ASCE STANDARD

ASCE/SEI 55–10

# Tensile Membrane Structures

This document uses both the International System of Units (SI) and customary units

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American Society of Civil Engineers

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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# STANDARDS

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The following standards have been issued:

ANSI/ASCE 1-82 N-725 Guideline for Design and Analysis of Nuclear Safety Related Earth Structures
ASCE/EWRI 2-06 Measurement of Oxygen Transfer in Clean Water
ANSI/ASCE 3-91 Standard for the Structural Design of Composite Slabs and ANSI/ASCE 9-91 Standard Practice for the Construction and Inspection of Composite Slabs
ASCE 4-98 Seismic Analysis of Safety-Related Nuclear Structures
Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02) and Specifications for Masonry Structures (ACI 530.1-02/ ASCE 6-02/TMS 602-02)
ASCE/SEI 7-10 Minimum Design Loads for Buildings and Other Structures
SEI/ASCE 8-02 Standard Specification for the Design of Cold-Formed Stainless Steel Structural Members
ANSI/ASCE 9-91 listed with ASCE 3-91
ASCE 10-97 Design of Latticed Steel Transmission Structures
SEI/ASCE 11-99 Guideline for Structural Condition Assessment of Existing Buildings
ASCE/EWRI 12-05 Guideline for the Design of Urban Subsurface Drainage
ASCE/EWRI 13-05 Standard Guidelines for Installation of Urban Subsurface Drainage
ASCE/EWRI 14-05 Standard Guidelines for Operation and Maintenance of Urban Subsurface Drainage
ASCE 15-98 Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)
ASCE 16-95 Standard for Load Resistance Factor Design (LRFD) of Engineered Wood Construction
ASCE 17-96 Air-Supported Structures
ASCE 18-96 Standard Guidelines for In-Process Oxygen Transfer Testing
ASCE 19-96 Structural Applications of Steel Cables for Buildings
ASCE 20-96 Standard Guidelines for the Design and Installation of Pile Foundations
ANSI/ASCE/T&DI 21-05 Automated People Mover Standards—Part 1
ANSI/ASCE/T&DI 21.2-08 Automated People Mover Standards—Part 2
ANSI/ASCE/T&DI 21.3-08 Automated People Mover Standards—Part 3
ANSI/ASCE/T&DI 21.4-08 Automated People Mover Standards—Part 4
SEI/ASCE 23-97 Specification for Structural Steel Beams with Web Openings
ASCE/SEI 24-05 Flood Resistant Design and Construction
ASCE/SEI 25-06 Earthquake-Actuated Automatic Gas Shutoff Devices
ASCE 26-97 Standard Practice for Design of Buried Precast Concrete Box Sections
ASCE 27-00 Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction
ASCE 28-00 Standard Practice for Direct Design of Precast Concrete Box Sections for Jacking in Trenchless Construction
ASCE/SEI/SFPE 29-05 Standard Calculation Methods for Structural Fire Protection
SEI/ASCE 30-00 Guideline for Condition Assessment of the Building Envelope
SEI/ASCE 31-03 Seismic Evaluation of Existing Buildings
SEI/ASCE 32-01 Design and Construction of Frost-Protected Shallow Foundations
EWRI/ASCE 33-01 Comprehensive Transboundary International Water Quality Management Agreement

EWRI/ASCE 34-01 Standard Guidelines for Artificial Recharge of Ground Water
EWRI/ASCE 35-01 Guidelines for Quality Assurance of Installed Fine-Pore Aeration Equipment
CI/ASCE 36-01 Standard Construction Guidelines for Microtunneling
SEI/ASCE 37-02 Design Loads on Structures during Construction
CI/ASCE 38-02 Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data
EWRI/ASCE 39-03 Standard Practice for the Design and Operation of Hail Suppression Projects
ASCE/EWRI 40-03 Regulated Riparian Model Water Code
ASCE/SEI 41-06 Seismic Rehabilitation of Existing Buildings
ASCE/EWRI 42-04 Standard Practice for the Design and Operation of Precipitation Enhancement Projects
ASCE/SEI 43-05 Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities
ASCE/EWRI 44-05 Standard Practice for the Design and Operation of Supercooled Fog Dispersal Projects
ASCE/EWRI 45-05 Standard Guidelines for the Design of Urban Stormwater Systems
ASCE/EWRI 46-05 Standard Guidelines for the Installation of Urban Stormwater Systems
ASCE/EWRI 47-05 Standard Guidelines for the Operation and Maintenance of Urban Stormwater Systems
ASCE/SEI 48-05 Design of Steel Transmission Pole Structures
ASCE/EWRI 50-08 Standard Guideline for Fitting Saturated Hydraulic Conductivity Using Probability Density Functions
ASCE/EWRI 51-08 Standard Guideline for Calculating the Effective Saturated Hydraulic Conductivity
ASCE/SEI 52-10 Design of Fiberglass-Reinforced Plastic (FRP) Stacks
ASCE/G-I 53-10 Compaction Grouting Consensus Guide
ASCE/EWRI 54-10 Standard Guideline for the Geostatistical Estimation and Block-Averaging of Homogeneous and Isotropic Saturated Hydraulic Conductivity
ASCE/SEI 55-10 Tensile Membrane Structures

# FOREWORD

The material presented in this standard has been prepared to be in accordance with recognized engineering principles. This standard should not be used without first securing competent advice with respect to its suitability for any given application. The publication of the material contained herein is not intended as a representation or warranty on the part of the American Society of Civil Engineers, or of any other person named herein, that this information is suitable for any general or particular use or promises freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability from such use.

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# 1
# GENERAL

## 1.1 SCOPE

**1.1.1** This standard provides minimum criteria for the design and performance of membrane-covered cable and rigid member structures, including frame structures, collectively known as tensile membrane structures, including permanent and temporary structures as defined herein. The requirements of this standard shall apply whether the tensile membrane structure is independent of or attached to another structure. This standard does not apply to air-supported or air-inflated structures.

**1.1.2** This standard is applicable to all tensile membrane structures as follows:

a. temporary structures with a plan area greater than 1,000 $ft^2$ (100 $m^2$) or with any membrane span exceeding 10 ft (3 m) or
b. permanent structures with a plan area greater than 225 $ft^2$ (22.5 $m^2$), regardless of span.

**1.1.3** This standard is applicable to tensile membrane structures erected under the requirements of the legally adopted building code of which this standard forms a part. In areas without a legally adopted building code, this standard defines minimum acceptable standards of design and construction practice.

**1.1.4** This standard supplements the building code and shall govern in all matters pertaining to design, construction, and material properties. This standard may be used in the absence of a building code or where the building code does not adequately address membrane structures.

**1.1.5** Elements of a tensile membrane structure not governed by this standard (e.g., structural steel, cables, timber, aluminum, or concrete) shall be proportioned in accordance with their respective standards.

## 1.2 DEFINITIONS

The following definitions apply in this standard:

**Air-inflated structure**—A membrane structure with a shape that is maintained by air pressure acting within cells or tubes enclosing all or part of the occupied space.

**Air-supported structure**—A membrane structure that encloses an occupied space and has a shape that is maintained by air pressure acting within the occupied space.

**Anchorage**—A device used to secure a membrane or cable to a support.

**Authority having jurisdiction**—The organization, political subdivision, office, or individual charged with responsibility of administering and enforcing the provisions of this standard.

**Biaxial stress**—Stresses taken simultaneously along two concurrent orthogonal directions, usually warp and fill.

**Cable**—A flexible linear or curvilinear element acting in tension. Cable may be wire rope, strand, or web.

**Compensation (and decompensation)**—Adjustment during patterning of membrane panel dimensions to allow for stretching of the material as required to achieve the desired initial prestress and geometry.

**Design strength**—The strength determined by multiplying the ultimate strength by one or more strength reduction factors.

**Effective membrane breaking strength**—The strength of the membrane or seam, whichever is less.

**Effective prestress**—The prestress remaining in the structure after all losses, including long-term losses, have occurred.

**Fabric**—A two-dimensional cloth made up of yarns or slit tapes that may be impregnated with a matrix that binds them together. The yarns may be woven or laid. The fabric is frequently coated or laminated.

**Factored load**—The product of the nominal loads and load factors used to proportion members by strength design.

**Fibers**—Lengths of threads of a material. When twisted together, they make a yarn.

**Fill**—The yarns that are placed in the narrow direction of the fabric as it is manufactured (also known as Weft).

**Film**—An unreinforced plastic. Film does not contain fibers or yarn.

**Frame-supported structure**—A membrane structure consisting of a series of arches or frames where the membrane is pretensioned primarily uniaxially and the membrane is ignored in the design of the structure's overall stability but may be considered in the stability of individual components.

**Life-cycle factor**—A factor included to account for the fact that the strength of some materials decreases with time because of the effects of continuous loading, environmental exposure, and aging.

**Load factor**—A number, usually greater than 1.0, applied to loads to increase the effects of the loads on the structure to account for uncertainties in the load estimation.

**Material manufacturer**—A business entity whose primary purpose is the production of membrane roll-goods that are subject to membrane fabricator testing requirements as referenced herein, where membrane assemblies are produced for a specific project. See Membrane fabricator.

**Membrane**—The flexible, coated, or laminated structural fabric or film that supports the imposed loads and transmits them to the supporting structure. For the purpose of this standard, the membrane carries only tension or shear in the plane of the membrane.

**Membrane component**—Material required to resist prestress and all applied loads that is not subject to requirements of other design standards, or where the applicable design standards do not apply. Materials include, but are not limited to, membrane, nonmetallic cables and rope, and web made from nonmetallic material.

**Membrane fabricator**—A business entity whose primary purpose is the production of membrane assemblies using roll-goods supplied by a material manufacturer for tensile membrane structures. See Material manufacturer.

**Membrane liner**—An interior fabric or film used for decorative, acoustical, thermal insulation, or other nonstructural purposes.

**Membrane tensile strength**—The tensile strength established by rational methods and applicable standards. For fabric, this is the strip tensile strength, as determined in accordance with ASTM D4851.

**Minimum test value—A** published value that is exceeded by 95% of all samples tested.

**Nominal strength**—The capacity of a member before applying any strength reduction factors.

**Patterning**—The process of determining how to cut the pieces of two-dimensional flat fabric so that when joined together and prestressed, they produce a three-dimensional structure.

**Permanent structure**—A structure intended to remain in its erected position and location for a period of 180 days or more.

**Prestress**—The stress induced in the structure for the purpose of defining the geometry and the initial state of the structure.

**Scrim**—A nonwoven or loosely woven fabric.

**Seam**—A joining of two or more pieces of membrane material.

**Service load**—Any load anticipated to be imposed on the structure, to which no factors have been applied.

**Strength reduction factor**—A factor (less than or equal to 1.0) that accounts for the deviation of the actual strength from the nominal strength caused by the variance of material properties and workmanship and by the manner and consequences of failure.

**Stress**—For support structure and anchorages, this is force per unit area; for membranes, it is force per unit length.

**Support structure**—Arches, beams, columns, cables, foundations, and other nonmembrane elements.

**Temporary structure**—A structure intended to remain in its erected position and location for a period of fewer than 180 days.

**Tensile membrane structure**—A membrane structure with a shape that is determined by tension in the membrane and the geometry of the support structure. Typically, the structure consists of flexible elements (e.g., membrane and cables), nonflexible elements (e.g., struts, masts, beams, and arches), and the anchorage (e.g., supports and foundations). Tensile membrane structures include Frame-supported structures.

**Ultimate strength**—The anticipated breaking strength of a member (or failure strength where failure is defined as other than breaking) based on material values.

**Uniaxial stress**—A stress applied parallel to one axis (usually the warp or fill) where no stress is applied in the orthogonal direction.

**Warp**—The longitudinal or machine direction of a fabric.

**Web**—A belt of reinforcement material.

**Weft**—See Fill.

**Yarn**—An assemblage of fibers.

## 1.3 DESIGN DOCUMENTS

Design drawings and specifications shall, as a minimum, show

a. name and date of issue of code and supplement to which design conforms,
b. all loads used in the design,
c. reactions,
d. specified strength of fabric and seams for each part of structure,
e. type of fabric,
f. size and location of all structural elements,
g. maximum cable forces,
h. magnitude and location of prestress forces,
i. the directions of the warp and fill,
j. type and location of any mechanical connections,
k. for temporary or seasonal structures, designs shall clearly show the intended period of erection and the anticipated environmental conditions, and
l. schedule of required maintenance.

## 1.4 FIELD OBSERVATION

**1.4.1 Qualifications—**Construction shall be observed periodically throughout the various work stages by the engineer or architect of record or by a representative responsible to that engineer or architect and as required by the authority having jurisdiction.

**1.4.2 Records—**Construction records shall, as a minimum, include the following:

a. verification that the fabric is as specified;
b. construction and removal of temporary supports;
c. placing of fabric;
d. sequence of erection and connection of all members;
e. tensioning of prestressing elements;
f. any significant construction loadings on the structure;
g. documentation of any and all errors, defects, flaws, or repairs; and
h. general progress of work.

## 1.5 ALTERNATE DESIGNS

The provisions of this standard are not intended to limit the appropriate use of materials, systems, equipment, methods of design, or construction procedures not specifically described in this standard, provided that such alternate design methods and construction procedures are conducted by persons specially qualified in the specific methods applied and provided that such techniques demonstrate a level of safety and performance consistent with the requirements of Chapter 4. Structures and structural components that are not amenable to analysis using generally accepted theories may be designed by

a. evaluation of full-scale structure(s),
b. evaluation of a full-scale prototype through tests, or
c. studies of model analogues.

## 1.6 REFERENCES

The following standards are referred to in this document:

ASCE 7. (2006). *Minimum design loads for buildings and other structures*, American Society of Civil Engineers, Reston, Va., ASCE/SEI 7-05.

ASCE 19. (1997). *Structural applications of steel cables for buildings,* American Society of Civil Engineers, New York, ASCE 19-96.

ASCE 22. (1998). Independent project peer review, American Society of Civil Engineers, Reston, Va., ASCE 22–97.

ASTM D2136. (2007). *Standard Test Method for Coated Fabrics-Low-Temperature Bend Test*, ASTM International, West Conshohocken, Penn.

ASTM D2261. (2007). *Standard Test Method for Tearing Strength of Fabrics by the Tongue (Single Rip) Procedure (Constant-Rate-of-Extension Tensile Testing Machine)*, ASTM International, West Conshohocken, Penn.

ASTM D4851. (2003). *Standard test methods for coated and laminated fabrics for architectural use,* ASTM International, West Conshohocken, Penn.

ASTM D6193. (2009). *Standard practice for stitches and seams,* ASTM International, West Conshohocken, Penn.

ASTM E84. (2009). *Standard test method for surface burning characteristics of building materials,* ASTM International, West Conshohocken, Penn.

ASTM E136. (2009). *Standard test method for behavior of materials in a vertical tube furnace at 750°C,* ASTM International, West Conshohocken, Penn.

NFPA 701. (2010). *Standard methods of fire tests for flame propagation of textiles and films,* National Fire Protection Association, Quincy, Mass.

ICBO (1970). *Uniform building code*, International Conference of Building Officials, Whittier, CA.

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# 2
# MEMBRANE MATERIALS

## 2.1 GENERAL

**2.1.1 Membranes**—Membrane materials used in the tensile membrane shall conform to and shall be tested in conformance with the requirements of this chapter. Other materials (e.g., cables, steel, aluminum, timber, and concrete) shall conform to the requirements of their respective standards.

**2.1.2 Quality**—Membrane materials used in structures shall be of uniform quality and shall have properties required for the intended usage. The rolls of materials provided by the material manufacturer shall be marked to indicate any areas with defects that would impair their structural integrity or serviceability.

## 2.2 TESTING QUALIFICATIONS

Tests shall be performed by qualified testing agencies or by qualified employees of the material manufacturer or membrane fabricator acceptable to the authority having jurisdiction. Manufacturers and fabricators performing their own testing shall demonstrate conformance with the standards referenced in this chapter.

## 2.3 PHYSICAL TESTING

**2.3.1 Frequency**—Membranes shall have a published specification that identifies the minimum test values for the properties identified in Section 2.4.1. Testing frequency for physical properties of membranes shall be based on the surface area of membrane to be present in the finished structure. Unless otherwise specified in this chapter, the required tests shall be performed for every 10,000 $ft^2$ (900 $m^2$), or fractional part thereof, of membrane in the finished structure. For membranes with a history of consistent test results (coefficient of variation of 5% or less), the frequency of testing can be reduced to every 50,000 $ft^2$ (5,000 $m^2$). Except as limited by sample size of the specific test, the number of specimens per sample shall depend on the membrane roll width:

a. Samples from membrane rolls less than or equal to 80 in. (2.0 m) wide shall be divided into three equal zones across the width of the fabric. One specimen for each required test shall be taken from each zone.
b. Samples from membrane rolls greater than 80 in. (2.0 m) wide shall be divided into four equal zones across the width of the fabric. One specimen for each required test shall be taken from each zone.
c. When testing fabrics, specimens for the same physical test taken from the different zones across the width of the fabric shall be laid out so that they do not include the same warp or fill yarns.

**2.3.2 Conditions**—Coated fiberglass shall be tested in both wet and dry conditions. The wet tensile test shall be performed with the same size specimen as the dry tensile test. The specimen shall be fully immersed in water, exposing the open edges and face to the potential invasion of water. The specimen shall remain submerged for 24 h. After 24 h, the specimen shall be removed, patted dry, and tested in the same manner as is done for the dry tensile test. The minimum result, to be indicative of proper coating and sufficient protection of the yarn bundle, shall be 80% of the value obtained in the dry tensile test.

**2.3.3 Flexfold**—Coated fiberglass shall be tested for flexfold as described in ASTM D4851.

**2.3.4 Biaxial Testing**—As a minimum, biaxial testing shall be conducted by the material manufacturer for the purposes of quality control at the following times:

a. whenever a new manufacturing process is used and
b. for each 100,000 $ft^2$ (10,000 $m^2$). For membranes with a history of consistent test results (coefficient of variation of 5% or less), the frequency can be reduced to every 200,000 $ft^2$ (20,000 $m^2$).

**2.3.5 Uniaxial Testing**—As a minimum, uniaxial elongation testing, as described in Section 2.4.1, shall be undertaken by the material manufacturer for every 10,000 $ft^2$ (900 $m^2$) of membrane used in the finished structure with a minimum of one test per roll. For membranes with a history of consistent test results (coefficient of variation of 5% or less), the frequency of testing can be reduced to every 50,000 $ft^2$ (5,000 $m^2$) with a minimum of one test per roll. The number of specimens per sample shall be in accordance with Section 2.3.1.

**2.3.6 Frequency**—The frequency of testing may be increased as required by the architect or engineer of record. Such additional testing shall be clearly defined in the contract documents.

## 2.4 PHYSICAL PROPERTIES

**2.4.1 General**—Membrane physical properties shall be determined in accordance with ASTM D4851, except as modified herein. As a minimum requirement, testing as prescribed in Section 2.3 shall be undertaken for unit weight (coated and uncoated), thickness, strip tensile strength, trapezoidal tear strength, uniaxial elongation, and coating adhesion in both the warp and fill directions. The fabric construction (yarn count and type) shall also be provided. The material manufacturer shall maintain a record of compliance.

**2.4.2 Published Values**—The material manufacturer shall provide published values for the specified fabric, separate for the warp and fill directions, of the modulus of elasticity and Poisson's ratio. These values shall be based on biaxial tests in the stress range of 5 pli (0.175 kN/m) to 30% of the strip tensile strength. As a minimum, this range shall be applied in ratios of 2 : 1, 1 : 1, and 1 : 2 of warp to fill. To determine these values, the procedures in Appendix B may be used.

**2.4.3 Procedures**—For structures with a design prestress of 10 pli (0.175 kN/m) or greater in both biaxial directions, before fabrication of the membrane, membrane rolls shall be grouped based on their warp and fill elongation tests. A minimum of one specimen shall be selected from each group for biaxial testing. Biaxial elongation properties are to be determined in accordance with the membrane fabricator's standard procedures as approved by the design engineer or architect. During testing, a specimen shall be subjected to a series of loads (simultaneously in both the warp and fill directions) selected to simulate the design stresses predicted by analysis. The duration of each loading cycle or increment shall be selected with regard to the membrane's ability to respond to the test loads.

## 2.5 MEMBRANE CLASSIFICATION AND FIRE PERFORMANCE

**2.5.1 Classification**—Membranes for tensile membrane structures shall be classified according to their fire performance characteristics as follows:

**Class I Membrane**: Noncombustible membranes shall comply with the definition for noncombustible building materials as established by the authority having jurisdiction. They shall also meet the requirements of NFPA 701 and shall attain a flame spread index not greater than 25 and a smoke development index not greater than 50 when tested according to ASTM E84.

**Class II Membrane**: Limited combustible membranes shall meet the requirements of NFPA 701. In addition, they shall attain a flame spread index not greater than 25 and a smoke development index not greater than 450 when tested according to ASTM E84.

**Class III Membrane**: Combustible membranes are all membranes that do not meet the requirements for any other class.

**2.5.2 Liners**—Membrane liners shall not be less than Class II materials, except when the primary membrane is Class III.

**2.5.3 Height Limitations**—Tensile membrane structures shall not be limited in height except as required by applicable local zoning regulations.

**2.5.4 Conformance**—Membranes and membrane liners shall be used for tensile membrane structures in accordance with the classification given in this section and shall conform to the regulations of the authority having jurisdiction. In the absence of a legally adopted building code, Appendix A shall be used.

## 2.6 SEAMS

**2.6.1 General**—Seams shall be designed to properly transfer the applied loads through the membrane field to the supporting structure and shall be designed with due regard to proper flexibility, protection of the fabric material, and serviceability.

**2.6.2 Processes**—Membrane seams shall be sewn, electromechanically welded, fused, glued or mechanically connected, or connected by any other method that complies with the requirements of this section.

**2.6.3 Tolerances**—All seams shall be fabricated within the following tolerances when measured over a 10-ft (3-m) length:

a. Seams designed to be less than 2 in. (50 mm) wide shall not be less than 1/16 in. (1.5 mm) smaller than specified.
b. Seams designed to be 2 in. (50 mm) or more wide shall not be less than 1/8 in. (3 mm) smaller than specified.

**2.6.4 Quality**—Welded seams shall be fully sealed, with no cold spots (areas of little or no adhesion).

**2.6.5 Characteristics**—Sewn seams shall conform to ASTM D6193. Characteristics of properly constructed seams are strength, elasticity, durability, security, and appearance. These characteristics must be balanced with the properties of the material to develop the optimum seam for the specific application.

The membrane fabricator shall determine the particular seam stitch type based on the primary requirements of strength, durability, and security.

The membrane fabricator shall be prepared to demonstrate that the proposed manufacturing process for a particular seam intended for a particular engineered application will produce reliable finished assemblies meeting the project requirements. This demonstration shall include consideration for particular techniques and skills of sewing machine operators.

**2.6.6 Strength**—Membrane seams shall be designed and fabricated so that the seams meet the following strength criteria:

a. at 68 °F (20 °C), the seam shall resist a test load equal to 100% of the minimum specified tensile strength of the fabric when tested in accordance with ASTM D4851; and
b. at 68 °F (20 °C), the seam shall resist a continuous test load equal to 200% of the maximum service load for a minimum of 4 h and exhibit less than 1/8 in. (3 mm) slippage; and
c. at 158 °F (70 °C), the seam shall resist a continuous test load equal to 100% of the maximum service load for a minimum of 4 h.

**2.6.7 Breaking Strength**—The effective breaking strength of membranes using seam constructions that do not comply with the requirements of Section 2.6.6 shall be reduced to the strength of the seams.

## 2.7 CABLES AND REINFORCING

When reinforcing of the membrane or membrane liner is required, it shall consist of either metallic or nonmetallic cables or nonmetallic reinforcing. Such materials shall be of uniform quality and shall have properties required for the intended usage.

a. The strength of metallic cables shall be determined in accordance with ASCE 19.
b. The strength and fire characteristics of nonmetallic cables and web elements shall be determined in accordance with material standards provided by the manufacturer and approved by the authority having jurisdiction.
c. The strength and fire characteristics of nonmetallic fabric reinforcements of the membrane or membrane liner shall comply with Sections 2.5 and 2.6.

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# 3
# CONNECTIONS

**3.1 GENERAL**—Connections shall be designed to transfer all applied and internal forces and moments as required by analysis. Additionally, the effects of membrane creep, exposure to the weather, eccentricity, dynamic loads, fatigue, and movement caused by large deflections and rotations of the structure shall be accounted for. Corrosion protection shall be provided where necessary for the integrity and durability of the structure.

**3.2 FABRIC-TO-FABRIC**—Fabric-to-fabric connections shall be accomplished through the use of seams or mechanical joints in accordance with Section 2.6. In all areas where stress concentrations can occur, the membrane shall be reinforced as required with additional fabric. Deterioration of the fabric over the design life of the structure shall be accounted for by applying the appropriate life-cycle factor, as specified in Chapter 4.

**3.3 FABRIC-TO-NONFABRIC**—Fabric-to-nonfabric connection details shall be configured so as to minimize stress concentrations in the fabric and minimize fabric wear and damage over the life of the structure. Adequate strength and weather tightness shall be maintained when sectionalizing fabric for construction, installation, or fabrication considerations. The connections shall consider the requirements of the membrane for elongation and flexure in the direction of the joint.

**3.4 MECHANICAL**—When a mechanical joint in the membrane or membrane liner is required, the materials used shall be noncorrosive or shall be treated, finished, or both to protect against corrosion. Materials shall be free of rough spots, sharp edges, or other defects that may be injurious to the membrane material. If grommeting is used as a means of connection, capacities shall be determined by testing. As a minimum, mechanical membrane joints and other seams shall be designed to have a breaking strength greater than 200% of the maximum stress under service load. The design of mechanical joints shall consider the requirements of the membrane for elongation and flexure in the direction of the joint.

**3.5 OTHER**—Nonfabric connections such as cable-to-cable, cable-to-steel, and cable-to-anchorage shall provide for the anticipated rotations, shall have enough adjustability to maintain proper tension forces, shall allow for long-term effects, and shall take into consideration eccentricities in the connection details.

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# 4
# DESIGN

## 4.1 NOTATION

The following notations apply:

$D$ = Dead load
$D_s$ = Superimposed or collateral dead load
$L_r$ = Roof live load
$L_t$ = Life-cycle factor
$P$ = Member force or stress effect caused by prestress
$Q$ = Earthquake load
$R$ = Rain load
$S$ = Snow load
$T$ = Self-straining forces such as temperature expansion and contraction, creep, differential settlement, and moisture
$T_f$ = Tensile force or stress effect in the structural element or direction being considered caused by the load combinations
$T_{ff}$ = Tensile force in fill direction (as calculated by nonlinear analysis)
$T_{fw}$ = Tensile force in warp direction (as calculated by nonlinear analysis)
$T_r$ = Design strength of a membrane element
$T_s$ = Tensile strength of a membrane element. See Sections 1.2 and 2.3.1.
$T_{sf}$ = Tensile strength in the direction of the fill (weft) yarns. See Sections 1.2 and 2.3.1.
$T_{sm}$ = Tensile strength in the principal direction in the plane of the membrane. See Sections 1.2 and 2.3.1.
$T_{sw}$ = Tensile strength in the direction of the warp yarns. See Sections 1.2 and 2.3.1.
$W$ = Wind load
$\beta$ = Reduction factor (beta)

## 4.2 LOADS

**4.2.1 General**—Loads shall be determined in accordance with ASCE 7 or the applicable building code, except as modified herein. Provision shall be made for loads imposed on tensile membrane structures during erection or dismantling.

**4.2.2 Dead Load**—The design dead load for a tensile membrane structure shall consist of

a. the weight of the membrane;
b. the weight of reinforcement and joining systems;
c. the weight of structural frame elements that are integral with and supported by the membrane structural system; and
d. the weight of liners, insulation, and other fixed parts of the structure itself, if supported directly by the membrane or reinforcement.

**4.2.3 Superimposed Loads**—Superimposed dead load, such as lights, speakers, ducts, sprinklers, and other equipment related to the function of the structure, shall be treated as dead loads when they are intended to be permanent and shall be treated as live loads when they are intended to be temporary. These loads, both dead and live, shall be considered absent when they would counteract loads such as wind uplift.

**4.2.4 Snow, Rain, and Seismic Loads**

**4.2.4.1** Snow, rain, and seismic loads for tensile membrane structures shall be determined in accordance with ASCE 7 or the applicable building code. The deflection of the membrane under the accumulated snow and other loads shall be considered. The possibility of locally increased snow load caused by sliding shall be considered.

**4.2.4.2** Design snow loads shall not be reduced by implementation of snow-melting or -removal methods except on temporary structures if approved by the authority having jurisdiction.

**4.2.5 Wind Loads**—Wind loads for tensile membrane structures shall be determined in accordance with ASCE 7 or the applicable building code. Where the shape of the membrane does not fall within the limits of the prescriptive load requirements, wind tunnel analysis conforming to ASCE 7 shall be permitted to establish the design wind pressures. Consideration shall be made of wind–structure interaction, including both the effects of flutter at free edges of the structure and of resonance of the entire structure and its associated air mass.

**4.2.6 Minimum Roof Live Loads**—Live loads for tensile membrane structures shall be determined in accordance with ASCE 7 or the applicable building code.

**4.2.7 Ice Loads**—Where icing conditions occur, consideration shall be given to accumulation of ice on cables and on both upper and lower surfaces of the membrane, as well as to falling or sliding ice, which may initiate tearing in the membrane.

**4.2.8 Temporary Loads—**Applied loads, such as artworks and show rigging that will be in place for fewer than 14 days, shall be considered simultaneously with at least one-half the roof live load of Section 4.2.6. Such loads need not be considered simultaneously with environmental loads, such as snow, when not appropriate to the season of use.

## 4.3 CONSIDERATIONS FOR DESIGN AND ANALYSIS

**4.3.1 General—**Tensile membrane structures shall be designed considering both strength and serviceability.

**4.3.2 Progressive Collapse—**Tension membrane structures shall be designed so that failure of the membrane or of a single supporting element does not result in progressive collapse of the structure.

**4.3.3 Structural Stability—**Where the support structure relies on the tension membrane structure to provide stability to components or individual members of the support structure, the designer of the support structure must ensure that a local failure of the tension membrane structure does not cause collapse of the tension membrane structure and support structure by either

a. loss of capacity of the individual member of the support structure or
b. excess movement of the tension membrane structure.

**4.3.4 Design—**The design of tensile membrane structures shall include consideration of the following:

a. losses in prestress caused by support displacement, construction tolerance, material creep, or relaxation in any element;
b. deformations of any supporting element; or
c. potential of the membrane for ponding. As a minimum, the structure shall be shaped so as to maintain positive drainage from all areas of the roof.

   Exception: Where cable or connection configurations interfere with free drainage, ponded areas not exceeding 1.5 in. (37 mm) deep and 10 $ft^2$ (1 $m^2$) in area shall be permitted, provided that the structure is so designed that the weight of the impounded water does not cause a significant or detrimental progressive increase in depth or area of the pond.

**4.3.5 Analysis—**A rational method of analysis shall be used to determine the load effect on each element. All analysis and design shall consider behavior caused by the effects of large-deflection (geometric) nonlinearities and nonlinear material properties.

**4.3.5.1** The method of analysis shall take into account the geometrical nonlinear relationships of applied loads to the structure deformation. Such techniques usually do not permit the superposition of load effects.

**4.3.5.2** Consideration shall be given to the effect of membrane, cable, or web members attaining a state of zero tension (i.e., "going slack"). Where such a condition causes the structure to become unstable, the design must ensure that the instability does not lead to damage or collapse.

**4.3.5.3** The potential for differential movement between membrane and cables shall be evaluated and, where required, shall be incorporated in the analysis.

**4.3.6 Strength Requirements Under Sustained Loading—**Membranes shall be designed to resist the effects of sustained loading, accounting for the creep characteristics of the membrane and other structural materials.

**4.3.7 Corrosion Protection—**Metal structural components shall be designed so that the safety of the structure is not adversely affected by corrosion.

**4.3.8 Deterioration—**For the determination of the resistance of the structural elements, deterioration of the materials over the design life of the structure shall be accounted for by establishing an appropriate life-cycle factor, $L_t$, as specified in Section 4.4.2.

## 4.4 MEMBER PROPORTIONING

**4.4.1 General—**Components of the structure are to be proportioned in accordance with Sections 4.5 and 4.6.

**4.4.2 Life-Cycle Factor—**Each member selection shall include a life-cycle factor $L_t$, which adjusts the member capacity to allow for the effects of aging caused either by environmental effects or by the effects of wear and tear on membrane protective coatings. The life-cycle factor(s) shall be selected so that at no time during the intended service life of the structure is the member resistance less than that required by this standard.

**4.4.2.1** $L_t$ for membranes, nonmetallic cables, and all webbing materials shall be derived according to the following rules:

a. For membranes, nonmetallic cables, and webbing materials that retain at least 75% of their initial design strength over their intended life and are used in permanent structures not subjected to repeated handling, $L_t$ shall be taken as 0.75.
b. When initial design strength retention is below 75% for the intended life, $L_t$ shall be reduced proportionately.
c. For elements subjected to repeated handling, $L_t$ shall be selected as appropriate for the material but shall not exceed 0.6.
d. Membrane materials intended to be subjected to repeated handling shall be tested in accordance with the dry flexfold method of ASTM D4851 to determine if a further reduction of $L_t$ is warranted.

**4.4.2.2** In lieu of testing or other evidence, the values in Table 4-1 for $L_t$ shall be used for stresses perpendicular to a seam.

## 4.5 LOAD COMBINATIONS

**4.5.1 Applicability**—The load combinations and factors given in Section 4.5.2 shall be used for the design of membrane components. Load combinations for design of supporting structures and foundations shall be taken from ASCE 7 and ASCE 19.

**Table 4-1. Life-Cycle Factor for Seams or Joints**

| Seam or Joint | Value |
|---|---|
| Heat-sealed or welded seams | Same as for base fabric |
| Adhesive seams | 50% of value for base fabric |
| Sewn seams—unprotected | 60% of value for base fabric |
| Sewn seams—protected from weather or sunlight | 90% of value for base fabric |
| Mechanical joints or membrane components | Same as for seams |

**4.5.2 Load Combinations and Strength Reduction Factors**—Membrane components shall be designed for the combinations in Table 4-2.

**4.5.3 Overloads**—The analysis shall include the load combinations in Table 4-3 to determine the behavior of the structure and for member proportioning where that is critical under the overload condition.

## 4.6 COMPONENT RESISTANCE

**4.6.1 Membrane**—Breaking strengths $T_s$ in the warp and fill directions of the membrane shall be determined in accordance with Sections 2.3 and 2.4.

**a. Uniaxial Tension**—The design strength, $T_r$, developed by a membrane in uniaxial tension, in the direction under consideration, shall be calculated as follows:

$$T_r = \beta L_t T_s \geq T_f$$

**b. Biaxial Tension**—Membranes required to resist simultaneous tensile forces in two orthogonal directions shall be proportioned as follows:

$$T_r = \beta L_t T_{sw} \geq T_{fw}$$

and

$$T_r = \beta L_t T_{sf} \geq T_{ff}$$

and

$$0.8\beta L_t \,(T_{sw} + T_{sf}) \geq T_{fw} + T_{ff}$$

**Table 4-2. Load Combinations and Strength Reduction Factors**

| Combination No. | Load Combination | Strength Reduction Factor, β |
|---|---|---|
| 1 | $\boldsymbol{P} + D + D_s$ | 0.17 |
| 2 | $\boldsymbol{P} + D + (L_r$ or $S$ or $R) + D_s$ | 0.27 |
| 3 | $\boldsymbol{P} + D + D_s + W$ or $Q$ | 0.33 |
| 4 | $\boldsymbol{P} + D + D_s + T$ | 0.27 |

These combinations are not all-inclusive (as in the possibility of partial wind in combination with snow or vice versa), and the engineer shall exercise judgment in these situations. The reduction factor for the load case including wind is established using ASCE 7-98. In situations where ASCE 7 or the governing building code permits a 1/3 increase in allowable stress for wind, the 1/3 increase is not permitted to be used in conjunction with this standard.

**Table 4-3. Load Combinations**

| Combination No. | Load Combination |
|---|---|
| 5 | 1.4 ($\boldsymbol{P} + D$) |
| 6 | 1.0 ($\boldsymbol{P} + D$) + 1.2 $T$ |
| 7 | 1.0 ($\boldsymbol{P} + D$) + 1.6 [($L_r$ or $S$ or $R$) + $D_s$] |
| 8 | 1.0 ($\boldsymbol{P} + D$) + 1.6 $W$ |

The wind load combination given as No. 8 is established using ASCE 7-98 for wind load calculations. If wind loads are calculated using ASCE 7-93 or ASCE 7-95, the load factor shall be taken as 1.3.

c. **Tear Strength**—Consideration must be given to the trapezoidal tear strength as it pertains to the overall safety of the structure.

**4.6.2 Cables, Webs, and Mechanical Joints**—The design strength, $T_r$, developed by cables, webs, and mechanical joints shall be calculated as follows:

a. Steel cables:

$T_r$ (in accordance with ASCE 19)

b. Webs and nonmetallic cables:

$$T_r = \beta L_t T_s$$

c. Mechanical joints:

$T_r$ (in accordance with the appropriate standard)

## 4.7 ANCHORAGE

**4.7.1 Reactions**—Where the tensile membrane structure is to be supported by foundations or other structural elements to be designed by others, the design engineer of the tensile membrane structure shall provide separate reactions for each load combination used in the design of the structure.

**4.7.2 Design Consideration**—The anchorage system shall be designed to distribute individual anchor loads uniformly to the membrane so as to prevent excessive stress concentrations in the membrane. Movements and rotations of the membrane and/or the membrane structure under load and the changes in direction of the reaction or load application shall be considered in the design of all anchorages.

# 5
# FABRICATION AND ERECTION

## 5.1 FABRICATION

**5.1.1 Fabrication Drawings**—Detailed shop drawings shall be produced for the fabrication of all components of a tensile membrane structure. Membrane fabrication drawings shall include fabric assemblies with overall dimensions, seams, edge details, and template data. Template data shall be generated using reliable methods to develop the design surface geometry of the structure at the specified prestress levels. Component fabrication drawings shall comply with the requirements of their respective standards.

**5.1.2 Tolerances**—Fabricated components shall comply with the following requirements:

**5.1.2.1** Membrane fabrication tolerances shall be as follows:

a. Individual membrane panel dimensions shall not vary by more than 0.1% from the theoretical size, with a minimum of 1/16 in. (1.6 mm) and a maximum of 1/2 in. (12.7 mm).
b. Overall assembly dimensions shall not vary by more than 0.2% from the theoretical size, with a minimum of 1/8 in. (3 mm) and a maximum of 2 in. (50 mm).

**5.1.2.2 Other Components**—Tolerances for all other components in a tensile membrane structure shall comply with the requirements of their respective standards.

**5.1.3 Quality**—The membrane fabricator shall be responsible for the quality of the fabricated components.

**5.1.3.1** The membrane fabricator shall have in effect a written quality control program to ensure that fabricated materials conform to the requirements of this standard and the project specifications.

**5.1.3.2** The membrane fabricator shall maintain test data to document compliance with tests and standards as required in Chapter 2.

**5.1.4 Records**—When requested by the owner, the membrane fabricator shall submit records of quality control and testing to the owner for the purpose of future evaluations or alterations of the structure.

**5.1.5 Membrane Compensation**—Membranes shall be compensated during the fabrication process to permit installation at the design prestress.

a. For structures with a design prestress of 10 pli or greater in both directions, compensation values shall be based on the biaxial elongation properties of the membrane materials used for the project based on Section 2.4.3.
b. For other structures, compensation values shall be permitted to be based on Section 2.4.1.

## 5.2 ERECTION

**5.2.1 General**—For all structures, the erector shall develop a detailed installation procedure that considers potential instability inherent in an incomplete tensile membrane structure. The effects of low prestress in the membrane and cables shall be considered.

**5.2.2 Analysis**—For structures (or modules thereof) with a surface area greater than 30,000 $ft^2$ (3,000 $m^2$) or a span of greater than 100 ft (30 m), the installation procedure shall include a detailed numerical analysis as required in Chapter 4 and shall consider the effect of appropriate loadings on the partially erected structure. This analysis shall be performed by, or under the direct supervision of, a licensed professional engineer.

**5.2.3 Safety**—It shall be the responsibility of the erector to ensure the safety of persons and protection of the membrane structure during the period of erection of the structure. Access to the membrane surface shall be at the sole discretion of the erector.

**5.2.4 Rigging**—It shall be the responsibility of the erector to design and supply the necessary temporary rigging materials to ensure the proper erection of the structure.

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# Appendix A
# SPECIAL PROVISIONS

## A.1 SCOPE

This appendix is provided as a supplement to the legally adopted building code.

The following standards are referred to in this appendix:

NFPA 10 *Portable Fire Extinguishers*
NFPA 13 *Installation of Sprinkler Systems*
NFPA 14 *Installation of Standpipe and Hose Systems*
NFPA 72 *National Fire Alarm Code*

**A.1.1 Purpose**—The purpose of this appendix is to provide requirements for tensile membrane structure sizes to be used in conjunction with the legally adopted building code or when such provisions do not exist in a legally adopted building code. These provisions are based on a combination of factors, including occupancy types, separation from other buildings, and availability of sprinkler system(s). Building use and occupancy classifications are based on the 2000 International Building Code.

**A.1.2 Area Limits**—Table A-1 shall be used for structures constructed using Class I or Class II membranes. The areas in Table A-1 shall be permitted to be further increased by the authority having jurisdiction by performance-based approval, based on the structure design having appropriate levels of safety in terms of exiting provisions, sprinkler systems, fire alarms, standpipes, and internal and external fire separations.

**A.1.2.1** The base areas shown in Table A-1 shall be increased based on frontage ($I_f$) and automatic sprinkler system protection in accordance with the following:

$$A_a = A_t + (A_t I_f/100) + (A_t I_s/100) \qquad \text{(A-1)}$$

where

$A_a$ = Allowable area per floor (in square feet),
$A_t$ = Base area per floor (in square feet),
$I_f$ = Area increase due to frontage (percent), as calculated in accordance with Eq. A-2, and
$I_s$ = Area increase due to sprinkler protection (percent), as calculated in accordance with Section A.1.2.3.

**A.1.2.2** Where a building has more than 25 percent of its perimeter on a public way or open space at least 20 ft wide, the frontage increase shall be determined as follows:

$$I_f = 100(F/P - 0.25)(W/30) \qquad \text{(A-2)}$$

where

$I_f$ = Area increase generated by frontage (percent),
$F$ = Building perimeter that fronts on a public way or open space with 20-ft (6-m) open minimum width,
$P$ = Perimeter of the entire building, and
$W$ = Minimum width of the public way or open space.

**A.1.2.2.1** *W* must be at least 20 ft but less than 60 ft.

**A.1.2.2.2** Such open space shall be either on the same lot or dedicated for public use and shall be accessed from a street or approved fire lane.

**A.1.2.3** Where a building is protected throughout with an approved automatic sprinkler system in accordance with NFPA 13, the area limitation in Table A-1 shall be increased by 300 percent ($I_s$ = 300 percent).

**A.1.3 Class III, Combustible Membranes**—Tensile membrane structures using Class III membranes shall be limited to uses where occupancy by the general public is not authorized, such as greenhouses and aquaculture pond covers. Such structures shall have at least 20 ft of open space on all sides. The area is unlimited.

## A.2 MEZZANINES

Mezzanines may be constructed inside membrane structures as allowed by the applicable building codes.

## A.3 ROOF STRUCTURES

Membrane structures may be erected on roofs of conventional buildings and can be unlimited in height.

## A.4 ATTACHMENT TO EXISTING BUILDINGS

Membrane structures may be attached to existing buildings as allowed by the applicable building codes.

**Table A-1. Maximum Footprint Areas (in Square Feet)**

| Class I Membrane | | Base Area | With 30 ft Open Space on All Sides | With Sprinklers | With 30 ft Open Space on All Sides + Sprinklers | With 60 ft Open Space on All Sides | With 60 ft Open Space on All Sides + Sprinklers |
|---|---|---|---|---|---|---|---|
| Assembly | | | | | | | |
| A-1 | Assembly uses, usually with fixed seating, intended for the production and viewing of performing arts (theaters and studios) | 25,500 | 44,600 | 76,500 | 121,000 | 63,800 | 121,000 |
| A-2 | Food and drink consumption | 28,500 | 49,900 | 85,500 | 135,000 | 71,300 | 135,000 |
| A-3 | Worship, recreation, amusement, library | 28,500 | 49,900 | 85,500 | 135,000 | 71,300 | 135,000 |
| A-4 | Indoor sporting events | 28,500 | 49,900 | 85,500 | 135,000 | 71,300 | 135,000 |
| A-5 | Participation in or viewing outdoor activities | UL | UL | UL | UL | UL | UL |
| Business | Offices, professional services, outpatient clinics | 69,000 | 121,000 | UL | UL | UL | UL |
| Educational | | 43,500 | 76,100 | 131,000 | UL | 109,000 | UL |
| Factory/Industrial | | | | | | | |
| F-1 | Moderate hazard (not low hazard) | 46,500 | 81,400 | 140,000 | UL | 116,000 | UL |
| F-2 | Low hazard (involves manufacturing of noncombustible materials) | 69,000 | 121,000 | UL | UL | UL | UL |
| Hazardous | | | | | | | |
| H-1 | Buildings or structures which contain materials that present a detonation hazard—Explosives | 7,000 | 12,300 | 21,000 | 33,300 | 17,500 | 33,300 |
| H-2 | Buildings or structures which contain materials that present a deflagration hazard or a hazard from accelerated burning—Flammable or combustible liquids | 21,000 | 36,800 | 63,000 | 99,800 | 52,500 | 99,800 |
| H-3 | Buildings or structures which contain materials that readily support combustion or present a physical hazard—Aerosols, combustible fibers, and flammable solids | 42,000 | 73,500 | 126,000 | UL | 105,000 | UL |
| H-4 | Buildings or structures which contain materials that are health hazards—Corrosives, highly toxic materials, and radioactive materials | 52,500 | 91,900 | UL | UL | 131,000 | UL |
| H-5 | Semiconductor fabrication facilities and comparable research and development areas in which hazardous production materials are used (exceeding specified quantities) | 69,000 | 121,000 | UL | UL | UL | UL |

**Table A-1.** *Continued*

| Class I Membrane | | Base Area | With 30 ft Open Space on All Sides | With Sprinklers | With 30 ft Open Space on All Sides + Sprinklers | With 60 ft Open Space on All Sides | With 60 ft Open Space on All Sides + Sprinklers |
|---|---|---|---|---|---|---|---|
| Institutional | | | | | | | |
| I-1 | Supervised residential care facility with >16 people 24 h | 30,000 | 52,500 | 90,000 | UL | 75,000 | UL |
| I-2 | Medical or custodial care with >5 people 24 h, not capable of self-preservation | 11,000 | 19,300 | 33,000 | UL | 27,500 | UL |
| I-3 | More than 5 people not capable of self-preservation because of security measures | 30,000 | 52,500 | 90,000 | UL | 75,000 | UL |
| I-4 | Day-care facilities | 39,000 | 68,300 | 117,000 | UL | 97,500 | UL |
| Mercantile | | 37,500 | 65,600 | 113,000 | UL | 93,800 | UL |
| Residential | | | | | | | |
| R-1 | Transient (hotels and boarding houses) | 48,000 | 84,000 | UL | UL | 120,000 | UL |
| R-2 | More than two dwelling units (apartments and dormitories) | 48,000 | 84,000 | UL | UL | 120,000 | UL |
| R-3 | 1–2 family dwellings | UL | UL | UL | UL | UL | UL |
| R-4 | Assisted living facilities with <16 people | 48,000 | 84,000 | UL | UL | 120,000 | UL |
| Storage | | | | | | | |
| S-1 | Moderate hazard storage | 52,500 | 91,900 | UL | UL | 131,000 | UL |
| S-2 | Low hazard storage of noncombustible materials, may be on wood pallets or in cardboard | 78,000 | 136,500 | UL | UL | UL | UL |
| Miscellaneous | Private garages, carports, sheds, and agricultural buildings | 25,500 | 44,600 | 76,500 | 121,000 | 63,800 | 121,000 |

**Table A-1.** *Continued*

| Class II Membrane | | Base Area | With 30 ft Open Space on All Sides | With Sprinklers | With 30 ft Open Space on All Sides + Sprinklers | With 60 ft Open Space on All Sides | With 60 ft Open Space on All Sides + Sprinklers |
|---|---|---|---|---|---|---|---|
| Assembly | | | | | | | |
| A-1 | Assembly uses, usually with fixed seating, intended for the production and viewing of performing arts (theaters and studios) | 16,500 | 28,900 | 49,500 | 78,400 | 63,800 | 121,000 |
| A-2 | Food and drink consumption | 18,000 | 31,500 | 54,000 | 85,500 | 71,300 | 135,000 |
| A-3 | Worship, recreation, amusement, library | 18,000 | 31,500 | 54,000 | 85,500 | 71,300 | 135,000 |
| A-4 | Indoor sporting events | 18,000 | 31,500 | 54,000 | 85,500 | 71,300 | 135,000 |
| A-5 | Participation in or viewing outdoor activities | UL | UL | UL | UL | UL | UL |
| Business | Offices, professional services, outpatient clinics | 69,000 | 121,000 | UL | UL | UL | UL |
| Educational | | 43,500 | 76,100 | 131,000 | UL | 109,000 | UL |
| Factory/Industrial | | | | | | | |
| F-1 | Moderate hazard (not low hazard) | 46,500 | 81,400 | 140,000 | UL | 116,000 | UL |
| F-2 | Low hazard involves manufacturing of noncombustible materials | 69,000 | 121,000 | UL | UL | UL | UL |
| Hazardous | | | | | | | |
| H-1 | Buildings or structures which contain materials that present a detonation hazard—Explosives | 6,000 | 10,500 | 18,000 | 28,500 | 15,000 | 28,500 |
| H-2 | Buildings or structures which contain materials that present a deflagration hazard or a hazard from accelerated burning—Flammable or combustible liquids | 9,000 | 15,800 | 27,000 | 42,800 | 52,500 | 99,800 |
| H-3 | Buildings or structures which contain materials that readily support combustion or present a physical hazard—Aerosols, combustible fibers, and flammable solids | 15,000 | 26,300 | 45,000 | 71,300 | 105,000 | UL |
| H-4 | Buildings or structures which contain materials that are health hazards—Corrosives, highly toxic materials, and radioactive materials | 52,500 | 91,900 | UL | UL | 131,000 | UL |
| H-5 | Semiconductor fabrication facilities and comparable research and development areas in which hazardous production materials are used (exceeding specified quantities) | 69,000 | 121,000 | UL | UL | UL | UL |

**Table A-1.** *Continued*

| Class II Membrane | | Base Area | With 30 ft Open Space on All Sides | With Sprinklers | With 30 ft Open Space on All Sides + Sprinklers | With 60 ft Open Space on All Sides | With 60 ft Open Space on All Sides + Sprinklers |
|---|---|---|---|---|---|---|---|
| Institutional | | | | | | | |
| I-1 | Supervised residential care facility with >16 people 24 h | 13,500 | 23,600 | 40,500 | 64,100 | 75,000 | UL |
| I-2 | Medical or custodial care with >5 people, 24 h, not capable of self-preservation | 4,500 | 7,880 | 13,500 | 21,400 | 11,300 | 21,400 |
| I-3 | More than 5 people not capable of self-preservation because of security measures | 15,000 | 26,300 | 45,000 | 71,300 | 75,000 | UL |
| I-4 | Day-care facilities | 27,000 | 47,300 | 81,000 | 128,000 | 97,500 | UL |
| Mercantile | | 37,500 | 65,600 | 112,500 | UL | 93,800 | UL |
| Residential | | | | | | | |
| R-1 | Transient (hotels and boarding houses) | 21,000 | 36,800 | 63,000 | 99,800 | 120,000 | UL |
| R-2 | More than two dwelling units (apartments and dormitories) | 21,000 | 36,800 | 63,000 | 99,800 | 120,000 | UL |
| R-3 | 1–2 family dwellings | UL | UL | UL | UL | UL | UL |
| R-4 | Assisted living facilities with <16 people | 21,000 | 36,800 | 63,000 | 99,800 | 120,000 | UL |
| Storage | | | | | | | |
| S-1 | Moderate hazard storage | 52,500 | 91,900 | UL | UL | 131,000 | UL |
| S-2 | Low hazard storage of noncombustible materials, may be on wood pallets or in cardboard | 78,000 | 137,000 | UL | UL | UL | UL |
| Miscellaneous | Private garages, carports, sheds, and agricultural buildings | 25,500 | 44,600 | 76,500 | 121,000 | 63,800 | 121,000 |

NOTE: To obtain approximate metric equivalents, multiply distances by 0.3 and areas by 0.1. UL indicates unlimited

## A.5 SPECIAL PROTECTION

**A.5.1 Fire Extinguishers**—Fire extinguishers shall be provided in quantities, size, type, and location as required by the local fire code and NFPA 10.

**A.5.2 Standpipes**—Standpipes shall be provided as required by the authority having jurisdiction and shall comply with NFPA 14.

**A.5.3 Sprinkler Systems**—Sprinkler systems shall be provided as required by the authority having jurisdiction and shall comply with NFPA 13.

**A.5.4 Fire Detection and Alarm Systems**—Fire detection and alarm systems shall be provided as required by the authority having jurisdiction and shall comply with NFPA 72.

**A.5.5 Emergency Exits**—Emergency exits shall be provided as required by the authority having jurisdiction.

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# Appendix B
# A PROCEDURE FOR DETERMINING MODULUS OF ELASTICITY

## B.1 GENERAL

Architectural membranes that contain a woven or laid fabric substrate are composite materials. Composites are defined as materials made up of fibers of one type of material embedded in a matrix of another type of material. One such layer is known as a *lamina*, two or more laminae are known as a *laminate*. Composites where the orientation influences the structural behavior are *anisotropic*. If the fibers in a lamina or laminate are oriented at 90 degrees to each other, the material is *orthotropic*.

Most architectural membranes have a woven or knit substrate and are orthotropic. They are usually one lamina thick. Their compression capacity is generally negligible.

The analysis of orthotropic and anisotropic composites is well developed and has been incorporated into many finite element programs. Most of the programs used to analyze architectural membranes consider nonlinear displacements but treat the materials as linear and elastic.

A significant source of nonlinearity in woven membranes is a direct consequence of the weaving process. Woven warp and fill yarns cross over and under each other. The warp yarns are often initially straighter than the subsequently woven fill yarns. When the composite material is loaded in one direction, the yarns parallel to that direction tend to straighten. The yarns perpendicular to the direction of load tend to accept more crimp. The elongation characteristics of architectural membranes tend to be dependent on the direction of load, the magnitude of the load, and the relative amount of load distributed among the orthogonal yarns. The geometric interaction of the yarns caused by varying orthogonal load ratios is analytically modeled as a Poisson effect. The geometric interaction of warp and fill yarns may result in Poisson values significantly larger or smaller than those associated with most materials.

Laid membranes and woven membranes have nonlinearity associated with the elongation characteristics of the material used in the yarn, the regularity of the yarn, and the interaction of the yarn with the matrix material.

## B.2 THEORY OF ELASTICITY FOR FABRICS

The general relationship between stress and strain is

$$\sigma_i = C_{ij}\varepsilon_j \qquad \text{(B-1)}$$

where $\sigma$ is the stress, $\varepsilon$ is the strain, and $C$, the stiffness matrix, defines the relationship between stress and strain.. Equation B-1 as written is for the generalized complex case of stress and strain in the three $x$, $y$, and $z$ direction coordinates. Architectural membranes are usually modeled with orthotropic plane stress properties. In this case, the stress–strain relationship may be written as

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix} = \begin{bmatrix}C_{11} & C_{12} & o\\ C_{21} & C_{22} & o\\ o & o & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \qquad \text{(B-2)}$$

where $\tau$ is the shear stress and $\gamma$ is the shear strain. Although the $C$ terms are multiplied by the strain terms to give the stress, the $C$ terms are *not* the moduli of elasticity (MOEs). They are *used* to get the MOEs by the following relationships:

$$C_{11} = \frac{E_w}{1-\upsilon_{wf}\upsilon_{fw}}, \quad C_{22} = \frac{E_f}{1-\upsilon_{wf}\upsilon_{fw}}, \quad C_{22} = \frac{\upsilon_{fw}E_w}{1-\upsilon_{wf}\upsilon_{fw}}, \quad C_{12} = C_{21} \qquad \text{(B-3)}$$

where $E_w$ and $E_f$ *are* the MOEs in the warp and fill direction, respectively. $E_w$ and $E_f$ are properties of the material solely and do not vary with the loading conditions. They are not the slopes of the stress–strain curves of the material. The slope of the stress–strain curve is the MOE of a material only for the isotropic case. The Poisson's ratio $\upsilon_{wf}$ means that a stress in the warp direction produces a strain in the fill direction. We are working with the warp and fill directions; therefore, it is appropriate to change $\sigma$ and $\varepsilon$ to these designations. Accordingly, $\sigma_l$ becomes $\sigma_w$. Because the shear stress in a fabric is usually low compared with the tensile stress, it is customary to simplify

Eq. B-2 further by eliminating the shear terms. Thus, Eq. B-2 becomes

$$\begin{bmatrix} \sigma_w \\ \sigma_f \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{12} & C_{22} \end{bmatrix} \bullet \begin{bmatrix} \varepsilon_w \\ \varepsilon_f \end{bmatrix} \tag{B-4}$$

or

$$\begin{aligned} \sigma_w &= C_{11}\varepsilon_w + C_{12}\varepsilon_f \\ \sigma_f &= C_{12}\varepsilon_w + C_{22}\varepsilon_f \end{aligned} \tag{B-5}$$

It is a property of linear elastic materials that

$$\frac{E_w}{\upsilon_{wf}} = \frac{E_f}{\upsilon_{fw}} \tag{B-6}$$

Because fabrics are only capable of carrying tensile loads, Eq. B-5 is written

$$\begin{aligned} T_w &= C_{11}\varepsilon_w + C_{12}\varepsilon_f \\ T_f &= C_{12}\varepsilon_w + C_{22}\varepsilon_f \end{aligned} \tag{B-7}$$

where $T$ stands for tension. The equations in Eq. B-7 must be solved to obtain the MOEs, $E_w$ and $E_f$. The $T$ and $\varepsilon$ in the Eq. B-7 equations are furnished from test data where the $T$ is in units of force per unit length instead of force per unit area, as is customary with conventional materials. There are three unknowns in Eq. B-7: $E_w$, $E_f$, and $\upsilon_{wf}$ or $\upsilon_{fw}$. The solution of the two equations with three unknowns is made possible through use of test data, as will be shown later.

## B.3 METHODS OF TESTING FABRICS

The most common method of testing fabrics today is to test a cruciform specimen (Fig. B-1). In this test, stress and strain are concurrently measured in the two orthogonal directions of warp and fill. One way of doing this is to keep a fixed ratio of warp–fill force and vary both while keeping the ratio constant. This is the manner in which Figs. B-2 and B-3 were obtained (Minami and Motobayashi 1984). The curves in both figures designated as warp 1 : 2 plot the stress–strain curve of the warp when the ratio of warp to fill forces is held constant at 1 to 2. The curves in both figures designated as fill 1 : 2 plot the stress–strain curve of the fill subject to the same ratio.

Numerous testing techniques are not discussed here but are discussed fully elsewhere (Membrane Structures Association of Japan 1995). Figures B-2 and B-3 show typical results of stress–strain tests on fiberglass and polyester, respectively. Table B-1 gives the properties of the fiberglass and the polyester that were tested.

Several observations can be made from examination of Figs. B-2 and B-3. Both the fiberglass and the polyester test results show the nonlinear nature of both materials, particularly on the first application of

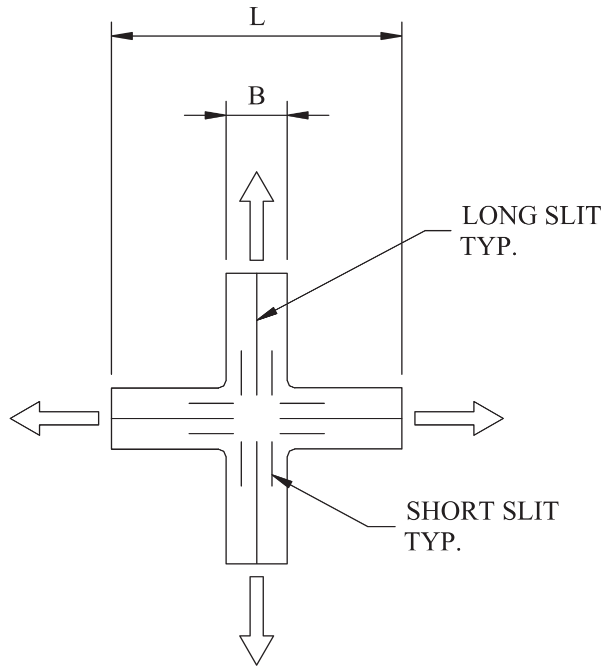


**FIGURE B-1. Specimen for Biaxial Test**

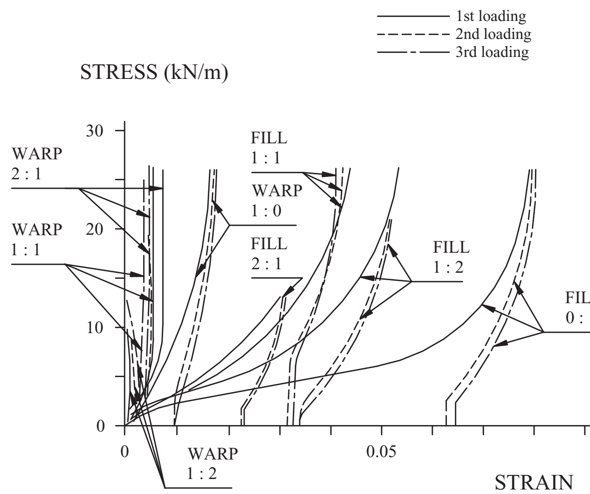


**FIGURE B-2. Biaxial Stress–Strain Curve of Fiberglass**

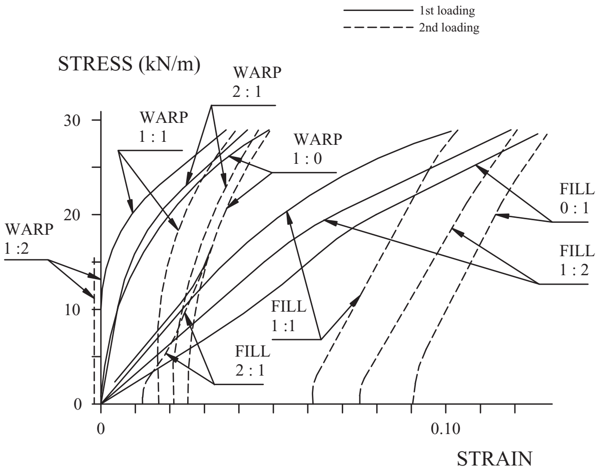


**FIGURE B-3. Biaxial Stress–Strain Curve of Polyester**

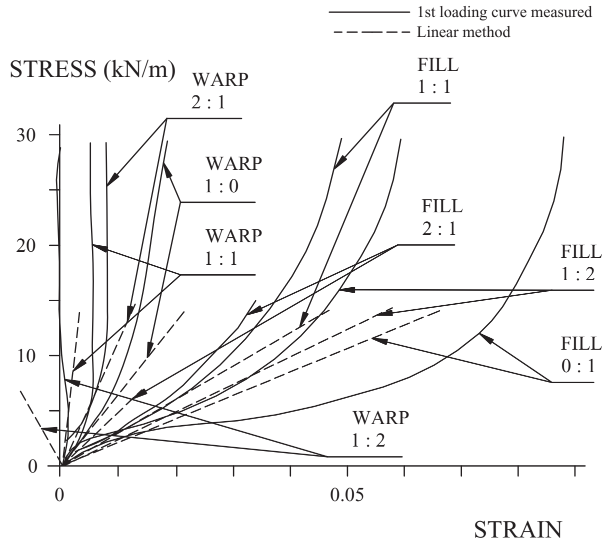


**FIGURE B-4. Biaxial Stress–Strain Curve of Fiberglass with Linearization Lines**

**Table B-1. Materials Tested Using Alternative Test Method**

| Yarn | Coating Material | Breaking Strength (kN/m) |
|---|---|---|
| Glass Fiber | Polytetrafluroethylene (PTFE) (Teflon) | 144/128 (warp/fill) |
| Polyester | Polyvinylchoride (PVC) | 128/90 (warp/fill) |

loading. The behavior more closely approaches the linear on the second and subsequent loadings. The fiberglass shows strain hardening as the force increases. The increasing slope of the stress–strain curve shows this change as the force increases. In contrast, the polyester shows strain softening by the decreasing slope of the stress–strain curves.

It is generally not necessary to examine these curves when stresses are a high percentage of the breaking stress, as shown in Table B-1, because these high stresses are not permitted to occur in the fabric design. Accordingly the one-quarter breaking strength limitations of Table B-1 are shown on Figs. B-2 and B-3. Nothing above these lines need be examined. For simplicity, the lower values of one quarter of the breaking strength of the fill are chosen as the cutoff values. The curves for the first few kilonewtons of force can also be ignored because at these low forces the coating carries a high percentage of the load. Also, at low forces the slack in the weaving of the yarns skews the results.

## B.4 LINEARIZING THE CURVES

The curves in Figs. B-2 and B-3 show the results of the stress vs. strain tests. The stress–strain relationship is not linear; the slope of the curve varies from point to point. Hence, if the MOE were to be found directly from these curves, the MOE would vary with the stress. It is difficult and usually not necessary to work with an MOE that varies with stress. Most practical design is done using a single value for the MOE. To get this single value for each of the two MOEs, it is necessary to choose a slope for the stress–strain curves, i.e., choose representative straight lines. There are many ways to linearize test data. The usual procedure is to use the least squares method (LSM). The LSM is straightforward and is described in math texts, frequently under the heading of linear algebra. It is not necessary to be familiar with the method to use it. Many computerized mathematics programs include it under the single command of “Least Squares.” If the test data are entered, the Least Squares command performs all the mathematical steps and produces a straight-line linearization.

Figure B-4 is adopted from Fig. B-2 and shows the LSM linearization of the test curves of Fig. B-2. There are seven straight lines shown for the linearization of warp and fill test results for the three different warp–fill ratios of loading. These seven lines may be used in place of the curved test results. Fig. B-4 has been simplified by showing only the curves of first loading from Fig. B-2. Also, the uniaxial curves of fill 0 : 1 and warp 1 : 0 are removed because they are not biaxial behavior curves and they give erroneous values. The negative slope to the warp 1 : 2 line can be explained by the way in which the fabric is made. When the fabric is made, the warp fibers are pulled straight and the fill fibers are woven around the straight warp threads. If there is a high fill stress accompanied with a low warp stress, the warp fibers are bent and hence shorten. It should be noted that, contrary to uniaxial tests, both directions of the fabric stretch for most loadings.

The equations in Eq. B-7 combined with the six straight lines are used to get the four unknowns of $E_w$, $E_f$, $\upsilon_{wf}$, and $\upsilon_{fw}$. The slopes of the six straight lines are not themselves MOEs; however, they are used to get the MOEs. The technique used is to take stress values along with their associated strain values from the straight lines and insert them into Eq. B-7. The values used must be consistent with the actual test procedures, i.e., if the warp–fill lines associated with a 2 : 1 ratio are used, then the fill stresses used in Eq. B-7 must equal half the warp stresses, and so forth. In principle, any of the six straight lines could be used to get the four unknowns. However, in practice all the lines should be used and the results averaged. Table B-2 shows the values for the MOE and Poisson's ratio that were obtained from the foregoing procedure.

The MOE and Poisson's ratios shown in Table B-2 are only for the specific fiberglass material tested and only for the first loading. As would be expected from the much steeper stress–strain curves in Fig. B-2 for the second and third loadings, the MOE for these loadings would be considerably higher. Some materials have been preloaded to partially eliminate the high permanent stretch of the first loading. The final selection of MOEs, of necessity, requires modification by engineering judgment. Only the engineering designer can estimate the level of stress attained by the structure over its lifetime. This level in turn affects the actual MOE to be selected for design of the structure.

**Table B-2. Sample Moduli of Elasticity and Poisson Ratios**

| $E_w$ | $E_f$ | $\upsilon_{wf}$ | $\upsilon_{fw}$ |
|---|---|---|---|
| 634 kN/m | 213 kN/m | 0.29 | 0.87 |

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# COMMENTARY

## C.1 GENERAL

For basic information about the unique nature of tensile membrane structures, the user is referred to *Tensioned Fabric Structures: A Practical Introduction*, a special publication of the American Society of Civil Engineers (1996).

### C1.1 Scope

Tensile membrane structures are an engineered system that serves as the primary architectural building envelope. These structures are unique, they behave nonlinearly, and much of the membrane analysis is done by proprietary software. Construction of tensile membrane structures can be done several different ways. ASCE (2000) lists and describes several alternative construction methods that can be used in building these structures.

This standard covers structural applications of tensile membrane in buildings. The standard is intended to cover significant aspects of the design and construction of tensile membrane structures not covered by existing standards or codes. It must be recognized that most tensile membrane structures are integrated systems of components, such as cables, steel, and aluminum or timber elements, in addition to the tensile membrane. As such, the structure must be considered as a single entity and have appropriate structural integrity, although the use of various components and materials is subject to their respective standards.

Temporary or seasonal structures are usually erected by special permit from the authority having jurisdiction and allowed to remain for only a specified and limited time period. Temporary structures may be constructed for use any time of year, whereas seasonal structures are not usually erected when they would be subjected to the most severe loading, e.g., during the winter in northern climates, where they would be subjected to snow loads. They also do not have to comply with the same type of construction or fire code requirements as permanent structures. Their inclusion in this standard represents the fact that this industry requires and accepts a high standard for these types of structures.

### C1.2 Definitions

These are additional definitions not included in the standard but still helpful to understand how these structures are designed and function.

**Anisotropic lamina**—A lamina which has mechanical properties that are different in all directions at a point in the body. Thus the properties are a function of the orientation at a point in the body.

**Anticlastic**—A differential geometry term defining a class of surfaces. The mathematical definition depends on the properties of the equation used to define the surface. For tensioned fabric structures, it is sufficient to define anticlastic as having two principal radii of curvature on opposite sides of the surface (i.e., saddle shaped) (Fig. C-1). Note: the same mathematical equation may define a surface that is part anticlastic and part synclastic.

**Bias**—A direction at an angle to the warp and fill fibers. Bias-cut fabric is fabric that has been cut with its primary axes in a bias direction.

**Boundary cable**—Cable at the edge or termination of the membrane (Fig. C-2).

**Breaking strength**—Usually the same as strip tensile strength. The breaking strength of a two-dimensional orthotropic material, such as fabric, can be different from that of rigid materials, such as steel or concrete. The breaking strength of a fabric in the warp direction varies depending on the tension in the fill direction and the width of the specimen. In narrow specimens, severed fill threads can slide through the warp threads and not contribute to biaxial restraint. Simplification is made by referring to breaking strength of a strip of fabric under simple uniaxial tension.

**Cable, boundary**—Cable at the edge or termination of the membrane (Fig. C-2).

**Cable, ridge**—A concave upward cable usually used to resist downward loads.

**Cable, valley**—A concave downward cable usually used to resist upward loads.

**Cable cuff or cable pocket**—The method of wrapping the fabric around a cable at a boundary condition (Fig. C-3).

**Cable fittings**—Any accessories used as an attachment to, or support for, a cable.

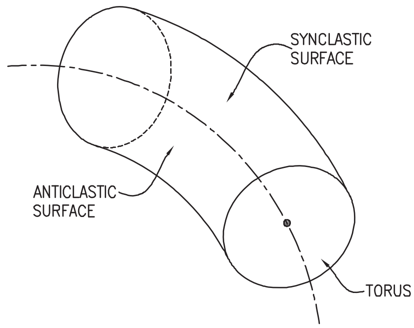


**FIGURE C-1. Anticlastic and Synclastic Surfaces**

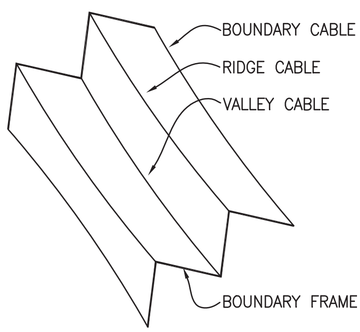


**FIGURE C-2. Boundary, Ridge, and Valley Cables**

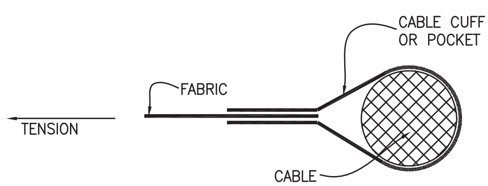


**FIGURE C-3. Cable Cuff or Pocket**

**Catenary**—The curve assumed by a perfectly flexible cable of uniform density and cross section supported between two supports. For convenience, in tensile membrane structures, the term is used to describe the curve assumed by any cable support member.

**Crimp and crimp interchange**—In weaving fabric, fill threads are deformed by being woven (in the roll widthwise or short direction) perpendicular to and around the tightly drawn full length of the roll warp threads. When the fabric is loaded in tension, the fill threads also deform the warp threads, causing a crimp in the fabric (Fig. C-4).

**Curvature**—The maximum and minimum curvature through a point on the surface of the structure (generally orthogonal to each other). Their

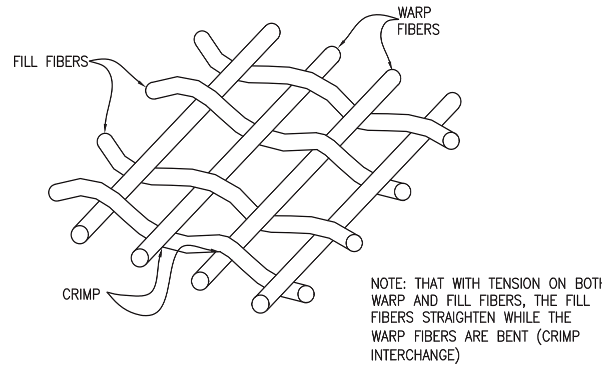


**FIGURE C-4. Crimp and Crimp Interchange**

products define the curvature (Gaussian) of the surface. Mathematically, curvature is the reciprocal of the radius of curvature.

**Fabric assembly**—A panel of membrane material fabricated from one or more pieces of fabric having seams and edge and/or connection details incorporated in the finished structure.

**Field joint**—A connection made on the site between two or more pieces of fabric.

**Geodesic**—A mathematical term defined as the shortest distance or path between two points on a curved surface.

**Isotropic lamina**—A lamina which has mechanical properties that are the same in every direction, i.e., the properties are not a function of orientation at a point in the body.

**Jacking force**—A force exerted by a device that introduces tension into the fabric and/or cables.

**Laid fabric**—A fabric with no crimp during weaving; it therefore exhibits less stretch under load.

**Orthotropic lamina**—A lamina which has mechanical properties that are different in two mutually perpendicular directions at a point in the body. Thus, the properties are a function of the orientation at a point in the body.

**Sectionalize**—To subdivide a tensile fabric structure into separate sections so that damage to one section does not extend to other sections.

**Synclastic**—A surface with both radii of curvature on the same side of the surface (e.g., a spherical or bowl shape) (Fig. C-1).

**Warp-knit, weft-inserted fabric**—A fabric with the warp yarns and fill yarns laid flat in separate layers and held together with a stitching yarn.

**Woven fabric**—A fabric in which the yarns interweave together.

### C1.3 Design Documents

This standard lists some of the important items of information that must be included in the design drawings, details, or specifications. It is not intended to be an all-inclusive list, and additional items may be required by the authority having jurisdiction.

The structural engineer of record may not be experienced in the design of tensile membrane structures. Therefore, it is advisable to either add a specialty structural design engineer to the design team or have the fabricator's engineer produce both the design and fabrication drawings.

In addition to the minimum requirements of information to be included on the drawings, it may be necessary to also include information relating to deflections at key points, which may move and interfere with new or existing construction.

### C1.4 Field Observation

The quality of tensile membrane structures depends on the workmanship in construction. The best of materials and design practice are not effective unless the construction is performed well. Inspection is necessary to ensure satisfactory work in accordance with the design drawings and specifications. Inspection of construction by or under the supervision of the engineer or architect responsible for the design should be considered because the person in charge of the design is the best qualified to inspect for conformance with the design. A record of inspection in the form of a job diary is recommended, and images documenting the progress of the project may also be desirable.

### C1.6 References

For additional reference material, see the bibliography after the appendixes.

## C.2 MEMBRANE MATERIALS

### C2.1 General

The membrane material is usually fabric made of woven or laid yarns, but it can also be a film or foil. The yarns are most commonly made of nylon, polyester, glass, aramid, polyolefin, or PTFE fibers, which may be parallel or twisted together. Films are commonly made of any of the materials used in fabric coatings. In woven fabrics, the yarns pass alternatively over and under each other. In laid fabrics, yarns are placed on top of each other. Fabrics are usually coated with polyvinylchloride (PVC), polytetrafluoroethylene (PTFE), polyolefins, or silicon.

Coatings are typically used to enhance properties such as fire resistance, weather tightness, ultraviolet protection, durability, aesthetics, weldability, workability, ease of maintenance, strength, and stiffness.

### C2.3 Physical Testing

Because of a lack of existing tests for many of these properties, manufacturers have had to develop their own in-house tests to ensure sufficient quality control and assurance.

An in-house test performed by manufacturers of fiberglass products is the flexfold test (tension after flexing). This test is performed on a strip tensile sample, which is folded in half lengthwise and rolled over by a 10-lb weight three times. The sample is then unfolded and a strip tensile test is performed. The level of strength retention is affected by variables such as count, crimp, coating process, and elongation. This test measures the ability of the woven yarns to bend without fracturing individual filaments or losing tensile strength. Composites that allow the yarn to splay or spread have high retention of tensile strength, and those with yarns in close proximity do not. Retention levels normally are in the range of 65 percent to 85 percent. These measurements should be consistent during production. Large deviations from established levels indicate that process variables may have occurred. Lower tensile retention indicates that this fabric is more susceptible to damage during fabrication, handling, and erection.

### C2.4 Physical Properties

The moduli of elasticity (in both directions) and Poisson's ratio (in both directions) are necessary properties for the determination of the basic material properties to be used by the engineer in the analysis of the structure. See Appendix B for additional information.

### C2.5 Membrane Classification and Fire Performance

The performance of tensile membrane structures is unique in terms of its response to fires, as compared to conventional types of construction. The most common tensile membrane construction uses noncombustible elements (steel beams, trusses, or masts and cables) or aluminum frames and heavy timber members supporting a tensioned fabric that is relatively lightweight compared to conventional construction materials.

Although the building fabrics are combustible to some degree, the fire hazard from the structure as a complete building is comparable or even possibly slightly better than that of a plain metal building. The metal building provides the advantage that until the building collapses (which can occur fairly quickly) the fire is contained completely within the building and the building contributes little fuel to the fire. On the negative side, however, the containment of the fire in that manner can cause the fire to progress further and more rapidly because of energy feedback from the enclosure and containment of the heat within the space. In addition, the building contains the smoke, making escape and fire fighting more difficult and smoke damage more severe. The tensile membrane structure, on the other hand, melts where it is in direct contact with the flame, which creates an opening, which can allow smoke and heat to escape. The Class I or Class II fabrics also contribute a small amount of fuel to the fire as they burn. None of the code-complying fabrics traditionally or currently in use, however, ignite and spread the fire across the fabric. This opening of the fabric provides a significant benefit to controlling the fire in that much of the heat and smoke escape the building, reducing the energy feedback to the fire, acting as a smoke and heat vent.

There are two major types of fabric used for tensile membrane structures. The traditional materials have been synthetic, woven fabrics of either polyester or polyolofin, which are coated primarily with vinyl or polyolefin. The other membranes are woven glass fiber fabrics. Over the years, they have been coated with vinyl, PTFE, and silicone. The primary difference from a fire performance standpoint is that the fiberglass-based fabrics contribute less fuel to the fire and do not melt as rapidly as the synthetic, organic fabrics.

There are three situations in which Appendix A can be used. First, where there is no legally adopted code, Appendix A is recommended for use. Second, in many places where there exists a legally adopted building code, it may not contain a methodology for dealing with membrane structures. In this case, Appendix A can be considered by the authority having jurisdiction as an acceptable alternative. And lastly, where codes are in place that provide for regulation of such structures, they may do so as a patchwork addendum to provisions that were historically generated to deal with traditional building materials. In such a case, Appendix A can be considered.

Appendix A is intended to recognize the uniqueness of membrane structures that are inherently incapable of containing a fire. Therefore, lateral protection of adjacent property must be accomplished either by distance or hardening of the adjacent property against exposure. Some of these structures are better at resisting penetration by flying embers or brands than others and, hence, better at protecting the occupants or contents from such external exposures. The limiting provisions of Appendix A were developed considering these concerns.

Under the current building code definitions for noncombustible materials, the glass fiber fabrics can generally be classified as noncombustible. The building code definition allows for a composite product, the core of which passes the ASTM E136 heated tube test, with a facing material having a flame spread rating by the ASTM E84 tunnel test of less than 50. The core of the glass fiber fabrics, being glass fibers, are noncombustible by that test method. The various coatings being used have flame spreads significantly below 50. In spite of that definition, these membranes generally are 50 to 60 percent organic polymer, so in the true scientific sense, they should be considered combustible materials. On the other hand, their fire safety performance is certainly as good as sheet aluminum, and the fuel contribution to a fire by the coatings is insignificant.

Based on these facts, categories of fabric were established to recognize the differences between the two major types of materials in use. As with all materials, no single test is adequate to evaluate the fire safety or hazard of a given material. Therefore, fabrics for tensile membrane structures are required to be evaluated by a number of tests that evaluate the material’s ignitability, contribution of heat to the fire, spread of flame on both interior and exterior surfaces, and resistance to penetration by a burning brand. In reviewing the various test methods that have been used to evaluate fabrics and conventional building materials, the three most common test methods were chosen to be used. These are the NFPA 701, the ASTM E136 combustibility test, and the ASTM E84 tunnel test for evaluation of the interior flame spread.

Although for many applications building codes permit interior finishes to have flame spread ratings as high as 200, we feel, because of the variability of testing thin membranes and the questionable validity of the rating on such materials, that the limit should be set at 25 for all Class I and Class II membranes.

Many membrane structures have high, sloped roof lines and therefore exceed the height limitations outlined in conventional building codes for conventional structures.

Height limits have traditionally been placed on conventional single-story buildings so that when and if there is a fire, fire fighters can get onto the roof to vent the heat and smoke of a fire. Membrane structures are not intended to have people, mechanical equipment, or other things on the roof. During a significant internal fire, the membrane adjacent to the fire source melts. This melting automatically creates a roof opening, allowing the fire, smoke, and heat to vent. This situation is also true for insulated membrane structures. The interior liner would melt and the insulation would fall away, exposing the outer membrane, which would also melt.

In the event that the fire is not close to the structure membrane, the membrane structure may not self-vent. However, because of the high vaulted ceilings in a membrane structure, it has been found that smoke and heat have a tendency to collect in the high roof areas, leaving the occupied floor area clear of smoke, thus making it easier for the public to safely exit the building. Roof monitors with dampers can be installed to remove smoke as it collects in the high roof smoke reservoir areas.

### C2.6 Seams

ASTM D2136 is the standard test method for coated fabric temperature bend testing. It is a pass–fail test at a user-specified temperature. There is no requirement for a low-temperature seam test; however, it is recommended that the seams be tested at the same low temperatures expected of the constructed structure.

## C.3 CONNECTIONS

Fabric-to-fabric connections are required because membranes may be cut into patterns before being shipped to the jobsite. These patterns are selected to minimize seams and splices and to reduce stress concentrations. The final assembly is constructed by attaching the various patterns together at the edges with seams.

Fabric-to-fabric connections are necessary because membranes are often patterned into doubly curved surfaces. The cut strips are selected to maximize the use of material, minimize seams, and minimize the potential for stress concentrations. The assembled strips, usually called panels, are shipped and assembled as individual elements in the field.

Termination of a membrane can occur at rigid edges or boundary conditions, such as arches, masts, beams, walls, or foundations. These types of connections are usually made at reinforced, fabric rope, or clamped edges. Clamping hardware is usually continuous, with rounded edges, to minimize stress concentrations and membrane distortions.

## C.4 DESIGN

### C4.2 Loads

Loads used for design of tensile membrane structures can be determined by ASCE 7, except for cases where the unique geometry or behavior have the potential to create unusual loading conditions.

Superimposed dead loads are more variable than self-weight, and other permanent loads and are not imposed on the structure all the time. The designer must be aware that the presence or absence of superimposed dead loads may have a substantial effect on the design and must be considered, especially in conditions of uplift caused by wind loads. The standard requires the designer to consider this type of load as a permanent load when determining the shape of the structure and as a live load when sizing members and calculating deflections.

Tension membrane structures can have unique shapes that are not covered by ASCE 7, which does not provide a procedure to calculate snow loads for uniquely curved and folded roofs. As in most standards, this document permits the use of research and testing to establish roof snow loads. When experimental procedures are used to establish roof snow loads, the analysis must take into account the additional accumulated snow caused by the deflection of the membrane. Wind tunnel model studies, similar tests using fluids other than air (for example, water flumes), and other special experimental and computational methods have been used with success to establish design roof loads for complex roof geometries.

### C4.3 Considerations for Design and Analysis

Tension membrane structures are usually complex in their geometry and behavior, and their design and analysis require judgment and experience, as well as technical knowledge of structural engineering. Because of the uniqueness of these structures, the use of a special consultant or even a project peer review is highly recommended, especially when designing large or complex structures. ASCE Standard 22–97, *Civil Engineering Independent Project Peer Review*, is a valuable guide for properly implementing a project peer review.

A number of conditions affect tensile membrane structures more than other types of structures. Section 4.3.4 provides a list of common critical conditions to be considered.

Most engineering structures are considered to behave linearly. It is normally assumed that if an external load is applied to the structure, the stresses and deflections have a linear relationship to the external load. If this assumption is not true, the structure is said to behave nonlinearly. Nonlinear behavior may be the result of large changes in shape under load (geometric nonlinearity) or by nonlinear material behavior (material nonlinearity). Nonlinear analysis is required when there is a significant nonlinear relationship between the loads (input) and the stresses and displacements (output).

Membrane and cable elements of tensile membrane structures are primarily loaded in tension and have little or no bending or shear stiffness. Therefore, they rely on their shape and internal prestress to achieve stability and carry loads. These structural elements tend to be nonlinear in behavior, though remaining more or less linearly elastic. When analyzing the structure, industry practice is to assume that the material behavior remains linear over the load range considered and that changes in geometry cause the nonlinear behavior.

In a linear structure, if the load doubles, the stresses are doubled, and if the load is halved, the stresses are halved; the stresses are proportional to the loads. Some membrane structures behave in this fashion, although most behave nonlinearly. In a prestressed membrane spanning between two supports, as the load increases, the sag increases, and the stresses grow at a lower rate than the loads. Depending on the boundary conditions, in some cases as the load increases, the stresses grow at a faster rate and the deflections grow at a slower rate. It is possible that both conditions can occur in the same structure.

The following example illustrates the differences between a linear and nonlinear structure. Both use a factor of safety of 5, and the membrane has been selected to support a 30-lb/ft$^2$ snow load at a 20-lb/in. stress. In the nonlinear structure, when the load increases from 1 to 1.6, the load effect increases from 1 to 1.4.

From a snowstorm with an average snow load of 40 lb/ft$^2$, the load effect is $20 \times 40/30 = 26.7$ lb/in. for the linear structure. For the nonlinear structure, the load effect is $20 \times 40/30 \times 1.4/1.6 = 23.3$ lb/in. The nonlinear structure has a lower stress and is safer than the linear one under the 40-lb/ft$^2$ load. If the nonlinearity is such that the load effects increase faster than the loads, and assuming that for a 1.4 load increase the load effect increase is 1.6, the actual load effect under the 40-lb/ft$^2$snowstorm is $20 \times 40/30 \times 1.6/1.4 = 30.5$ lb/in. For this case, the linear structure has a lower stress and is safer than the nonlinear one.

To gain a clear understanding of the behavior of the membrane, the designer should run several analyses: one at the service load value and others at higher and lower loads to determine the membrane stresses. The structure should be designed for the maximum stress.

**C4.5 Load Combinations**

During the preparation of this standard, there was much discussion about whether the design of the membrane elements should be based on an allowable stress design (ASD) or a load resistance factor design (LRFD) approach. The standard recognizes the complexities of these types of structures and their geometric and material nonlinearities and how they represent a challenge to the designer, not only in determining the appropriate loads, but in understanding the material behavior as well.

Even more of a concern with membrane design is the fact that the resistance of these materials is not dependent on a single property like tensile strength but rather on a complex combination of biaxial properties, which include tear strength (see below) and tear propagation. Even the modulus of elasticity, a property required during the analysis procedures to determine stiffness, is not only highly variable between types of materials and manufacturers, but it is also not very well defined and is significantly affected by the load history of the individual sample. It is somewhat difficult to calculate.

Current industry practice is to use a factor of safety of 8.0 for prestress plus dead load, 5.0 for prestress plus snow load, and 4.0 for prestress plus wind load. Using the life-cycle factor of 0.75 given in Section 4.4.2.1 and the strength reduction factors given in Section 4.5.2, the results are equivalent factors of safety of 7.85 for prestress plus dead load, 4.93 for prestress plus snow load, and 4.04 for prestress plus wind.

A structure that appears to behave well under normal loading may become unstable with the addition of more load or with the removal of some load (e.g., insufficient prestress), or it may be temporarily unstable at some point in the nonlinear analysis that falls between load steps. Similarly, the load–member force response curve for one or more members in a complex tensile membrane structure may exhibit an unexpected peak at values above or below the normal loading. Because of this, the provisions of Section 4.5.3 represent overload and underload possibilities to force the designer to examine the behavior of the structure beyond the standard envelope and over a wide range of load applications.

Because of the low degree of accuracy to which membrane materials can be uniformly determined and because of the wide range and complexities of the loadings on tensile membrane structures, the standard is based on past successful usage of safety factors in thousands of constructed projects. Accurate statistical and probabilistic methods for determining load and resistance factors are currently not possible because of the lack of data for each of them. The majority of knowledge and experience with safety factors derives from polyester and glass fibers fabrics.

The loading combinations given in Sections 4.5.2 and 4.5.3 are not all inclusive, and designers must exercise judgment with the analysis. The design should be based on the load combination causing the most unfavorable effect, keeping in mind that in some cases, this effect may occur when one or more loads are not acting. Furthermore, the full and partial intensity of live loads over portions of the structure should be considered. Partial loads can produce higher local load effects in a structure than a full-intensity load over the complete structure.

Attention to fabric detailing to prevent high-stress concentrations and/or tearing is critical with stiff fabrics with low tear strengths. The greater the possibility of a cut in the fabric caused by airborne objects or vandalism, the higher the factor of safety should be.

### C4.6 Component Resistance

Membranes can be assembled from a wide variety of materials, and numerous fabrics are commercially available. Many fabrics are manufactured for specific properties (e.g., translucency or weatherability), which in turn may affect the other properties. It is the responsibility of the engineer to fully understand the properties, behavior, and response of the selected membrane material.

Examinations of actual fabric membrane failures indicate that tensile ruptures are extremely rare. Commonly, fabric membrane failures occur at seams. If not at a seam, they are the results of tear propagation subsequent to a puncture or snag caused by the unrestrained propagation of discontinuities in the membrane. This design standard checks the tensile capacity of the fabric and relies on historical data indicating that limiting tensile stresses provides structures with adequate levels of safety against failure, whether tensile or tearing. To account for these effects, standard industry practice has been to require a reduction of strip tensile capacity up to 20 percent under biaxial tension.

Tear strength is the property of a membrane that describes its ability to resist the propagation of a discontinuity. This discontinuity may originate through a tensile failure of the membrane or through a puncture from an object. Tear strength is dependent on a number of variables, including the weave of the fabric. Films have a significantly lower tear strength than fabric. The tear strength is tested in accordance with the trapezoidal tear test in ASTM D4851. Because the tear strength is significantly lower than the strip tensile strength, failures of membrane envelopes occur through tearing from a discontinuity in the membrane.

Two types of tests are available to evaluate laboratory tear resistance: the tongue tear method in ASTM D2261 and the trapezoidal tear method (ASTM D4851). Whereas both tests evaluate tear resistance, the in-plane trapezoidal tear method is more appropriate for tensile membrane structures. However, even trapezoidal tear results are incomplete, and resistance to tear propagation of fabrics in use also varies with other properties, such as yarn tenacity, yarn count, yarn mobility, coating stiffness, and stresses in the fabric under actual field conditions.

The present state of industry knowledge does not provide designers the ability to analyze a structure for or calculate a failure limit state for tear capacity. Caution must be used if attempting to set a limit state defined by tear propagation caused by an induced puncture at ultimate loads. Fabric does not benefit from load redistribution around a failure, and the fabric tear failure is sudden and brittle. Furthermore, because the driving force for tear propagation in a fabric membrane is the elastic energy stored in its extended, deflected condition, the resistance to tear at higher fabric stress levels can be less than that inferred by the tensile analysis. Limiting tensile stresses used in the standard are based on experience with known fabric and applications. New fabric materials and applications may warrant different factors.

As new fabrics and applications evolve, additional caution and detailed evaluation and testing are required.

### C4.7 Anchorage

In some cases, the engineer of the foundations is not the same engineer as the designer of the tensile membrane structure, and it is therefore important that there be good communication and cooperation between the two. This section provides the minimum criteria that the engineer of the structure should provide to the engineer of the foundation.

Close coordination is required, especially where the anchorage system is concerned, to ensure that the behavior of the structure under load (i.e., movement) does not have a negative effect on the membrane, its support elements, or its connections.

## C.5 FABRICATION AND ERECTION

### C5.1 Fabrication

Various methods exist for the development of template data, including physical models, geometric calculations, and three-dimensional computer surface modeling. Any method that gives reliable dimensions across the design surface can be used. The method selected should be based on such factors as size and complexity of the structure, amount of curvature in the surface, seam pattern desired, and the physical properties of the membrane.

To achieve a structure with the desired shape and the design prestress, it is critical to maintain membrane fabrication tolerances. The fabric, which is compensated for elongation, is stretched during installation, which induces prestress. The actual deformation depends primarily on the amount of prestress, the dimensions of the fabric panels, and the membrane elongation properties.

In general, the fabricator is responsible for obtaining the various raw materials intended for use in the tensile membrane structure, as well as for assembling those materials. An effective quality control program specifies methods required to purchase materials meeting the project specifications, proper storage and handling, cutting and assembly to required tolerances, and packaging and shipping practices consistent with the materials' properties.

Compensation values are determined from biaxial elongation testing of the membrane. Rolls can be sorted into groups with similar uniaxial properties and tested in accordance with Section 2.3.

As a minimum, it is recommended that the contractor maintain the following:

- membrane strength and elongation test;
- material test reports for fasteners and steel and aluminum fabrications;
- full traceability of the membrane source, including roll numbers;
- a fabrication shop practice manual;
- records of membrane cutting tolerances;
- seam sealing records, including power and/or temperature and pressure settings;
- folding and unfolding instructions; and
- recommended membrane stressing procedures.

### C5.2 Erection

It is recommended that the erection of tensile membrane structures be performed under the supervision of the fabricator. This supervision helps to ensure that handling and stressing of the membrane are correctly performed. A well-documented erection procedure, designed for the individual structure, is an essential quality control measure.

A detailed installation procedure helps to ensure that the membrane is deployed in such a way as to minimize the risk of damage from handling and exposure to wind and rain and to facilitate the installation and prestressing process. In some cases, low-membrane prestress levels can create high stress levels in other parts of the structure.

Structures that are large and/or complex may require computer analysis of the structure (and its effects on the substructure) at various stages of construction. This analysis is often accomplished by modeling construction steps of the finished structure in reverse order, essentially disassembling the structure. Attention should be paid to unbalanced loads, where one area is stressed to a higher level than an adjacent area.

The erector must take all precautions necessary to ensure that the structure remains stable during erection and does not pose a threat to the public safety or to the integrity of adjacent structures. Methods of erecting and stressing the membrane, although subject to review by the engineer of record, are the responsibility of the erector.

Structures with large unsupported membrane areas are highly susceptible to damage from all but the lightest winds (under 10 mi/h). The erector must be able to erect and stress the membrane under low wind conditions or must have a contingency plan to control the membrane in the event of a sudden increase in local wind speed.

## C.A APPENDIX A SPECIAL PROVISIONS

The history of tensile membrane structure regulation dates back to efforts to control circus tent flammability as a result of the circus fire in Hartford, Connecticut, in 1944, in which 168 lives were lost. These regulations focused on requiring that the tent fabric be flame resistant, that there be adequate exiting from the grandstands and from the tent, and that there be sufficient cleared space around the tent to control ignition sources there and to permit rapid emergency exiting.

When membrane structures first came into common use, their primary applications were as temporary, seasonal covers for outdoor areas, such as swimming pools and tennis courts. These covers would be put up during the winter and taken down for the summer. They were, therefore, classified as temporary structures, which today is generally defined as being in place for fewer than 180 consecutive calendar days. The requirements for such structures were essentially the same as for tents.

Large, permanent tensile membrane structures began to see significant use in the United States in the early 1960s. At that time, no provisions in any of the building codes defined and accepted such a structure. In the late 1960s, as a result of the erection of several major architectural fabric buildings and roof structures in California, an effort was begun to develop new provisions in the *Uniform Building Code* published by the International Conference of Building Officials. That effort, however, specifically addressed the PTFE-coated glass fiber membrane that was being used on those projects and, therefore, the provisions were written around that material. The provisions as written effectively banned the use of any of the other membranes, even though they had been used for many years in more traditional fabric structure applications.

The code permits allowable floor area to be increased when the perimeter of the building is more accessible to the local fire department. No increase is allowed until at least 25 percent of the building perimeter is accessible. It also mandates that the open space be at least 20 ft wide before area increases are allowed. The equations shown provide the method for calculating the amount of increase. Table A-1 shows the allowable increase when the entire perimeter of the building is accessible and when the open space width is at least 30 ft. For conditions where the open perimeter is more than 25 percent but less than 100 percent, or the open space width is more than 20 ft but less than 30 ft, it is necessary to use the equations to determine the allowable area increase.

Class III materials are limited to occupancies that are intended to be well away from adjacent exposures and to be occupied only by those few who use them in the course of their work. Examples would include agricultural buildings, such as greenhouses.

**Table A-1 Maximum Footprint Areas**
Allowable floor areas for membrane structures were established by adding a multiplication factor of three (3) to the formulas in the International Building Code for Type IIB and Type VB construction. All other allowable area increases are then added, such as side yards and sprinkler systems, using the formulas in Section A.1.2.

This increase is based on the following:

1. An internal fire source may generate sufficient heat to damage the membrane, which allows for the venting of smoke and heat.
2. Conventional sprinkler and fire alarm systems can be designed and installed to activate if and when a fire occurs away from the structure membrane. Other fire suppression systems are on the market, such as foam deluge and water cannons, which can be incorporated.
3. Membrane structures can be set back from existing buildings and vegetation to prevent the spread of a fire from external sources.
4. Membrane structures can be easily penetrated by fire-fighting personnel. Fire fighters can fight the fire from the perimeter of the structure.
5. The risk of flashover is also greatly minimized because of early heat and smoke venting.
6. Because of the high vaulted ceilings in a membrane structure, it has been found that smoke and heat have a tendency to collect in the high roof areas, leaving the floor clear of smoke and making it easier for the public to safely exit the building and for fire fighters to locate and extinguish the fire.
7. Emergency exits with panic hardware can be easily installed into a membrane structure. Exit distances can be reduced or increased based on occupancy, exit distances, width, and quantity.
8. Roof monitors with dampers can be installed to remove smoke as it collects in the high roof (smoke reservoir) areas.

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