area of 8,000 square meters, spanning 130 x 105 meters in two directions (see plan in Figure 4). The shape of the roof is determined by a set of support masts, which vary in height from 14 to 38 meters, and anchor points dispersed throughout the site (German Pavilion, Expo ‘67, Frei Otto).

(C) U.S. Pavilion, World’s Fair, Osaka, Japan

The U.S. Pavilion at the 1970 World’s Fair in Osaka, Japan is one of the first, large-scale air supported structures constructed. The lightweight roof option was first considered because of the site’s poor soil conditions and high exposure to seismic activity. Designed by architects Davis and Brody and engineered by David Geiger, the 139 x 78 meter plan forms into the shape of a super-ellipse, somewhere between ellipse and rectangle.

(D) Haj Airport Terminal, Jeddah International Airport, Saudi Arabia

As the world’s largest roof structure to date, the Haj terminal of the Jeddah International airport features a unique and interesting radial tent design. It was designed by architect Skidmore, Owings, Merrill and engineer Horst Berger in 1981. Here again, one can see how fabric structures are efficient for creating visual interest in a publicly exposed space. For this project in particular, the properties of fabric chosen were of special importance. Located in the middle of the desert, the tent modules were designed to transmit daylight while protecting...
the huge number of people travelling through the airport on their way to Mecca. The structure consists of 210 square tent units, each measuring 45 meters along its edge cable.

Types of Fabric Structure

Though fabric structures come in varying size, scale, shape and form, all of them consist of the same basic elements:

- A lightweight and flexible fabric membrane, tensioned for stability and usually used as a roofing element,
- Flexible linear elements such as ties or cables, which are commonly used at boundaries or edges, and
- Rigid supporting members such as masts, frames, rings, arches, and edge beams, which usually transfer loads in compression

Though there are a variety of ways to categorize tensioned fabric structures, Lewis (2003) divides them into three main groups:

(1) Boundary tensioned membranes,
(2) Pneumatic or air-supported structures, and
(3) Cable-nets or cable-beams.

Fabric Materials

Advances in the design of fabric structures often go hand-in-hand with the development of new, high-performance materials. Materials used for structural fabric satisfy all of the requirements of a typical roof, while maintaining only a fraction of the weight, volume, and cost. These requirements include, but are not limited to, coverage and protection from exterior weather conditions, air tightness, waterproofing, fire-resistance, durability, acoustic and heat-control.

A. Components of Structural Fabric

As implied by their name, the most important and defining component of a fabric structure is the fabric material itself. Structural fabric can be broken down into yarns, which in turn are made of fibers. The basic element of fabric material is therefore the individual fiber. There are a variety of ways to join fibers to create yarn and a number of ways to weave yarn into fabric.

B. Behavioural Properties Of Fabric Materials

A proper understanding of elongation and elastic properties of fabric materials is essential to creating a desired shape. The application of new materials can be frustrating because if one of the properties is not sufficient, it usually requires the development of an entirely new fabric, with different yarns and weaving techniques. Sometimes, the resulting new fabric can have a totally different set of properties than the ones previously specified. Conventional structures often require lower factors of safety because the materials they use have more dependable strength properties. In contrast, fabric materials exhibit unreliable behaviour and low durability, as properties can change drastically over time as a result of weathering, UV degradation, and repeated loading.

Tearing and Tensile Strength

Tearing and tensile strength describe a fabric’s ability to carry load along the plane of the fabric. While tensile strength is a measure of fabric stretching from opposite ends, tearing strength refers to local failure, when forces are applied at one location in opposite directions. The tear and tensile strength of fabric are indirectly related; as tensile strength increases, tearing strength decreases. This relationship is analogous to cutting a string; a taut string is easier to cut than a slack one. Similarly, a fabric that is capable of carrying higher planar stresses will tear more easily.

Stretching and Dimensional Stability

As mentioned previously, the weaving process of fabric results in a material that elongates and deforms a great deal. The main way to mitigate this problem is to pre-stretch or pre-tension the fabric. This can be done to the fabric as a whole before installation or during the weaving process to individual fibers, in which case the force in warp and fill fibers can be adjusted to produce equal deflection in both directions. Fabrics tend to have more strength in the straight, warp direction rather than
the “crimped” fill direction, and can often become dimensionally unstable as a result of crimp interchange. Other factors can affect the dimensional stability of fabric material. These include changes in temperature and water content. Increases in temperature will increase fiber elongation as a function of the material’s coefficient of thermal expansion. Water is bad for fabric materials for a number of reasons. In addition to promoting freeze-thaw action, water also carries microorganisms that degrade the material over time. For these reasons, water-proofing is an important function of fabric coatings. Stretching and dimensional stability are significant considerations because fabric membranes must always remain in tension. If any section of a fabric loses tension, it “bags” and “flutters” and can no longer contribute to the load-resisting structural system.

Ultraviolet Radiation Protection

Many fabric structures degrade with exposure to UV light. Though glass is not significantly affected, tests have shown that polyester loses 20% and nylon 90% of its strength when exposed for 110 weeks. UV protection can be achieved with light-resistant additives in the fiber material or UV absorbers in the coating.

Fire Protection

Fireproofing is a major consideration in the design of fabric structures. Several common fire tests and standards exist for fabrics and other textile materials. These include:-
- The American Society for Testing and Materials (ASTM) E84 - Surface Burning Characteristics of Building Materials (Flame Spread Test)
- E108 - Fire Tests of Roof Coverings

Translucency and Thermal Resistance

Fabric materials feature several properties that render them effective in warmer climates. These include low insulating ability, low thermal mass, high reflectivity of light, and low translucency. Translucency is an important material property of architectural fabrics because it has both aesthetic and technical implications: allowing natural daylight into a building space and resulting in higher energy savings. Fabrics are available in a range of translucency, from as little as 1% to as much as 95%, though the most commonly-used fabric materials can only achieve about 25%.

C. Comparison of Common Fabric Materials And Coatings

PVC Coated Polyester

PVC-coated polyester fabric is the oldest and one of the most commonly used materials on fabric structures. It has a high tensile and tear strength but low durability as it tends to deteriorate from UV radiation. It also exhibits creep behavior, losing significant levels of pre-stress over time and sometimes requiring membrane re-stressing. Their tendency to retain dirt

<table>
<thead>
<tr>
<th>PVC-Coated Polyester</th>
<th>PTFE-Coated Fiberglass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Fiber Tensile Strength</strong></td>
<td>350-1200 MPa</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>800 - 1100 g/m²</td>
</tr>
<tr>
<td><strong>Strip Tensile Strength</strong></td>
<td>3100-5800 N/5cm</td>
</tr>
<tr>
<td><strong>Tear strength</strong></td>
<td>Good</td>
</tr>
<tr>
<td><strong>Stiffness</strong></td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>Creep Behavior</strong></td>
<td>Moderate</td>
</tr>
<tr>
<td><strong>UV Resistance</strong></td>
<td>Coating protects for 10-15 years</td>
</tr>
<tr>
<td><strong>Light Transmission</strong></td>
<td>Up to 22% translucency</td>
</tr>
<tr>
<td><strong>Fire Resistance</strong></td>
<td>Good</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$90-$150/m² (fabric) $400-$700/m² (entire roof)</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>Least Expensive Good Tear Strength</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Relatively low durability</td>
</tr>
</tbody>
</table>

Table 1: Comparison of PTFE coated fibreglass and PVC coated polyester
can be overcome with the application of fluro polymers on top of the PVC coating. Though this material was popular in the 1960's, it has since been surpassed by glass fiber fabrics, partly because many consider its low durability and lifespan of 10-15 years a barrier to application as permanent structure.

PTFE-Coated Fiberglass

Teflon-coated glass and silicone-coated glass fabrics have considerably higher tensile strengths, but poor tear strengths in comparison to PVC-coated polyester. They also exhibit less creep and require minimal maintenance, though water damage is sometimes a serious concern. Because glass is more susceptible to brittle failure, PTFE-coated fiberglass must be handled with care during transport. Silicone-coated fabrics are more flexible and therefore less brittle than Teflon-coated fabrics. It is worth noting that fiberglass is typically much more expensive than polyester both as a raw material and as a finished roof application.

How Fabric Structures Work

Depending on specified boundary conditions and internal prestressing, fabrics can either form into an anticlastic shape with negative Gaussian curvature or a synclastic shape with positive Gaussian curvature. The term anticlastic refers to the opposing directions of perpendicular fiber elements. Joining together to form a saddle-like shape, these elements exert equal forces on each other and internally brace against themselves. Synclastic shapes consist of elements that are curved in the same direction like a balloon. In the design of fabric structures, upwardly curved elements are usually called “ridge” cables while downwardly curved ones are “valley” cables. The minimum number of anchor points needed for any section of fabric is four. Three points are insufficient because the resulting surface is a simple, flat triangle; as mentioned in the previous discussion about cables, fabric elements gain stability with curvature. The four shapes consist of elements that are curved in the point structure is therefore the most basic element of a fabric structure. It can be created with an endless number of boundary conditions and joined together to make a variety of interesting shapes and patterns. Refer Figure below for four point structure.

Analysis Methods - Theory and Methods For Shape-Finding

Analysis models for conventional structures assume a linear relationship between applied forces and displacements. These linear models can accurately describe a structure’s shape, but are limited to a range of small displacements. Conversely, the design and analysis of fabric structures requires a thoroughly non-linear approach, modelling large deformation behavior through the use of iterative numerical methods. The Newton-Raphson method is a classical approach to the analysis of nonlinear structures, which does not apply well to the behaviour of fabric because convergence is slow and sometimes does not happen at all. However, Newton-Raphson works better when an initial estimate of shape or geometry is specified. Newer analysis methods have been developed for the direct application of analysing cable-net and tensioned fabric structures. These include the Grid Method and the Force Density Method, which are both used to estimate initial system geometries before applying Newton-Raphson. Another nonlinear analysis that can be applied to fabric structures is the Dynamic Relaxation Method. The theory behind each of these methods is described in detail in the following sections. Methods used for structural analysis are:

(A) Linear Structural Analysis
(B) Tangent Stiffness Method
(C) Grid Method
(D) Force Density Method
(E) Dynamic Relaxation Method

Construction Considerations

The constructor of fabric structures has a more important role to play than those of conventional structures, because they are dealing with relatively new materials, methods, and technologies. Indeed, fabric roof design is often considered so special that it falls under a separate contract from the main structural system of a building; clients will even sometimes appoint a different structural engineer for the fabric and for the main structure. More often than not, the design of fabric structure is limited by manufacturing capabilities. A fabric contractor must therefore be chosen with care.

Types of Connections

The design of connections in fabric structures often requires careful and thorough consideration. Unlike connections in conventional buildings, they play a crucial role in the creation of architectural form and concept, as the geometry of a fabric roof is entirely dependent on the proper placement and design of these connections. Furthermore, they are often exposed to view and must therefore be constructed with aesthetics in mind. One of the most important considerations when designing fabric connections is the stress concentration that may occur in the local area surrounding it. Being highly sensitive to concentrated
applied forces, clamps, cables, and seams should almost always fully develop stresses into the fabric.

Patterning

Fabric patterning is the construction stage in which large fabric rolls are cut into smaller, two dimensional sections. In the past and up until the 1970’s, procedures for patterning fabric were based on physical models and hand calculations. Today, fabricators use form-finding software as well as geometry monitoring technologies to ensure accuracy in production. The process of patterning becomes complicated when pre-stresses are considered. Because fabric membranes are stretched during installation to produce a certain state of pre-stressing, sections must be cut smaller than their final dimensions, a consideration commonly referred to as “compensation”. The problem is further complicated by the multi-axial nature of fabric material, which generally causes it to elongate more in the fill direction than in the warp direction. Biaxial tests on fabric materials help to determine the compensation factors to be applied for the reduction of each pattern section.

Erection and Installation

Fabric structures are more vulnerable to failure during installation because they are not fully stable until they have been fully erected and tensioned. For this reason, installation periods for these structures should be minimized and construction sequences must be carefully planned. The materials in fabric structure form a hierarchy in terms of stiffness and flexibility. Fabric membranes are more flexible than the edge cables and ties, which are still more flexible than the supports. Typical fabric structures are assembled in order from stiffest to most flexible element; beginning with rigid support members and ending with the fabric membrane itself. In general, rigid frames or masts are erected first, along with rings or structural units that may be located at the top of vertical supports. These members are usually held in place with temporary erection cables and ties until cable and fabric panels are lifted up and connected. Strips of fabric membrane are typically seamed together on the ground and lifted as larger sections

Prestressing

Though pre-stresses in a fabric membrane are typically specified by the designer, they constitute a big concern for the fabric contractor. Pre-stressing is done for a variety of reasons. It can control unnecessary flapping or flutter, which sometimes leads to severe dynamic effects by imposing high forces on the overall structural system. Pre-stress also helps to mitigate the effects of ponding by decreasing the overall curvature of the membrane. Perhaps most importantly, the pre-stress allows the membrane to sustain a certain amount of unloading without losing tension and going slack. Though high levels of pre-stress are desirable for these reasons, there exists a practical upper limit as more accuracy and effort are required in patterning and assembly when pre-stress levels are very high. Typical pre-stress levels range from 2 kN/m to 10 kN/m, depending on the fabric material and the design loads. There are several mechanisms employed to pre-stress a fabric membrane. These vary from simple fabric clamps to tensioning cable and mast systems.

Conclusion

Fabric structures represent a new chapter in the history of building structures. Capable of spanning large distances while incurring very little weight on supporting structure, developments in the design of fabric structure can dramatically change the way we conceptualize permanent building construction. Though fabric materials, computational analysis techniques, and construction methods have come a long way since the first modern fabric structure which was built fifty years ago, there are still several challenges to be overcome before fabric can be considered a viable option for the majority of new building projects. However a better understanding of fabric structures design and construction may one day allow for the extensive and common application of fabric to permanent structures.

Reference

- The Design and Construction of Fabric Structures, Rosemarie Fang, B.S. Civil and Environmental Engineering, Cornell University, 2008
- http://fabricarchitecturemag.com/articles/0409_f2_structures.html