Introduction to Tensioned Fabric Structures

Denver Airport, Denver, CO
Learning Objectives

After listening to this presentation you should be able to:

Â Understand the concepts of analysis, design, fabrication and installation of tensioned fabric structures.

Â Understand the structural characteristics and physical properties of architectural fabrics.

Â Understand the requirement for pretensioning and clamping for the installation of tensioned fabric.

Â Understand the methods for patterning and fabricating architectural fabrics.

Â Identify the practical applications for tensioned fabric structures.
Definition of Tensioned Fabric Structure

A cover or enclosure in which fabric is pre-shaped and pre-tensioned to provide a shape that is stable under environmental loads.
Overview

Background
Structural Characteristics
Materials
Environmental Issues
Performance Issues
Technology
Applications for Tensioned Fabric
Background

Types of Fabric Structures
Conventional Tent
Air-supported Air Fabric Structure
Air-inflated Air Fabric Structures

Figure 1. Air Supported Shelter Types

Section on typical internal pressure air dome

2 - 4 kPa
Air lock entrance

These joints subject to high peel stresses

Cross section through wall of low pressure air beam structure

3 - 6 kPa
Pressure tubes in sleeves attached to outer skin

20 kPa for medium spans up to 12m
500 kPa for large spans up to 25m

Cross section through wall of medium and high pressure air beam structures
Tensioned Fabric Structures
Background

Fabric Engineers – Ancient and Modern
And because he was of the same craft, he abode with them, and wrought: for by their occupation they were tentmakers.

Acts 18:3

St. Paul – Tentmaker
Omar the Tentmaker
Frei Otto

Founded the famous Institute for Lightweight Structures at the University of Stuttgart.

Major Structures:
  Munich Olympic Arena
  Montreal Expo
Horst Berger

Graduated from University of Stuttgart.

Came to USA in 60’s and founded Geiger Berger Associates.

Major Structures:
   Haj Terminal, Jeddah
   Denver Airport
Munich Olympic Stadium, Munich, Germany

1972 Olympics
BC Place, Vancouver, BC, Canada
Georgia Dome, Atlanta, GA
Structural Characteristics

Analysis of Forces
## Structural Behavior

<table>
<thead>
<tr>
<th>Conventional Structures</th>
<th>Fabric Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal rigidity (stiffness)</td>
<td>Form and prestress</td>
</tr>
<tr>
<td>Beams and columns</td>
<td>Cables and membrane</td>
</tr>
<tr>
<td>Load resistance in bending and shear</td>
<td>Load resistance in tension</td>
</tr>
<tr>
<td>Linear behavior</td>
<td>Non-linear behavior</td>
</tr>
</tbody>
</table>
Analysis of Catenary Forces

Catenary with Uniform Load

Catenary with Uniform Load

\[ F = \frac{A l w}{h} \]

\[ = \left( \frac{- + }{+} \right) \]

\[ = \left( \frac{- + }{+} \right) \text{ (approximate)} \]

\[ = \quad \]

\[ = \quad + \]

\[ = \quad \sqrt{\sqrt{\quad}} \]

F = cable force

A = arc length

w = uniform load

l = span length

h = cable sag

E = elastic modulus of cable
Design of the Fabric Envelope

Anticlastic shape

Tension in both directions

Fabric prestress resists the external forces
Analysis

Finite element analysis

Large deflection theory

Balanced forces
Structural Characteristics

Shapes and Anchoring Systems
The properties of fabric limit the range of shapes available for membrane.

- Cone
- Rigid-and-Valley
- Saddle
Supporting and Anchoring System

Hypars

Cone
Supporting and Anchoring Systems

Parallel Arches

Crossed Arches
Supporting and Anchoring Systems

Cones and Hypars
Pretensioning

Jacking columns

Jacking struts
Pretensioning

Pulling roped edges
Pulling catenary cable edges
Connections

Fabric-to-Fabric

Fabric-to-Rigid Edge
Connections

Fabric-to-Cable

Cable-to-Cable
Connections

Cable-to-Mast

Cable-to-Rigid Edge
Connections

Rigid-Sectionalizing
Materials

Substrate and Coatings, Characteristics and Physical Properties
Substrates and Coatings

Fabric Construction
- Conventional Woven
- Flat Weave Fabric
- Open Weave Fabric

Coating Materials
- Polyvinyl Chloride (PVC)
- Polytetrafluoroethylene (PTFE) (Teflon)
- Others (e.g. Silicon)

Substrates
- Filament Materials Substrates
  - Glass Fiber (Fiberglas)
  - Polyester (Dacron)

Top Coating Materials
- Acrylic
- Tedlar Laminate
- Polyurethane
Characteristics of Composite Materials

PTFE Glass Fiber

- White only
- Relatively high manufacturing cost
- Long service life
- Joint strength equal to the fabric strength
- Translucency reflects most solar heating
- Classified as non-combustible

PVC Polyester

- Colors
- Relatively low manufacturing cost
- Short service life
- Requires top coat to prevent UV degradation
- Poor dimensional stability – May require re-tensioning
- Smoke generation is too high for high-occupancy applications
# Physical Properties

## PTFE Glass Fiber

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated Fabric Weight, oz./sq. yd.</td>
<td>ASTM 4851</td>
<td>38-45.5</td>
</tr>
<tr>
<td>Thickness, mils</td>
<td>ASTM 4851</td>
<td>28-36</td>
</tr>
<tr>
<td>Strip Tensile, lbs./inch</td>
<td>ASTM 4851</td>
<td></td>
</tr>
<tr>
<td>Dry, Warp</td>
<td></td>
<td>640-975</td>
</tr>
<tr>
<td>Dry, Fill</td>
<td></td>
<td>640-900</td>
</tr>
<tr>
<td>Trapezoidal Tear, lbs./inch</td>
<td>ASTM 4851</td>
<td></td>
</tr>
<tr>
<td>Dry, Warp</td>
<td></td>
<td>60-95</td>
</tr>
<tr>
<td>Dry, Fill</td>
<td></td>
<td>65-120</td>
</tr>
</tbody>
</table>

## PVC Polyester

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated Fabric Weight, oz./sq. yd.</td>
<td>ASTM D751</td>
<td>28-34</td>
</tr>
<tr>
<td>Strip Tensile, lbs./inch</td>
<td>ASTM D751</td>
<td></td>
</tr>
<tr>
<td>Warp</td>
<td></td>
<td>515-650</td>
</tr>
<tr>
<td>Fill</td>
<td></td>
<td>515-650</td>
</tr>
<tr>
<td>Trapezoidal Tear, lbs./inch</td>
<td>ASTM D751</td>
<td></td>
</tr>
<tr>
<td>Dry, Warp</td>
<td></td>
<td>85-100</td>
</tr>
</tbody>
</table>
Environmental Issues

Thermal and Lighting Prosperities
Thermal and Lighting Properties

Translucence
Daylighting
Backlighting
Insulation
# Thermal and Lighting Properties

## Solar Properties (%)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Conventional Roofing</th>
<th>PTFE Glass Fiber</th>
<th>PVC Polyester Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectance</td>
<td>10%-50%</td>
<td>70%-75%</td>
<td>30%-60%</td>
</tr>
<tr>
<td>Absorption</td>
<td>50%-90%</td>
<td>12%-18%</td>
<td>13%-65%</td>
</tr>
<tr>
<td>Transmission</td>
<td>0%</td>
<td>7%-18%</td>
<td>2%-12%</td>
</tr>
</tbody>
</table>

## R-value

| Flat metal roof with 3 inches of insulation | R-9   | R-1   | R-1   |
Thermal and Lighting Properties

Light intensity and quality

Illumination of roof forms

Effects of dirt accumulation

Solar Transmission
ASTM E424 10% -16%

Solar Reflectance
ASTM E424 70%-73%
Environmental Issues

Energy Impact
Energy Impact

Low insulating ability
Low thermal mass
High reflectivity of light
Low to moderate translucency
Energy Impact

Energy Usage Trade-off

Decreased lighting use because of moderate translucency

VS

Increased heating load because of low insulation value

Decreased cooling load because of high reflectivity
Environmental Issues

Weather and Acoustics
Adverse Weather Conditions

Sufficient slope to prevent rain ponding.

Sufficient slope to shed snow.

5% slope on a structure loaded with a 10 psf uniform load.
Acoustics

Single layer fabric offers a poor barrier to sound transmission and high reflectivity of sound vibrations.

Liners are often added where there is concern.
Performance Issues

Fire Safety, Security and Maintenance
Fire Safety

Low mass of fabric material

Higher and larger internal spaces

<table>
<thead>
<tr>
<th>PTFE Glass Fiber</th>
<th>PVC Polyester</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFPA 701</td>
<td>Non-combustible</td>
</tr>
<tr>
<td>ASTM E84</td>
<td>Flame Spread - 5 max</td>
</tr>
<tr>
<td>ASTM E108</td>
<td>Burning Brand - Class A</td>
</tr>
<tr>
<td>NFPA 701</td>
<td>Fire-retardant</td>
</tr>
</tbody>
</table>
Security

Keep fabric out of people’s reach
Maintenance

PTFE Glass Fiber
Â Self-cleaning in areas with some rainfall
Â Very little creep – no re-tensioning

PVC Polyester
Â Degradation by UV and can collect dirt
Â Creep – may require re-tensioning
Technology

Analysis and Design Example
Design Concept and Development

Design Parameters

Typical Levels

4%-10% of breaking strength for cables
35 pli-45 pli for heavy PTFE/glass
20 pli-35 pli for light PTFE/glass
7 pli-15 pli for light lining PTFE/glass
7 pli-35 pli for PVC/polyester
Design Concept and Development

Design of supporting framework:
- fabric
- arches
- masts
- anchorages
- cables
- weldments
Design Concept and Development

Develop a practical geometric shape:

- Form-finding
- Prestress
- Perform centerline analysis
Determine the structural loading:

- Wind
- Snow
- Rain (ponding)
- Special loads (point loads, e.g. lighting)
Design of components - fabric

Fabric stresses – warp direction  
Fabric stresses - fill direction
Design of Components – Steel

Moment Diagrams
Design of components - Steel

Check that beam is satisfactory using steel design formulae.
Design of components - Steel

Steel Sizes
Compute the reactions for the prestress, dead and live loads cases, including combined load cases.
Technology

Fabric Patterning and Fabrication
Prepare patterning models and determine the location and design of the seams.
Architectural fabric is manufactured and delivered to the fabrication shop in rolls. PTFE Glass Fiber comes in rolls 12 feet wide x 200 yards.

Receive materials and perform visual and laboratory tests.
Lay out the fabric sub panels to full size using measured offsets or computer plotting methods.
Heat Sealing

Seal fabric with thermal heat sealing devices.
Seal fabric assemblies as designed in a clean handling environment.
Consideration should be given to the installation procedure and how the fabric will be “unfolded”.

Packing in the form of tubes and bubble wrap are necessary to keep from creasing the fabric.
Technology

Installation
Installation

Plan and execute the rolling or folding of the fabric assemblies as required by the Installation Plan with care to not crease or otherwise damage the fabric.
Installation

Site installation planning

- method of pretensioning
- field jointing
- equipment limitations
Installation

Water drainage and removal
ponding
flashing gutters
cone tops

Coordination with other trades
foundations
electrical
mechanical
Applications for Tensioned Fabric
Recreational - Sports Venues

Inchon Stadium, Inchon, South Korea
Meyer Amphitheater, Palm Beach, FL

Recreational - Entertainment
Commercial

Brentwood Mall, Vancouver, BC Canada
Institutional

Sky Song, Arizona State University, Phoenix, AZ
Transportation

TRI Rail Miami Airport, Miami, FL
References

Architectural Fabric Structures, Federal Agencies, 1985
Tensioned Fabric Structures, Edited by R. E. Shaeffer, 1996
The Tensioned Fabric Roof, Craig G. Huntington, 2004
Questions and Discussion

RDU Airport Parking Structure, Raleigh, NC