TENSIONED FABRIC STRUCTURES

A Practical Introduction

Task Committee on Tensioned Fabric Structures

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Chapter 2 The Design and Construction Process

2.1 Conventional Organization of the Design and Construction Team

Most buildings constructed in the United States today are designed by a team of engineering specialists working under the direction of an architectural generalist. Their design, once completed, is constructed by a general contractor, usually working with the assistance of subcontractors. The architect and his consultants, often in conjunction with building officials and an owner’s testing agency, oversee the work of the contractor to ensure that it is built in accordance with the design. This approach is often selected because of the generally well-defined roles of the various parties to the design and construction process, and because the designers are directly accountable to the owner and can provide expert representation of his interests in working with the contractor.

2.2 Design/Build Construction

There is a growing trend towards having contractors, through their subs, perform all or a portion of the work on a design/build basis, wherein the architect or one of his consultants provides general parameters and performance standards for a building component, and the subcontractor installing that component is responsible for its detailed design.

There are several reasons for this practice, currently common with such elements as fascia, fire sprinklers, and skylights. Most importantly, building technology has become so complex and diverse that few architects, even together with their consultants, have detailed knowledge of all the elements that comprise a major building. Second, as architects and engineers are increasingly pressed by competition to minimize fees, they look to turn more of the detailed design work over to subcontractors and other parties as a means of maintaining profitability. Third, rising expectation for minimization of risk to property or building occupants are resulting in the need for steadily increasing documentation and validation of building design and construction. Much of this work has fallen on subcontractors. The design/build approach is typically best applied to specialized building technologies in which skills and technical knowledge are not widespread, and in which prefabricated construction and proprietary technology are common.

2.3 Organization of the Design and Construction Team for Tensioned Fabric Structures

The vast majority of contemporary building construction is rectilinear in
its geometry, and the general proportioning and configuration of structural members are fairly predictable to architects with even a modest knowledge of structural design. Since the building’s structure is most often clad in some manner and hidden from view, the architect is typically not concerned with the appearance of structural elements or their detailing.

However, the means by which a fabric roof stands up and the way that it looks are inseparable. Supporting masts typically are left exposed, and steel cables pass through space or lay against the fabric so that they remain visible from either above or below the roof. Even the layout of the seaming of the fabric, selected to minimize material waste and reflect predominant stress patterns, becomes a strong visual element of the design. These seams help the observer to appreciate the shape of the roof, and, depending on their orientation, may serve to visually emphasize radial, circumferential, linear, or other aspects of its geometry.

The unusual structural properties of the fabrics themselves have a great impact on the working relationship between the architect and the structural engineer. Due to their slenderness, fabrics typically have negligible resistance to either bending or compression. Because of these limitations in load carrying ability, the fabric must be shaped in a very precise manner that allows it to carry all applied loads purely in tension. The determination of these shapes is both less commonplace and more complex than determination of the layout of a conventional concrete or steel frame, and the architect is typically dependent on a structural engineer specializing in tensioned fabric structures for assistance in determining the form of the roof.

Among the thousands of structural engineering firms practicing in the United States today, only a handful have staff members experienced in fabric structures, with knowledge of their specialized detailing, and versed in use of the non-linear finite element analysis computer programs required to shape and analyze a tensioned fabric roof.

Some fabric structure contractors have worked to fill this void by offering their work on a design/build basis, with services that range from initial consulting on design concepts and fabric capabilities to determination of precise shapes, stress analysis of fabric and supporting structures, and preparation of detailed cutting patterns for the fabric.

In other instances, the architect or owner retains a structural engineer with specialized knowledge of tensioned fabric structures. This engineer may design all structural elements for the project or may be retained only to structurally design the fabric membrane and related elements. In the latter case, the design of the foundations, walls, floors, and other conventional elements is left to a different
structural engineer, typically one proximate to the building site and already familiar to the architect. The scope of the tension structure engineer’s work may vary, too, from specification writing and schematic design of the roof up to full shaping and patterning of the fabric membrane and detailed design of supporting elements. In the former case, detailed design remains the responsibility of the fabric roof contractor, whose work is generally subject to the review of the consulting engineer.

Whatever the final arrangement of the design and construction team, it is imperative that a designer or consultant with detailed knowledge of fabric structure behavior be involved at the inception of the project, so that a shape is derived which responds to fabric and cable curvature requirements and provides appropriate behavior under load. Lack of such initial input can lead to designs that are, at best, uneconomical and, at worst, infeasible to build.

2.4 Building Department Interface

The lack of widespread knowledge of tensioned fabric structures and the limited recognition of this construction type in building codes pose special problems in interfacing with building officials, problems that are shared by other new or esoteric building technologies. While officials are not inherently adverse to the application of such technologies, they may require a high degree of technical validation from the engineer in order to fulfill their obligation to assure public safety and adherence to building codes.

A number of items of documentation may be required, many of them unique to tensioned fabric structures. These include the following:

1. A general description of the characteristics of these structures, including large deflection behavior and anisotropic material properties.

2. Information required to understand the methodology of shapefinding and analysis computer programs as well as to read and interpret input and output.

3. Reports on relevant fire testing.

4. Shapefinding and analysis computer runs.

5. Calculations for cables and steel or other supporting members.

6. Drawings showing the layout of fabric panels, typical fabric seams, interfaces of fabric with the supporting structure, typical cable details.

2-3
fabric tensioning details, etc.

Other items generated as part of the design and fabrication process are most often viewed as shop drawing type submittals and not subject to review by the building official. These include computer patterning runs, fabric compensation data, steel fabrication drawings, individual fabric clamp and gasketing details, and similar items.

2.5 Conclusions

Tensioned fabric roof structures may be designed either by the design/build approach or by an engineering consultant with specialized knowledge of this technology who is retained by the architect or the owner. The consultant may completely design the roof or may be retained only to provide general parameters and review of the roof contractor’s detailed engineering. The design/build approach offers several advantages. The architect and owner are assured of the engineering services of a party that is familiar with the unique construction requirements associated with the material. Retaining a single source for both design and construction, furthermore, offers at least the possibility for fewer conflicts over responsibility in the event of a problem in the finished product.

Many owners avoid the design/build approach, however, preferring the engineer to work independently of the contractor in order to best represent the owner’s interests and to assure quality control. Design/build work also becomes problematic for those owners who wish to obtain multiple bids for a project rather than negotiate with a single contractor, as it is more difficult for bidders to submit accurate quotations for work that has only been schematically designed. Architects, too, sometimes prefer to avoid design/build construction, in part because it lessens their primacy in the design process.

The appropriate formulation of the architect, structural engineer, and contractor team for completion of a given tensioned fabric roof will in the end be dependant on the qualifications and experience of the parties involved as well as the characteristics of the project itself.
Chapter 3 Performance Considerations

3.1 Loads and Climate

While contemporary tensioned fabric structures have been designed for a wide range of loadings and for climatic conditions found throughout the globe, the nature of membrane construction and the commonly used fabric materials lead to certain generalizations about appropriate design loads and climatic applications.

The load bearing characteristics of tensioned fabric structures are governed by the high deformability of membranes under load, and may be generalized as follows:

1. Dead load from the membrane is generally less than 50 N/m² and hence negligible.

2. Roof live loads are generally intended to account for construction phase loads such as roofing materials that are not relevant to fabric construction. Code provisions generally make no loading exceptions for membrane construction, however, and fabric roofs are therefore typically designed for normal live loads, subject to code provisions for live load reduction based on tributary area.

3. Seismic loads are generally not a factor in design, because of the low mass of the fabric.

4. Wind is often the predominant loading on the fabric roof. The membrane must have adequate curvature and pretensioning to resist wind loads without excessive flutter. The curving forms of the roofs often make adaption of Code formulas for wind loading problematic. Larger or more complex structures, particularly those in highly variable terrain, often require wind tunnel testing for accurate prediction of wind loads.

5. Moderate snowfall can successfully be resisted in structures that have prestress sufficient to prevent large deflections that will lead to ponding, additional deflection, and eventual overload of the roof. Relatively high roof slopes are useful in helping the slippery fabric surface shed snow, and also aid in preventing ponding. Snow melting equipment, usually in the form of a furnace producing forced hot air under the membrane, can be useful in regions of heavy snow load.
6. Point loads such as heavy lights, signs, or scoreboards present special design problems due to the high deformability of membranes. Heavy loads must generally be supported from rigid mast or arch supports or at angle changes in cabling.

The characteristics of most contemporary fabrics: translucency, high reflectivity of light, and low insulating value, have made them most readily adapted to use in temperate or hot climates with ample sunshine. In climates that combine warmth with high humidity, caution must be taken against the growth of mold or algae caused either by condensation or standing water on the outside of the fabric.

While tensioned fabric structures have traditionally provided less favorable energy use in cold climates, the use of liner membranes with dead air space and, more recently, insulated fabrics have improved their performance dramatically. In such climates, measures must often be taken to prevent excessive condensation, particularly for applications such as swimming pools, zoos, or botanical gardens. Condensation is likely to occur when the temperature of the membrane and the relative humidity of the inside air are such that the air on the inside surface of the membrane can reach the dew point. Where this is a possibility, consideration should be given to venting the inside air, installing condensate gutters, or providing an air circulation system.

3.2 Availability of Materials and Labor

Contemporary structural fabrics are specialized, high technology products produced by only a few manufacturers. Nearly all applications require that they be shop fabricated and shipped long distances to the construction site. Because of the light weight and compact form of the fabric, however, this is not a major cost factor or hindrance to their use.

Field erection of the membrane is also a highly specialized activity, and, if not performed by a crew experienced with fabric, requires the direction of an experienced superintendent.

Only a limited number of qualified fabricators and contractors work in the field of tensioned fabric structures, particularly with the fiberglass fabrics typically used in permanent construction. These structures are therefore often constructed under design/build contracts rather than through bidding.
3.3 Spatial Considerations

Variability of form is a hallmark of tensioned fabric construction and roofs can be adapted to fit a wide range of building footprints. Because of the curvature requirements of the membrane, however, tensioned fabric structures typically have fairly tall profiles in elevation, and cannot easily be adapted to the flat roof profile characteristic of conventional construction. Near flat profiles are only possible on small structures or those with a complex supporting structure (such as a space frame) that supports the fabric at close intervals. In the latter type of application, the fabric is more a cladding material than a true structural element.

An attractive feature of tensioned fabric structures is their enormous range of spanning capability. Membranes have been used in a number of applications as an alternative to translucent glazing, using pretensioned fabric without curvature over spans up to about 4 meters. Tensioned fabric supported on arches or other shaping elements is common in skylight applications with spans of up to 15 meters or more.

Fabric has been applied just as effectively in stadiums and other assembly structures with spans of up to 250 meters. In these applications, the fabric is typically restrained or supported by steel cabling in conjunction with air pressure or rigid steel elements, so that the unsupported span of the fabric itself is seldom greater than 15 meters. While air-supported and cable dome roofs can and have been sheathed in materials other than fabric, the fabric provides a significant portion of the strength and stiffness of these roofs, and is integral to their global behavior. Good design of these structures explicitly considers the properties of the fabric, and these roofs are therefore appropriately considered true tensioned fabric roofs rather than fabric clad roofs.

3.4 Aesthetics

Tensioned fabric structures have a unique visual character founded on the following features:

1. Fabric roof forms are curved between supporting elements in a manner reflective of the flow of tension forces within the membrane. With the exception of air-supported or air-inflated structures, these curvatures are anticlastic in nature. The overwhelming majority of contemporary construction is based on rectilinear forms, and the curving forms of fabric roofs give them an inherently dramatic and eye-catching character.
2. Structural, lighting, fire safety, and other elements serving the roof must generally remain exposed inside the space, as the opaque ceilings of most conventional structures are absent. Well engineered structures are sensitively detailed to provide visually "clean" connections that are expressive of the transfer of forces between members. Similarly, lighting and fire sprinklers can often be hung directly from roof cabling or otherwise detailed so that they complement rather than compete with the curving roof form.

3. A wide variety of colors are available in polyester fabrics and fabric strips of alternating color are sometimes used within one structure for dramatic effect. Fiberglass fabrics are currently available only in white, although research is underway to develop colored fabrics.

The inherent visual drama of tensioned fabric structures, primarily a function of their curving form, is a key factor both in their use for certain architectural functions and their avoidance for others. Architects have found both this appearance and the long span ability of fabric particularly appropriate for athletic and entertainment facilities.

In most types of construction, it is common for the structural engineer to defer almost all consideration of aesthetics to the architect. Because of their membrane behavior, however, the forms of fabric roofs can be manipulated only within limited bounds determined by the engineer. The exposure of structural connections in the finished structure, furthermore, makes the detailing of connections by the engineer an important part of the structure's appearance. Because of these factors, the tensioned fabric structure engineer must have a strong sensitivity to aesthetic issues, and is often required to lead the architect towards attractive design solutions.

3.5 Fire Safety

Contemporary tensioned fabric structures have the ability to provide fire safety far better than that of traditional non-synthetic tenting materials. The standard fire tests that have been adapted for use in measuring the fire performance characteristics of these materials are described in Chapter 4. These tests provide the basis for determining the applicability of various fabrics to the various occupancies given in the building codes.

For purposes of the Uniform Building Code, materials which can both pass ASTM E136 and have flame spread (per ASTM E84) of less than 50 qualify as non-combustible and can be used in Type II-N construction. Combustible roofing
materials are restricted to use in Type V-N construction. Additionally, noncombustible materials used exclusively as a roof and located more than 8 meters above any floor, balcony or gallery are deemed to comply with the roof construction requirements for Type I and Type II fire-resistant construction. In general, contemporary fiberglass fabrics are able to achieve the non-combustible rating while polyester fabrics are not.

### 3.6 Energy Use and Lighting

Fabrics in common use are characterized by low insulating ability, low thermal mass, high reflectivity of light, and low to moderate translucency. These characteristics have made them readily applicable to use in temperate or hot climates with high solar radiation. In these conditions, the low insulating value does not result in high heating loads, the reflectivity reduces heat gain, and the translucency can be utilized for natural daylighting, thereby reducing lighting cost as well as the cooling loads resulting from the heat produced by the light fixtures. As noted earlier, liner membranes and insulated fabrics often give tensioned fabric roofs good thermal efficiency in colder climates, although sometimes these measures eliminate much of the translucency of the base fabric.

Daylighting under the white fabrics that are commonly used for permanent architectural applications is characteristically bright and diffused. These features are favorable to applications such as sports facilities, exhibit halls, and atriums or other skylight type applications. Where spotlighting is required or a space must be darkened during daylight, however, translucent fabrics may not be appropriate. The magnitude of daylighting is often altered by varying the translucency of the fabric or adding a liner membrane or insulation.

Fiberglass fabrics coated with either PTFE or silicone are available with translucencies in excess of 20%, adequate to support a wide range of plant growth. A summary of the characteristics of various roofing assemblies is given in Table 3.1.

### 3.7 Acoustic Performance

The acoustical performance of structural fabrics is characterized by high reflectivity of sound vibrations, particularly in the frequency range of 500 to 2000 Hertz. This reflectivity can result in poor sound for musical performances and difficulty in understanding speech. The focused reflection of sound due to the geometrical shape of certain roofs can also hamper acoustic performance, particularly in air-supported structures or arch supported roofs that have a generally concave roof profile from the interior.
Sound transmission loss through fabric is another important consideration in airports or other structures where it is important to shield building occupants from outside noise. Like sound reflectivity, transmission loss is highly dependant on frequency of vibration, with tests on structural fabrics indicating a moderate transmission loss of approximately 5 decibels at 100 Hertz, ranging up to about 30 decibels at 5000 Hertz.

Sound reflectivity can be decreased and transmission loss increased by the installation of lightweight, porous liner fabrics. Fiberglass insulation between the two fabric layers can further increase transmission loss. The effects of such measures on daylighting, insulation, and fire safety must be considered in their selection, however. Vertical banners can also be suspended at intervals under the fabric in order to increase sound absorption and break up the geometry of the curved fabric.

<table>
<thead>
<tr>
<th>Solar Properties</th>
<th>Assembly 1</th>
<th>Assembly 2</th>
<th>Assembly 3</th>
<th>Assembly 4</th>
<th>Assembly 5</th>
<th>Assembly 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectance</td>
<td>10-50%</td>
<td>30-75%</td>
<td>65-75%</td>
<td>60-65%</td>
<td>60-70%</td>
<td>60-70%</td>
</tr>
<tr>
<td>Absorption</td>
<td>50-90%</td>
<td>13-68%</td>
<td>13-19%</td>
<td>12-20%</td>
<td>28-34%</td>
<td>28-35%</td>
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<tr>
<td>Transmission</td>
<td>0</td>
<td>2-12%</td>
<td>6-22%</td>
<td>15-28%</td>
<td>4-6%</td>
<td>2-5%</td>
</tr>
<tr>
<td>Summer (12 km/h Wind)</td>
<td>Varies</td>
<td>0.75</td>
<td>0.81</td>
<td>0.81</td>
<td>0.45</td>
<td>0.08-0.14</td>
</tr>
<tr>
<td>Winter (24 km/h Wind)</td>
<td>Varies</td>
<td>1.15</td>
<td>1.20</td>
<td>1.20</td>
<td>0.54</td>
<td>0.08-0.14</td>
</tr>
</tbody>
</table>

Assembly 1: Conventional Roofing  
Assembly 2: PVC Fabric  
Assembly 3: PTFE Glass Fabric  
Assembly 4: Silicone/Glass Fabric  
Assembly 5: PTFE Glass w/Liner & 250 mm Air Space  
Assembly 6: PTFE Glass w/Translucent Insulation

Table 3.1 (3,4)

3.8 Maintenance, Durability, and Inspection

The durability of tensioned fabric structures and their maintenance requirements represent the combined result of design, materials, construction, and environment. Design factors that influence durability and maintenance include the following:
1. Determination of appropriate loads and accurate stress analysis as required to prevent overstresses in the fabric that may result in tears or other damage.

2. Where structures are located in an unsafe area or on an unsecured site, structures should be configured so that the fabric is not subject to knife cuts or other vandalism.

3. Cables, arches, mast peaks, and other discontinuities in the fabric provide potential locations of stress concentration or abrasion. Care must be taken to provide accurate patterning at such locations, and supporting elements must be detailed to eliminate or protect the fabric from corners or edges that might lead to tears. In some structures, the fabric is reinforced by a second fabric layer at such locations.

The properties of various fabrics are described in Chapter 4 of this document. Ultraviolet (UV) radiation exposure, lighting requirements, fire safety requirements, cost, and the required strength and durability of the structure must all be considered in selecting the appropriate fabric for a particular application.

The degree of care taken in packaging of fabric for shipment to the site and in erecting the fabric are critical to preventing soiling, weakening of the material due to sharp folds, and fabric tears (See Chapter 8). The risk of such damage is partially a function of the material choice, with PTFE-coated fiberglass being generally both most vulnerable to damage caused by folding and most resistant to soiling.

Exposure to ultraviolet radiation from direct sunlight is the primary environmental factor in fabric durability. Polyester based fabrics are generally more susceptible to UV damage than fiberglass-based fabrics, although coatings of Tedlar and other materials have improved their durability. At certain sites, consideration must also be given to soiling effects from air pollution, engine exhaust, or other sources, and to potential abrasion damage from wind-driven sand or other matter.

Properly designed and constructed fabric roofs generally require very little maintenance until such time as degradation from ultraviolet radiation or other sources necessitates replacement of the fabric or demolition of the structure. Roof owners are generally supplied with kits for repair of small tears, and may occasionally require the services of the roof supplier to effect patching or replacement of sections of fabric where more severe damage has occurred.
Periodic inspection by the manufacturer or other qualified personnel is recommended. The scope of such inspections should generally include checking for abrasion of the fabric at interfaces with other elements.

3.9 Cost Issues

In addition to the appeal of natural lighting and dramatic form, a potential building owner's interest in a tensioned fabric structure is often based in part on the assumption that "tent" construction is inexpensive. In reality, the cost of tensioned fabric structures varies widely with the choice of fabric and other parameters, and whether they represent a cost savings or a cost premium is dependent on the type of roof with which they are compared. The costs given for tensioned fabric roofs generally include the fabric itself, cables, masts or arches that support the fabric, and the attachment of the fabric at its perimeter. They generally exclude any foundations, the walls or beams on which the fabric terminates, and any fire safety or lighting items which are added to the roof.

Within the above parameters, the cost ranges for different types of tensioned fabric structures (in 1995 dollars) are approximately as follows:

1. Prefabricated, pre-engineered structures using repetitive forms and vinyl-coated polyester fabric, $75-100/m².

2. Custom structures using vinyl-coated polyester, $150-300/m².


The costs given above may be exceeded in the case of structures with unusually complex shapes or other design features. In addition to choice of fabric, some of the factors affecting cost relative to plan area include the following:

1. Symmetry and Repetition
   By designing the structure with symmetry about one or more axes, and by providing repetitive modules, the analysis, pattern, and fabrication costs can all be significantly reduced.

2. Scale
   Because its dead load is very small and because the cost of fabricated fabric does not vary dramatically with increases in fabric stress, cost per unit plan area does not rise as dramatically with increases in span as it does with conventional construction.
3. Aspect Ratio
Reasonable fabric curvature is required in order to limit fabric stress and cable force, and to achieve stability under wind load. Increases in curvature result in an increase in the structure's aspect ratio: a measure of the relationship between its height and its span. Excessive aspect ratios, however, causes a significant increase in the amount of fabric required to cover a given plan area, as well as in increase in wind exposure.

The most economical structures therefore have an aspect ratio that provides a balance between these divergent concerns.

References

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(2) ASTM E136 Behavior of Materials in a Vertical Tube Furnace at 750 Degrees Celsius.
(3) Chemfab Corporation, product literature for Sheerfill fabrics.
(4) DCI, Inc., product literature for Softglass fabrics.

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