

CONCEPTUAL DESIGN OF MEMBRANE STRUCTURES

BY

VITTORIO C. AGNESI

BACHELOR OF SCIENCE IN CIVIL ENGINEERING
JUNE 1997
SWARTHMORE COLLEGE

SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY


MAY 1998

Copyright © 1998 Massachusetts Institute of Technology
All Rights Reserved

SIGNATURE OF AUTHOR

VITTORIO C. AGNESI
MAY 8, 1998

CERTIFIED BY


JEROME J. CONNOR
PROFESSOR, DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
THESIS SUPERVISOR

APPROVED BY


JOSEPH M. SUSSMAN
CHAIRMAN, DEPARTMENTAL COMMITTEE ON GRADUATE STUDIES

JUN 02 1998

LIBRARIES

CONCEPTUAL DESIGN OF MEMBRANE STRUCTURES

BY

VITTORIO C. AGNESI

SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING ON
MAY 8, 1998

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING

ABSTRACT

Since the introduction of the contemporary tensile structures in the 1950's, technological advances throughout the decades have lead to dramatic improvements over their early counterparts. Membrane structures are a class of tensile structure that require the entire surface to remain in tension and have opposing radii of curvature in order to maintain stability. Improved membrane strength and corrosion resistance in synthetic fabrics and films have allowed architects and engineers to create permanent and large-scale structures using this technology. However, the non-linearity, complexity in fabrication, and performance characteristics of membranes has limited their application.

The affordability and speed of computing power in the 1990's is changing the way membrane structures are designed and manufactured. The early membrane structures were designed using physical models to explore the curved surfaces inherent in membrane structures. Improved modeling capabilities on computers, along with information obtained from observations of existing membrane systems, are providing architects and engineers with the ability to explore efficient and innovative solutions. Computer modeling is also reducing the time required for the design of membrane structures, allowing them to compete on a cost-basis with conventional structural solutions.

The information contained in this thesis is intended to provide an introduction to the considerations that go into the design and suitability of membrane structures in various environments, with special emphasis on their incorporation into the urban context. The design of membrane structures is not covered by any building Code, and thus remains the product of specialized firms. However, commercially available computer-modeling packages (such as the one used in this thesis) and a better understanding of the behavior of these structures under service conditions, will undoubtedly lead to an increasing number of firms utilizing these exciting structures to solve the challenges of our built environment.

THESIS SUPERVISOR:

JEROME J. CONNOR

TITLE:

PROFESSOR OF CIVIL AND ENVIRONMENTAL ENGINEERING

ACKNOWLEDGMENTS

I would like to thank Prof. Jerome J. Connor and Charles H. Helliwell for their guidance and input throughout the Masters of Engineering program, and for giving me the opportunity to work with them in the management of the term project. I would also like to thank Erik Moncrieff from Technet-gmbh in Berlin, and the people in the Building Technology program in MIT: Chris Luebke and Dale Clifford. Special thanks to all those friends at MIT who helped me with this project, and made working on this thesis fun.

To my family, I reiterate my sentiments about your role in my life: all that I am, I owe to you.

TABLE OF CONTENTS

LIST OF FIGURES	5
LIST OF TABLES	7
SECTION I INTRODUCTION & DESIGN CONSIDERATIONS	
CHAPTER 1 INTRODUCTION TO MEMBRANE STRUCTURES	9
1.1 Background	9
1.2 Classification of Tension Structures	9
1.3 Behavior of Tension Structures	11
1.4 History	12
1.5 Incorporation Into the Urban Setting	15
CHAPTER 2 PERFORMANCE CONSIDERATIONS	20
2.1 Loads and Climate	20
2.2 Fire Safety	23
2.3 Acoustic Performance	24
2.4 Maintenance, Durability, and Inspection	25
2.5 Cost Issues	27
CHAPTER 3 CHARACTERISTICS OF FABRICS	29
3.1 Fabric Types	29
3.2 Fibers	31
3.3 Coatings	32
3.4 Membrane Properties	33
SECTION II THE DESIGN PROCESS	
CHAPTER 4 FORM DETERMINATION	38
4.1 Basic Design Principles	38
4.2 Physical Modeling	42
4.3 Computer Modeling	44
CHAPTER 5 ANALYSIS & DESIGN	53
5.1 General Parameters	53
5.2 Analysis Using EASY	56
CHAPTER 6 PATTERNING AND FABRICATION	62
6.1 General Patterning Information	62
6.2 Tendon Selection and Specification	65
6.3 Connections	67
6.4 Fabric Handling & Installation	76
REFERENCES	79

LIST OF FIGURES

CHAPTER 1		
Figure 1.1	The family of tensile structures.	10
Figure 1.2	Double curvature (anticlastic) of a tensile structure.	11
Figure 1.3	The 1955 music pavilion at Kassel, Germany.	14
Figure 1.4	Olympic stadium in Munich.	14
Figure 1.5	Hajj Terminal, Jeddah, Saudi Arabia.	15
Figure 1.6	Diplomatic Club in Riyadh.	16
Figure 1.7	Mound Stand, Lord's Cricket Ground in London	17
Figure 1.8	Imagination canopy roof in London, England.	18
CHAPTER 2		
Figure 2.1	Acoustic diagram for the first Pier Six Music Pavilion, Baltimore.	24
CHAPTER 3		
Figure 3.1	Typical diagram of fabric weaving.	30
CHAPTER 4		
Figure 4.1	Diagram showing the principal of membrane.	39
Figure 4.2	Four-point saddle shape membrane diagram.	40
Figure 4.3	Stages of the design of tensile structures.	42
Figure 4.4	Soap film model with an internal support.	43
Figure 4.5	Plan view of the boundary cables using EASY.	47
Figure 4.6	Isometric view of the boundary cables in EASY.	48
Figure 4.7	Typical edge cable detail.	49
Figure 4.8	Tendon terminations at Il Grande Bigo, Genoa.	49
Figure 4.9	Dialogue box for editing boundary lines in FRONTEND.	50
Figure 4.10	Net parameter dialogue box in FRONTEND.	50
Figure 4.11	Isometric view of the four-point membrane structure.	51
Figure 4.12	Isometric view of the membrane structure with finer mesh.	52
Figure 4.13	Isometric view of the surface generated by FRONTEND.	52
CHAPTER 5		
Figure 5.1	Sample membrane tent structure showing internal support.	55
Figure 5.2	Four-point membrane structure with supports.	57
Figure 5.3	Stress distribution (plan view) for unloaded membrane structure.	58
Figure 5.4	Deflection comparison for loaded membrane structure.	59
Figure 5.5	Deflection comparison for modified membrane structure.	60
Figure 5.6	Stress distribution for modified membrane structure.	60
CHAPTER 6		
Figure 6.1	Sample patterning output for Buckingham Palace ticket office.	64
Figure 6.2	Typical mechanical joints for membrane structures.	69
Figure 6.3	Typical seam width arrangement.	70
Figure 6.4	Typical clamping arrangement.	70
Figure 6.5	Plan view of a typical perimeter connection scheme.	71
Figure 6.6	Sketch of a pipe arch supporting a membrane seam.	71

Figure 6.7	Steel pipe support with a fixed fabric.	72
Figure 6.8	Cable cuff arrangement diagram.	73
Figure 6.9	Cable clamping arrangement.	73
Figure 6.10	Sectionalizing details for membranes.	73
Figure 6.11	Common methods of tendon terminations.	75
Figure 6.12	A toggle fork that allows movement in two planes.	75

LIST OF TABLES

CHAPTER 3

Table 3.1	Typical uniaxial breaking strength of glass & polyester fibers.	32
Table 3.2	Properties of glass & polyester membranes.	36

SECTION

I

INTRODUCTION & DESIGN CONSIDERATIONS

CHAPTER 1

INTRODUCTION TO MEMBRANE STRUCTURES

1.1 Background

Contemporary membrane structures are part of an ever-changing technology, which is allowing engineers and architects to explore new forms and create innovative solutions for an increasingly complex world. Tensile structures possess many properties that are not attainable using traditional design materials and geometrical arrangements. The suitability and feasibility of these structures should be carefully studied for each application, with special emphasis on performance, cost, and aesthetic characteristics.

Tensile structures are attractive to the designer wishing to demonstrate structural efficiency. Pure tension is by far the most efficient way of using a slender member, as the same member will fail at loads well below its ultimate strength in compression due to buckling. A member subjected to bending will do the same due to the generation of internal stresses that are very high in relation to the applied load. Tensile structures are also appealing because of their aesthetic properties, offering the possibility to contrast the typical “brutal” forms of architecture present in most concrete-dominated cities. Thus, tensile structures are a true physical representation of the combined effort of the structural engineer and architect.

1.2 Classification of Tensile Structures

Technological advances in the second half of this century have made the design and construction of tensile structures a feasible option for designers. This innovation has also brought with it the need to define and classify a broad range of different systems that can be considered tensile structures. Recent publications seem to have converged on a definition and classification that can be used by all disciplines involved in the process of

building tension structures. Tensile structures are ones in which the principal load-carrying members transmit the applied loads to the supporting structures or foundations by direct tensile stress without flexure or compression [16]. They are load-adaptive in that members change their geometry to accommodate changes in load rather than increase stress levels [5]. Figure 1.1 shows a breakdown of tensile structures into general classes of structures, although some structures may not conform to this categorization [11]. This report focuses on membrane structures, which are designed and behave much like cable-net structures, and fall within the category of doubly-curved structures. A doubly-curved structure is referred to here as one having curvatures in mutually opposite directions at every point of the surface of the membrane (see Figure 1.2).

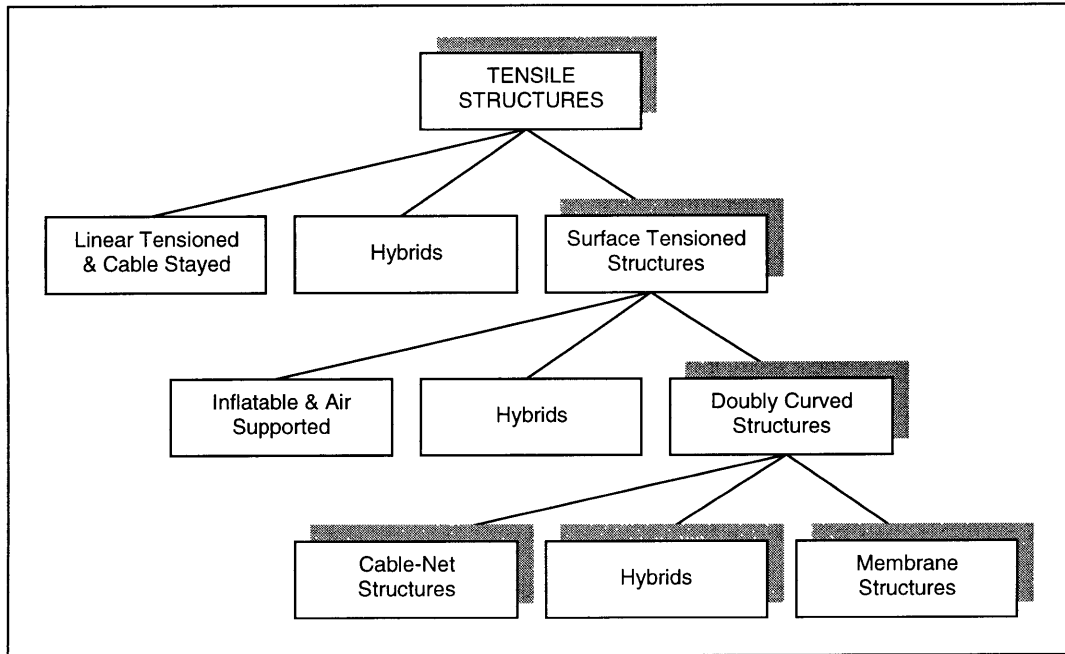


Figure 1.1 The family of tensile structures.

The definition of a membrane structure varies from one publication to the next, with the most controversial argument being that air-supported structures are also membrane structures. In general, however, these air-supported structures are now considered to be a special class of surface tensioned structure, also referred to as a pneumatic structure. Pneumatic structures are technically doubly-curved structures, but are synclastic (principal curvatures at a point are in the same direction). A broad

definition given by ASCE is: “A membrane structure is defined as a structure made of a thin, flexible membrane that is held in shape by the application of tension forces, and acting simultaneously as structure and as a weather shield [12].”

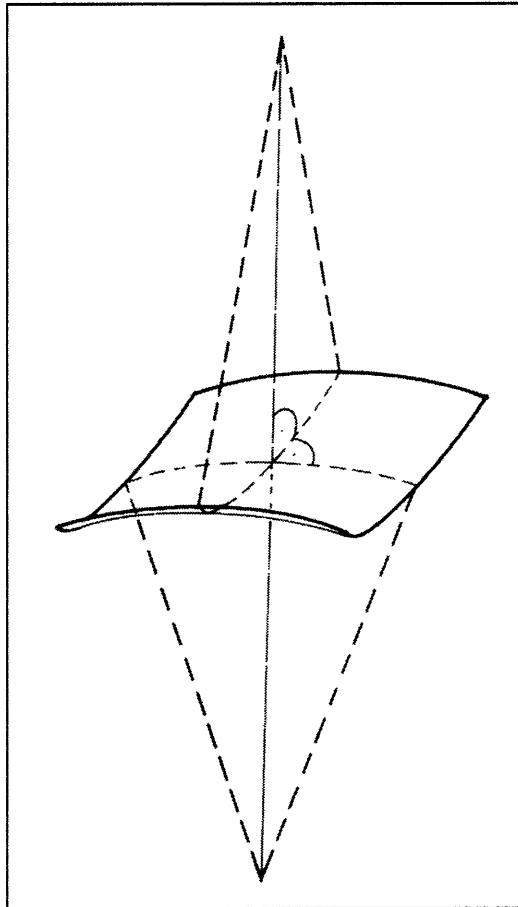


Figure 1.2 Double curvature (anticlastic) of a tensile structure.

1.3 Behavior of Tension Structures

The reduced stiffness characteristic of tension structures makes them susceptible to large motions due to concentrated loads and dynamic effects. Tension structures achieve their stiffness through curvature and pre-stressing, and respond in a nonlinear fashion to both pre-stressing loads and in-service forces. This nonlinear behavior is independent of the linearity of the material or the applied loads. Pre-stressing forces are those forces (edge loads, self-weight, or pressure) which act on a predominant configuration of static

equilibrium for the structure [16]. These pre-stress forces stabilize the structure and provide the stiffness required to resist further deflection. The response of a tension structure to pre-stressing is always nonlinear in that the equilibrium configurations, as well as the state of stress in the members, are dependent on the pre-stressing forces.

In-service forces are those variable live loads, static or dynamic, which are expected to occur regularly within the life of the structure. Each loading condition is superposed upon the pre-stressing forces. Because the response to in-service forces by tension structures is highly non-linear, superposition of the results for different loading conditions cannot be considered a reliable analysis technique. The non-linearity of tension structures is due mainly to the geometrical changes under applied loads, and thus the materials are usually assumed to behave linearly. There are some special cases for which non-linear behavior of materials should be considered and the overall performance of the structure under the applied loads reevaluated. Some examples of these cases are hyperelastic and viscoelastic behavior or polymer cables and membranes, non-isotropic woven fabrics, and thermal-elastic and elastoplastic behavior under extreme loads [5]. Another special case for non-linear behavior of tension structures that may arise is the interaction with hydrostatic and hydrodynamic loads. The magnitude of the drag force in these cases is non-linear, and the pressure loads depend on the orientations of the cable axes and membrane surface, which undergo significant rotations during loading.

1.4 History

TRADITIONAL MEMBRANE STRUCTURES

In terms of architectural function, membrane structures are the oldest dwelling except for the cave or the occasional hollow tree. Examples of these early tents or awnings include the native American tepee, the Mongolian yurt, and the Black Tent used by desert nomads of the Sahara, Arabia, and Iran. However, in terms of structural performance and appearance, the stressed surface of a nautical sail is a more accurate analogy [16].

The period between Roman times and the nineteenth century saw little advancement of the tent, perhaps because of a lack of demand or because of the lack of improvement in the strength of cables, textiles, and joints. The industrial revolution

changed these conditions, bringing a demand for large and portable structures (used for mass entertainment such as circuses) and the availability of stronger and cheaper materials.

TWENTIETH-CENTURY INNOVATIONS

The examples mentioned above drew their stability from a combination of guy ropes, self-weight, and the inherent stiffness of the comparatively thick, heavy materials. These less efficient materials and limited geometrical arrangements produced structures that were relatively slack and far from being considered durable structures. A new breed of membrane structures emerged after the second world war: lightweight and flexible structures with stability derived not from self-weight or stiffness, but by careful attention to curvature and deliberately induced pre-stressing forces.

There were two principal innovators during the early stages of modern tensile structures, and much of the success of tension structures is attributed to their early works. In the 1950's, architect and engineer Frei Otto developed a theory for the design of pre-stressed fabric structures [11]. With support from the German tent manufacturing company Stromeyer, Otto and his colleagues produced a large number of small-scale experimental fabric structures between 1955 and 1972 [11]. The first of these innovative structures was the simple music pavilion at the Federal Garden Exhibition at Kassel in 1955 (see Figure 1.3). This simple four-corner surface structure was made of a cotton canvas stretched between two high and two low points creating a dynamic, doubly-curved form.

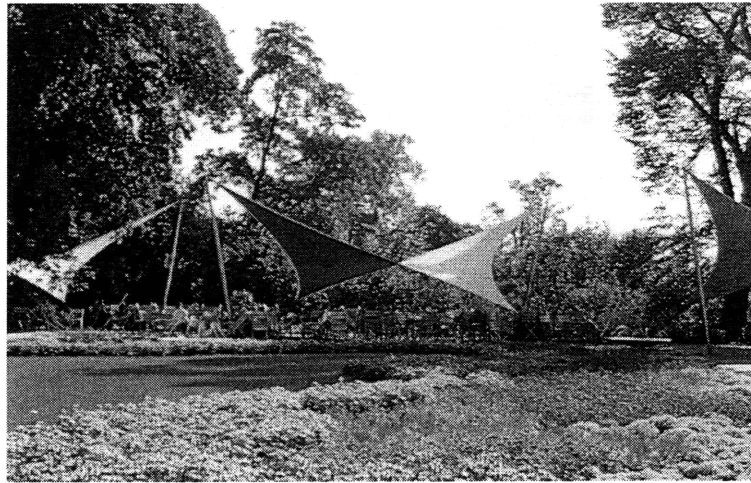


Figure 1.3 The 1955 music pavilion at Kassel, Germany.

These new structures, most of which were temporary, introduced new ideas about shape, erection techniques, stressing methods, material limitations, and connections. The combination of steel cables with fabric structures allowed for larger spans to be covered, while decreasing the stress levels in the membrane. The first notable use of tension structures in a permanent and large-scale application was for the 1972 Olympic Stadium in Munich (see Figure 1.4).



Figure 1.4 Olympic stadium in Munich.

The membrane materials available to Frei Otto during this time allowed for only a very limited span to be covered, and with a short life expectancy. At present, as a result of large advances in textile technology, there are many built examples of impressive scale, such as the Hajj Terminal in Saudi Arabia (see Figure 1.5). These new membranes have very high tensile strengths, excellent fire resistance, and life expectancies of twenty-five years or more [16].



Figure 1.5 Hajj Terminal, Jeddah, Saudi Arabia.

1.5 Incorporation Into the Urban Setting

Before the Olympic stadium in Munich, most of the pre-stressed surface structures remained consigned mainly to temporary canopies and pavilions at expositions and trade fairs. This created the association of tensile structures with non-permanent systems, rather than permanent and fully enclosed buildings [11]. The reason for many architects avoiding the implementation of tensile structure in their designs may stem from the suitability of membrane structures to natural settings and their temporary appearance. Other possible reasons include the difficulties of architects to reconcile the curved lines of tensile structures with the more conventional rectilinear construction of our cities, or simply a lack of understanding of these relatively new structures.

Before 1986, the superposition of membrane structures with traditional architecture had only been accomplished for buildings with curved walls or plan. Some examples of these are the famous Olympic Stadium in Munich, and the Diplomatic Club in Riyadh (Figure 1.6). The challenge remained for architects to determine how and when to incorporate the curved surfaces of tension structures with the rectilinear geometries of conventional structures. Many of the early projects that attempted to do this resulted in a combination that looked rather like a poorly fitting tent attached to a simple shed.



Figure 1.6 Masonry construction in combination with structural membranes and cable-nets, built to house the Diplomatic Club in Riyadh.

Shortly after 1986, several examples appeared throughout the world of combined structures, such as the small Cricket Ground in London (Figure 1.7). Lord's Cricket Ground is set in a traditionally built area of London, and is owned and run by a long-established and conservative organization. When a new grandstand was needed, the use of a membrane structure was proposed in order to evoke images of the traditional village cricket marquee [11]. The success of this building provided a clear example that appropriately used membrane roofs could make an architecturally satisfying contribution

within the urban context. Establishing what constitutes the “appropriate use” of membrane structures is of course subjective to each culture and architecture style.

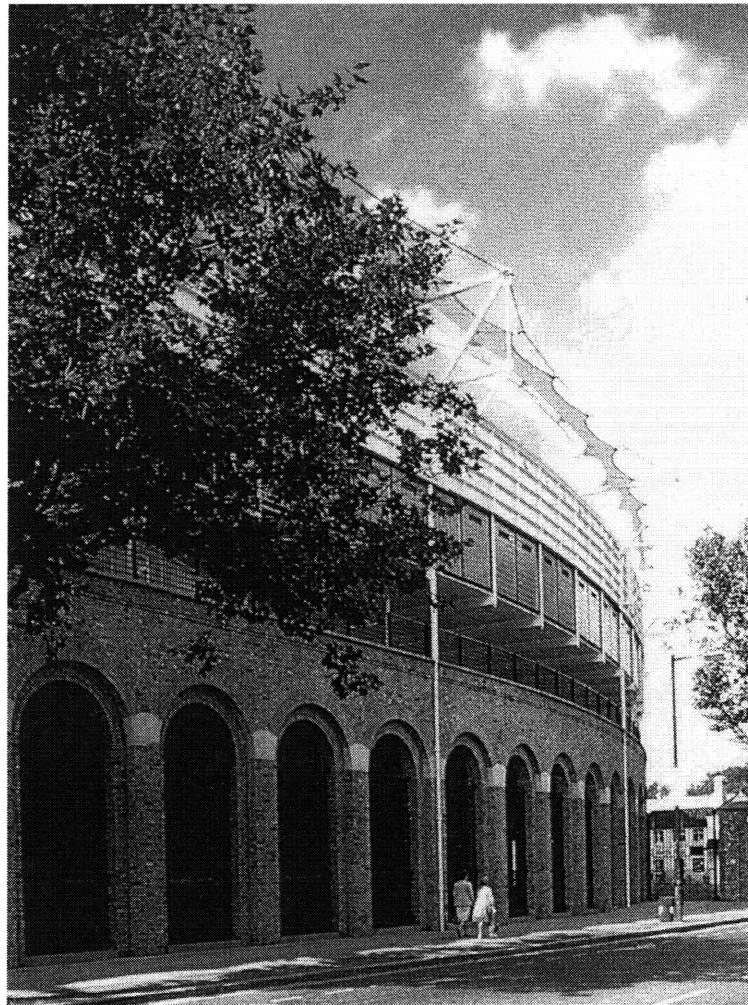


Figure 1.7 Mound Stand, Lord's Cricket Ground, London.

Because the structure at Lord's Cricket Ground used an open membrane, a significant building within a traditional urban setting that combined a membrane or cable-net supported roof with conventional construction while enclosing an environmentally conditioned space had yet to appear. However, about two years after the completion of the Cricket Ground in London, the headquarters building for Imagination in west London answered many of the remaining questions (Figure 1.8). The tension structure transformed a gap between two buildings into a useful and insulated space, demonstrating that fabric roofs need not be considered only where large spans are involved.

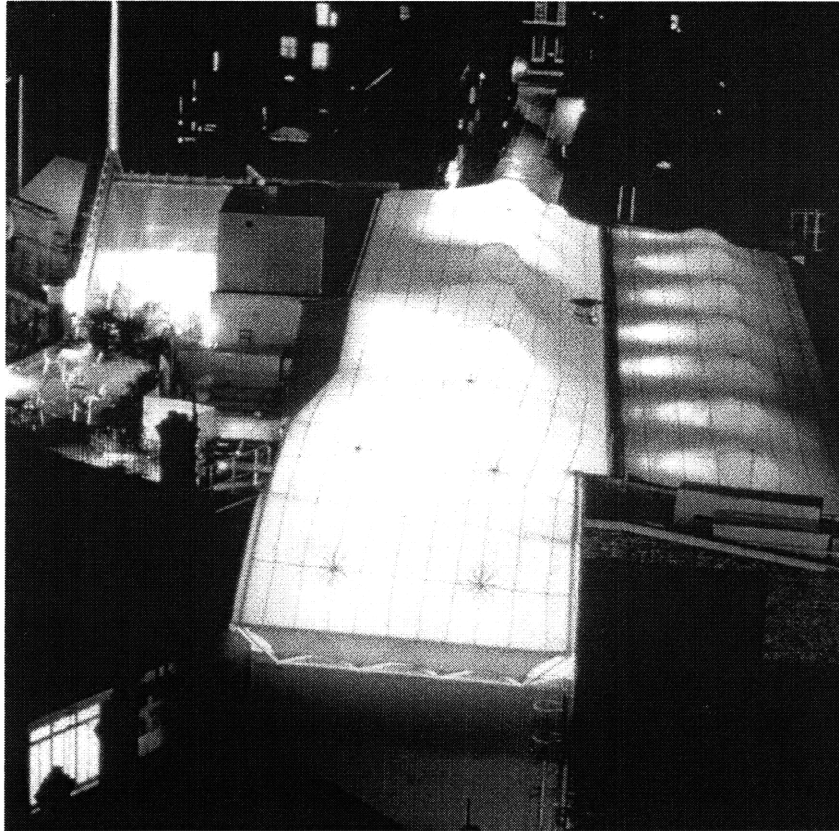


Figure 1.8 At Imagination, the tensile canopy provides environmental control for the gallery and atrium, and also forms an integral part of the image of the new building.

Most building structures are clad in some manner and hidden from view, making connection detailing and element appearance of little concern to architects. However, the means by which a fabric roof is supported and its appearance are inseparable. Supporting masts are usually left exposed, and steel cables pass through space or lay against the fabric so that they remain visible from either above or below the roof [12]. Even the patterns made by the seaming of the fabric can be used to reflect predominant stress patterns—a strong visual element of the design. Although urban tensile architecture is still in its infancy, contemporary structures are a great improvement over those from the 1950s and 1960s. The availability of stronger and more durable materials, along with a greater understanding of the performance and design tools of tensile structures, should allow for greater experimentation with incorporation into the urban setting by architects. As we head into the next century, overcoming the architectural and technical difficulties

of combining tensile structures with conventional architecture, will no doubt lead to exciting creations.

CHAPTER 2

PERFORMANCE CONSIDERATIONS

2.1 Loads and Climate

Membrane structures have been adapted to a wide range of loading and climactic conditions throughout the world. Their design has yielded some generalizations that can be made regarding the appropriate design loads and climactic suitability. The loading guidelines that follow are very useful for initial design purposes, but may not apply to certain structures or geographical regions.

- **Dead load** magnitudes for membranes are generally less than 50 N/m^2 (1.0 lb/ft^2), and hence negligible. When heavy insulation or other permanent distributed loading is to be placed on the membrane (e.g. special coatings), the appropriateness of neglecting the dead load should be reevaluated.
- **Roof live loads** are generally intended to account for construction phase loading such as roofing materials that are not relevant to fabric construction [12]. State Code provisions generally make no loading exceptions for membrane structures, and thus they are typically designed for normal live loads and subject to live load reductions based on tributary area.
- **Seismic loads** are generally not a factor in the design of membrane structures, due to the low mass of the fabric.
- **Wind** is often the predominant loading to be considered in the design of a membrane roof. Adequate curvature and pretensioning is essential in the membrane's ability to resist wind loads without excessive flutter. The adaptation of Code formulas for wind loading is generally difficult to apply to the complex curvatures of most membrane roofs, making wind tests a requirement for accurate prediction of wind loads. However, advances in computer models for membrane structures and computational fluid dynamics

technology (CFD), should allow designers to predict the wind loading magnitudes with greater accuracy. Computer analysis of wind loads should reduce the time and cost of designing membrane structures, making these structures even more attractive to architects, engineers, and their clients.

- **Moderate snowfall** can successfully be resisted in structures that have sufficient pre-stress to prevent large deflections that could lead to ponding, additional deflection, and eventual overload of the roof [12]. Relatively large curvatures and slippery coatings (e.g. Teflon) help in the shedding of snow, and also aid in preventing ponding. In some cases, snow-melting equipment, such as a furnace producing forced hot air under the membrane, can be useful in areas of heavy snow load or low roof slopes. Snow loading magnitudes can be taken from the Code guidelines, but added snow load due to drift is generally difficult to adapt to curved surfaces. Roof areas with high slopes (usually above seventy degrees) can be considered free of snow, although this Code provision assumes the snow does not collect after the snow slides on the steep surface. Thus, the judgment of the engineer in determining the appropriate loading values is pivotal for the case of snow or ice loading.
- **Point loads** such as heavy lights, signs, or scoreboards present a special design problem due to the high deformability of membranes. Concentrated heavy loads should generally be supported from the rigid mast of arch supports or at angle changes in cabling [12].

The characteristics of most contemporary membranes (e.g. translucency, high reflectivity of light, and low insulation) have made them easier to adapt to temperate or hot climates with ample sunshine. In order to develop an understanding of the thermal characteristics of membrane structures, it is useful to consider their performance in cold and hot climates separately.

In hot climates, proper ventilation design should allow for the removal of excess heat and allow fresh air to enter the building whenever possible. In climates that combine warmth with high humidity, care must be taken to prevent the growth of mold or algae caused either by condensation or standing water on the outside of the fabric. The heat

generated by the sunlight penetrating the translucent membrane can be avoided by an opaque coating on either side of the membrane.

In cold climates the major concern is usually excessive heat loss through the membrane skin [11]. Given that a certain amount of heat loss is to be expected in all but the most highly insulated buildings, it is reasonable to utilize the inherent characteristics of the membrane that can counter this effect. If these characteristics don't provide sufficient insulation, additional materials and components may be utilized along with the membrane.

By taking advantage of heat gain due to solar radiation, which penetrates the fabric skin during the day, the requirement for heating can be reduced. Therefore, the fabric structure should be designed to allow the transmission of heat from the surrounding environment, yet also contain the heat as long as possible. This "greenhouse effect" is governed by the manner in which the materials and geometry of a building reflect, transmit or absorb any part of the electromagnetic spectrum. Transparent materials such as glass will transmit short-wave solar radiation, but reflect some of the long-wave radiation given off when the surfaces within an enclosed space are heated [11]. A transparent film capable of reflecting long-wave radiation can be used in combination with the translucent membrane to reduce the rate of heat loss back in to the environment. However, this approach can lead to undesirable excessive heat gains even in cold climates. To prevent this, movable insulation or sunshades should be incorporated in the thermal design, or make use of ventilation stacks as heat drains.

The use of liner membranes with dead air space and insulated fabrics have improved the performance of membranes in cold climates significantly. In cold climates, measures must often be taken to prevent excessive condensation, particularly for applications such as swimming pools, zoos, or botanical gardens [12]. Condensation is likely to occur when the temperature of the membrane and the relative humidity of the inside air are such that the air on the inside can reach the dew point. Again, ventilation or air conditioning systems can be designed to alleviate these problems. In general, with some careful design criteria and imagination, a solution for practically any climactic condition can be found.

2.2 *Fire Safety*

Contemporary tensile membrane structures provide far better fire resistance than that of traditional non-synthetic tenting materials. To determine the applicability of a fabric for a given construction type, several standard fire tests have been adapted for fabrics. These tests should be used in order to select the most appropriate material for the structure, but in general fiberglass fabrics are able to achieve the non-combustible rating while polyester or cotton fabrics are not [12].

1. **ASTM E84-Surface Burning Characteristics of Building Materials** (known as the Flame Spread Test). The test is applicable to exposed surfaces such as ceilings or walls, and measures the surface flame spread and smoke development relative to mineral fiber cement board (index of 0) and select grade red oak flooring (index of 100). Building codes limit smoke generation to an index of 450 and categorize flame spread as Class I (0-25), Class II (25-75) and Class III (75-200).
2. **ASTM E108-Fire Tests of Roof Coverings** (tests are known as burning brand, spread of flame, intermittent flame exposure, flying brand or rain test). These tests evaluate roof coverings to measure their resistance to simulated fire originating from the outside of the building. Class A tests are applicable to roof coverings that are effective against severe test exposure, Class B tests are applicable to coverings that are effective against moderate exposure, and Class C test are applicable to coverings that are effective only against light exposure. In all cases, the covering must not slip from position or present a flying brand hazard.
3. **ASTM E136-Behavior of Materials in Vertical Tube Furnace at 750 Degrees Celsius**. This is a test of base fabric material (greige goods), and is not intended to apply to laminated or coated materials. A 40 x 40 mm square stack of material is placed in the furnace to verify that the temperature of the material does not rise more than 30 degrees Celsius above that of the furnace and that no flaming from the specimen occurs after the first 30 seconds.

4. **NFPA 701-Fire Tests for Flame-Resistant Textiles and Films.** This test method determines the difficulty of igniting flame resistant textiles and films and the difficulty of propagating flame beyond the area exposed to ignition. Small and large-scale tests evaluate resistance to the respective small and large ignition sources.

The above tests are currently used by the various building codes in use throughout the United States to classify fabric structures according to their fire rating. For example, the Uniform Building Code regards materials which can both pass ASTM E136 and have a flame spread (per ASTM E84) of less than 50, qualify as non-combustible and can be used in Type II-N construction [12].

2.3 Acoustic Performance

The acoustic performance of a membrane covered space is determined by three main criteria: (1) the sound absorptive/reflective characteristics of the type of membrane used; (2) the geometry of the internal space; and (3) the volume of the enclosed space [11]. Because membrane structures are often used for temporary performance pavilions, a fair amount of research has been carried out into the acoustical performance of membrane covered spaces. Jaffe Acoustic in the U.S. helped architects of New York in analyzing the acoustic criteria of the first Pier Six Music Pavilion in Baltimore (see Figure 2.1).

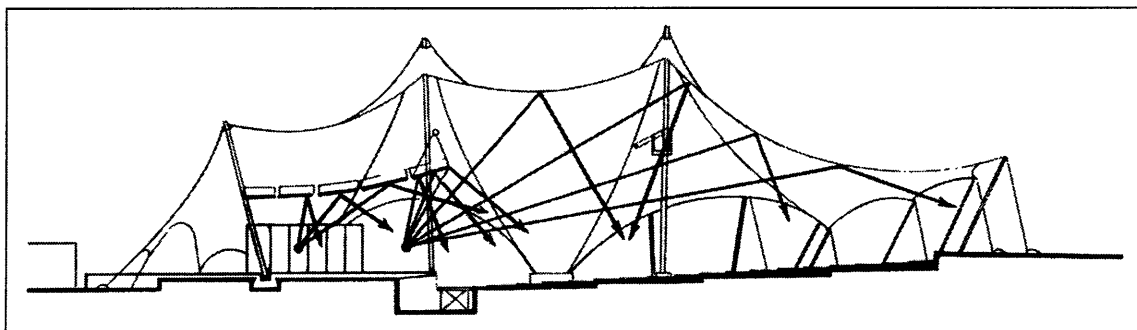


Figure 2.1 Acoustic diagram for the first Pier Six Music Pavilion.

Membranes are characterized by high reflectivity of sound vibrations, particularly in the frequency range of 500 to 2000 Hertz [12]. This reflectivity may result in poor sound quality in musical performances and difficulty in understanding speech. The fact that the membrane is not completely rigid also means that a certain amount of low frequency sound is absorbed by damping effects, and thus special care must be taken if the space is to be used for non-amplified performances.

Sound transmission loss through the fabric is another important consideration in airports or other structures where it is important to shield the building occupants from outside noise. Lightweight membranes provide very little resistance to the transmission of sound. Like sound reflectivity, transmission loss is highly dependent on frequency of vibration, with tests on structural membranes indicating a moderate transmission loss of approximately 5 dB at 100 Hertz, ranging up to about 30 dB at 5000 Hertz [12].

Acoustic reflectivity can be decreased and transmission loss increased by the installation of lightweight, porous liner fabrics. Fiberglass insulation between the two fabric layers can further increase transmission loss, but mass is the best way of containing sound, especially at low frequencies. The effects of these measures on lighting, thermal insulation, and fire safety must be considered in the final design. Vertical banners can also be suspended at intervals under the fabric in order to increase sound absorption and break up the smooth geometry of the curved membrane. Because of the difficulty in improving the poor acoustic performance of membrane structures, it is advisable to try and avoid any problems in the first place by careful planning of the building in terms of its location and internal arrangement. In the case where a tensile structure is used in combination with a more massive structure, noise generating activities or those that may be acoustically sensitive, should be housed in the parts of the building with the massive construction.

2.4 Maintenance, Durability, and Inspection

Properly designed and constructed membrane structures generally require very little maintenance, until such time as degradation from ultraviolet radiation or other sources necessitates replacement of the fabric or demolition of the structure. Cleaning of the

membrane depends on the type of fabric chosen, and the environment in which it is. PVC coatings tend to pick up dirt and should be avoided if possible in urban or other dirty atmospheres. They must be regularly cleaned to avoid a loss of translucency and attractive appearance, although thin surface finishes can sometimes alleviate this problem. The more a PVC membrane is cleaned, the more they will embrittle by contact with soaps, solvents and oils. There is no real solution to this problem, except to ensure that cleaning is carried out according to the manufacturer's specifications.

PTFE (Teflon) coatings tend to remain clean, as dust particles do not stick to it and are washed away by rain. PTFE-coated glass fabric also shows no tendency to discolor with age and remains white. Cleaning is therefore less important than with PVC-coated membranes. Regardless of coating type, access for cleaning and repairing the membrane should be considered in the design phase [16].

Small tears or damage from vandalism can usually be repaired on site using a kit provided by the membrane manufacturer. Large tears should be referred to the manufacturer/installer, who may decide it is necessary to remove the membrane for repair. To avoid tears, careful attention should be given to accurate load during the analysis phase to avoid over-stressing the membrane, and to possible location of stress concentrations (cables, arches, mast peaks, and other discontinuities). Also, where structures are located in an unsafe area or an unsecured site, the structure should be configured so that the membrane is not subjected to knife cuts or other vandalism.

Periodic inspection by the manufacturer or other qualified personnel is recommended for all membrane structures. These inspections should include checking for abrasion of the fabric at the interfaces with other elements, re-tensioning, and cable inspection. Inspection of the tension in the membrane is recommended six months following the completion of the structure, and it is unlikely that any further re-tensioning will be needed, especially for glass-fiber membranes [16]. Cables in external situations are subject to corrosion and should be regularly inspected, especially at locations where the cables come into contact with fixings such as forks or eyes.

In woven fabrics, the durability for a given degree of exposure to the elements depends mainly on the nature of the coating: the more opaque the coating, the better the fabric will be protected and the longer its life [16]. Exposure to UV radiation from direct

sunlight is the primary environmental factor in fabric durability. PVC-coated membranes may last only three to five years if translucency is 30% but up to fifteen years with a translucency of 15%. An average lifespan for PVC-coated fabrics would be ten to twelve years, and twenty years in favorable conditions, and PTFE-coated fabrics may last up to thirty years.

2.5 Cost Issues

In addition to the appeal of being able to create dramatic forms with tension structures, many clients show interest in these structures based on the assumption that “tent” construction is inexpensive. In reality, the cost of manufacturing and erecting these structures varies widely with the choice of fabric and other material parameters, and whether they represent a cost saving or a premium depends on the traditional structure they are compared to.

The costs given by designers for tensioned fabric structure roofs generally include the fabric itself, cables, masts or arches that support the fabric, and the attachment of the fabric at its perimeter. They generally exclude any foundations, the beams or walls on which the fabric terminates, and any fire safety or lighting items that are added to the roof. With this definition, the cost ranges for different types of tensioned fabric structures (in 1995 dollars) are approximately as follows [12]:

1. Prefabricated, pre-engineered structures using repetitive forms and vinyl-coated polyester fabric, \$75-100/m² (\$7-10/ft²).
2. Custom structures using vinyl-coated polyester, \$150-300/m² (\$14-28/ft²).
3. Custom structures using fiberglass-based fabric, \$300-900/m² (\$28-84/ft²).

When calculating the cost of the structure, the longer life and lower cleaning costs of PTFE-coated glass must be taken into account when comparing these figures. In addition to membrane type, other factors which will determine the cost range for a membrane structure are [12]:

1. **Symmetry and Repetition.** Designing the structure with symmetry about one or more axes, and providing repetitive modules, the analysis, patterning, and fabrication costs can be dramatically reduced.
2. **Scale.** Due to the small self-weight of the membrane and because the cost of woven fabrics does not vary dramatically with increases in fabric stress, cost per unit plan area does not rise as dramatically with increases in span as it does with conventional construction.
3. **Aspect Ratio.** Reasonable aspect ratio is required in order to limit fabric stress and cable force, and to achieve stability under the various loading conditions. Increases in curvature result in an increase in the structure's aspect ratio (height/span). Excessive aspect ratios, however, can cause a significant increase in the amount of fabric required to cover a given plan area, as well as increase the surface exposed to wind loading. The most economical structures have an aspect ratio that provides a balance between these divergent considerations [12].

CHAPTER 3

CHARACTERISTICS OF FABRICS

3.1 Fabric Types

The fabrics referred to in this report are limited to those used in tensile membrane structures, and thus the description of the fibers, yarns, coatings, and fabrics given may be different for other products. There are three basic textile types used in tensile structures: woven fabrics, films, and reinforced films.

- **Woven Fabrics.** These are the most commonly used fabrics in tension structures. They are woven from yarns set at right angles to each other. The yarns stretched along the length of the cloth during weaving are known as the warp and those threaded across the width of the cloth, at lower tension, are known as the fill or weft (see Figure 3.1). Woven fabrics are normally anisotropic, though the difference in the performance in the direction of the fibers can be minimized by weaving or coating techniques [16]. Most membrane roofs are made of PVC-coated polyester or PTFE-coated glass fibers. PVC-coated polyester is easier to work with and is less expensive in initial cost than the PTFE-coated material, but requires more frequent cleaning and stretches more under load.

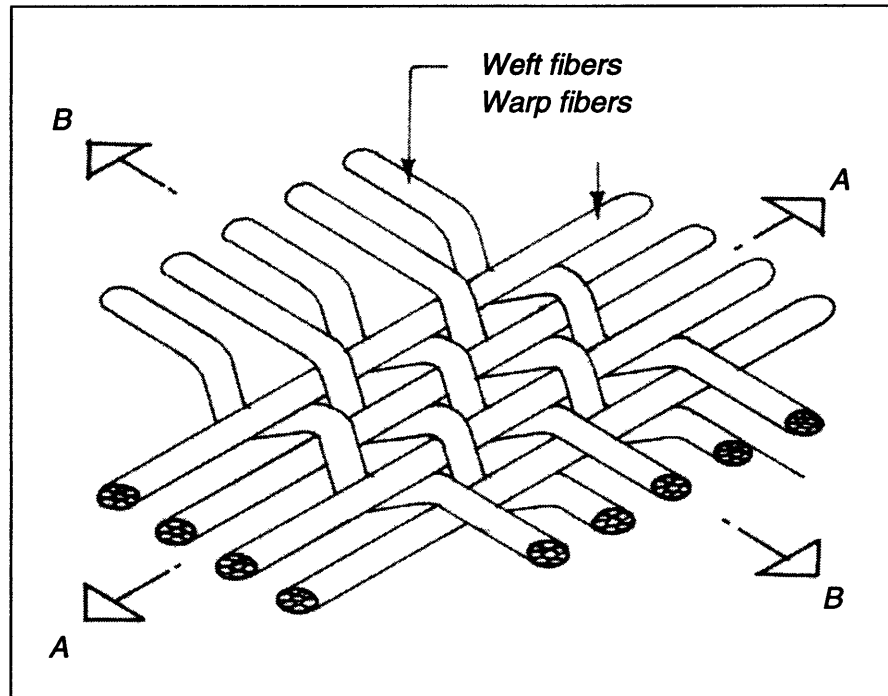


Figure 3.1 Typical diagram of a fabric showing the warp and fill or weft fibers.

- **Films.** These are thin homogeneous sheets of plastic or rubber. They can be completely transparent or completely opaque, are highly flexible, and are usually isotropic [16]. However, they are weaker, less durable, and less tear-resistant than woven fabrics. They are appropriate for temporary membrane structures or as an interface between the woven structure and the supporting system.
- **Reinforced Films.** These fabrics can be considered a hybrid of the above two materials. They consist of a woven fabric glued or heat-welded between two thin layers of film [16]. Laminates of this kind offer the strength and permanence of woven fabrics combined with the impermeability of films. Also, a high degree of translucency is possible when using an open-weave core fabric plus translucent film. They would be suitable for more permanent structures than those where film properties are desired.

3.2 *Fibers*

Most of the membrane structures built in the twentieth century have been made of four kinds of fibers: nylon, polyester, glass, and aramids. Today, glass and polyester are the most widely used due to either higher strength or resistance to degradation. A brief description of each of the fibers is given below.

- **Nylon.** Nylon has a slightly higher strength than polyester, but has a lower modulus of elasticity, causing larger deflections under a given load. It is also subject to dimensional instability when exposed to moisture, which is a serious problem in patterning as the dimensions of the nylon may change significantly between layout and cutting if the humidity changes. Also, nylon loses tensile strength over time under UV exposure, and thus must be used with a protective coating.
- **Polyester.** Although the tensile strength of polyester is lower than that of nylon, it is sometimes offset by its greater stiffness. The raw fibers of polyester are more vulnerable to UV degradation, but are more resistant in the final fabric because they are more effectively protected than nylon. Thus from a practical point of view, polyester is more durable than nylon, which is a key factor in the design of permanent membrane structures.
- **Glass.** Glass fibers have very high values of modulus of elasticity and tensile strength, but are also very brittle. By encasing the fibers in a flexible matrix, it is possible to take advantage of their high strength. However, the fabric is still subject to damage from repeated flexure or excessive bending during handling and installation. For this reason, glass fabrics are usually used for permanent structures or those that do not have to be erected repeatedly. Glass is not subject to UV degradation, making it a prime candidate for permanent installations. Uniaxial strength properties are given in Table 3.1 for polyester and glass fibers for comparison.

Table 3.1 Typical uniaxial breaking strength of glass and polyester fibers.

Fiber	# Fiber/m	Coating	Thickness (mm)	Breaking Stress (kN/m)	Breaking Strain
Glass Fiber	990/730 (warp/fill)	PTFE	0.7	144/128 (warp/fill)	0.086/0.087 (warp/fill)
Polyester	600/620	PVC	0.8	101/90	0.24/0.33

- **Aramids (Kevlar).** Aramids are an organic material that have a high modulus of elasticity and breaking strength. They can withstand considerably more flexing than glass but not as much as nylon or polyester. However, aramids are subject to deterioration from UV light, and thus have not been widely used in membrane structures compared to glass fibers.

3.3 Coatings

There are many materials that have been used as coatings in membrane structures. The ones listed below are the most widely used because of their superior performance, cost, and ease of application.

- **Polyvinylchloride (PVC).** PVC is a soft and pliable material, enabling it to conform to the shapes required to membrane structures. It is resistant to UV light and is available in practically any color. It is most commonly used with nylon or polyester fabrics [12].
- **Polytetrafluoroethylene (PTFE or Teflon).** PTFE is chemically inert, resistant to moisture and microorganisms, and has low deterioration with age [12]. It is currently only available in white, but work is in progress to create different shades of PTFE. The main drawback is that much care must be taken so as to avoid damaging the fibers, and is more expensive than PVC-coated polyester. It is flame resistant and has a high tensile strength and modulus of elasticity.
- **Silicone.** Similar to PTFE, silicone has excellent characteristics of UV resistance, long-term flexibility, flame resistance, tensile strength, and modulus of elasticity. It is used as a protective coating for glass, and has high light transmission.

- **Toppings.** Dirt and other pollutants, in addition to producing negative aesthetic and translucency characteristics, can increase the degradation rate of a fabric. One of the ways to protect the fabric coating is by giving it a surface coating or topping [12]. This topping not only serves to protect the fabric from UV light, but also to improve its self-cleaning characteristics. One such material is Tedlar, a polyvinylflouride (PVF), and is applied to both PTFE-coated fiberglass and PVC-coated polyester membranes.

3.4 Membrane Properties

The three most important properties of interest to designers regarding membrane structures are:

1. Short-term structural properties (determined mainly by the membrane material).
2. Long-term structural properties (how the properties are maintained over time and under cyclic loading).
3. Non-structural properties (e.g. translucency, resistance to fading, etc.).

These properties are summarized for the two most commonly used membranes in Table 3.2 at the end of the chapter.

SHORT TERM STRUCTURAL PROPERTIES

Tensile strength: The resistance to failure under load of a membrane material must be high enough to enable the fabric to maintain the stresses from pre-stressing and external loads. Both PVC-coated polyester and PTFE-coated fiberglass can be produced with strengths of up to 16 tons per meter width [16].

Tensile modulus: Higher modulus is a double-edged sword in that it can resist deformations under higher loads, but it also resists being molded to the prescribed structural profile. The latter makes the accuracy of cutting and installation of the membrane much more critical. Woven polyester fabrics have a medium modulus, are

easy to use, and their relative flexibility is normally not a problem from a structural point of view, except where large snow loads are expected [16]. Woven glass membranes have a high modulus of elasticity, but carry a risk of wrinkles, creases and sags if the cloth does not fit the site profiles exactly.

Tear strength: Most membrane failures are due to tearing, rather than by direct tensile failure, making tear strength and resistance to tear propagation a critical factor in selecting a fabric. PVC-coated polyester has medium tear resistance, whereas PTFE-coated glass has a high tear resistance [16]. Reinforced films have lower tear strengths than either of these materials, and plain films have the lowest tear strength of all.

Directionality: If isotropic material behavior is required for a given application, then only non-woven films may be used. Most woven fabrics display anisotropic characteristics, being stiffer in the warp direction than in the fill or weft, but this discrepancy is becoming smaller or even negligible with modern weaving and coating techniques (although still a cost premium). This technique consists of tensioning the fill as well as the warp fibers during weaving.

LONG TERM STRUCTURAL PROPERTIES

Construction stretch: All woven membranes undergo some non-recoverable initial stretch during construction as the “crimp” is pulled out with the pre-stressing. The degree of stretch will be much greater in the undulating fill or weft direction than in the warp direction, and appropriate considerations should be given to this property of the fabric during patterning. The membrane manufacturer supplies this data. This difference in stretching can be reduced by the weaving technique described earlier, or by pre-stretching the cloth before installation, thereby reducing the amount of stretch which occurs in the membrane during its lifetime.

Dimensional stability: The dimensional stability for woven fabrics (resistance to creep, deformation due to thermal or moisture conditions) under long term loading depends

more on the basic material than on the type of weave or coating [16]. Such deformations are undesirable in permanent structures, since they cause a loss of pre-stress. Polyester fabrics are relatively stable in terms of thermal and moisture conditions, but the creep is such that half of the pre-stress may be lost in the first ten days, a further half over the next hundred, and yet another half over the next thousand. This loss of pre-stress makes the need for re-stressing necessary after a certain period of time. Glass fabrics, on the other hand, have high dimensional stability.

NON-STRUCTURAL PROPERTIES

Translucency: In woven fabrics, translucency depends on the translucency of the fibers, coating material, and the spacing between the fibers. All three of these properties can be varied in order to obtain the desired translucency, while meeting other design criteria. PVC-coated polyester cloths may have translucencies of 8 to 30%, and PTFE-coated glass fabrics from 5 to 15%. The translucency of films depends on both the basic material and the coating,, and are available from almost 100% transparency to complete opacity.

Table 3.2 Properties of the two fabrics most commonly used for membranes [16].

PROPERTY	FABRIC	
	PVC-COATED POLYESTER	PTFE-COATED FIBERGLASS
Short term structural properties		
Tensile strength	Medium	High
Tensile modulus	Medium	High
Tear strength	Medium	High
Directionality	Stiffer in warp than weft, but there are fabrics available with virtually identical properties in both directions.	Similar properties to PVC-coated polyester.
Long term structural properties		
Construction stretch	Medium	Low
Dimensional stability	Medium	High
Non-Structural properties		
Durability	Lifetime normally 10 to 12 years, depending on the exposure and opacity of coating. Design life could be only 3 to 5 years with highly translucent coatings and up to 15 years with opaque coatings. A white finish will reduce surface temperature and enhance durability.	25 years or more.
Translucency	8% to 30%	5% to 15%
Appearance	All colors available. Can be opaque or translucent. Suffers from dirt retention so that visual rather than physical deterioration is likely to determine working life.	White and a few other colors are available. Dirt is not retained and surface remains clean. No discoloration occurs during lifetime.
Ease of Installation		
Flexibility	High, making for easy fabrication, transportation, and installation.	Low, creating a risk of damage during fabrication, transportation, or installation. Accurate cutting and installation vital.
Jointing	Easily done.	Special techniques needed.
Summary		
	Overall the most popular coated fabric, and there are many experienced installers. Cheap enough to be replaced every 10 years to maintain pristine appearance.	Used for membrane structures where long life and/or low maintenance are more important than low cost or ease of installation.

SECTION

II

THE DESIGN PROCESS

CHAPTER 4

FORM DETERMINATION

4.1 Basic Design Principles

Many designers are attracted to membrane structures because of the wide range of forms that can be created. The range of possible forms is extensive, yet these structures are by no means “free-form” structures. They must rigorously conform to the physical principles that govern their behavior as limited by the characteristics of the materials from which they are built [12]. The only way that a thin, flexible membrane can be made sufficiently stiff and flutter-proof when subjected to external loads is by the appropriate combination of curvature and pre-stressing.

TENSILE BEHAVIOR

The purpose of the pre-stressing in a membrane is to ensure that the fabric remains in tension, and therefore stable, even after the application of non-uniform loads such as wind or suction [16]. The basis for membrane structure design is to explore and exploit the nature of tensile behavior. Membranes are generally composed of numerous linear tension components, which act as tension surfaces both structurally and visually. Because membranes have negligible compressive, flexural and transverse shear strength, the applied loads must be resolved in their surface. Cables may be used to establish membrane boundaries or to reinforce a membrane by dividing the surface into smaller portions [12].

The elements supporting the membrane structure such as masts, arches, and perimeter beams, typically have significantly larger compressive, flexural and shear strengths. Although membrane structures are usually designed to highlight the structural elements used to carry tensile loads, this effect is amplified by the juxtaposition of the

tensile, compression, and bending components that support the membrane or surrounding structures.

GEOMETRICAL REQUIREMENTS

Surfaces are generally classified by their curvature. For cones and cylinders, one of their two curvatures has an infinite radius, and so they are classified as only having one curved direction on their surfaces. Tensile structures have two curvatures at each point on their surface of similar radius of curvature. Synclastic surfaces have double curvature, but in the same direction (or equal Gaussian sign curvatures), whereas anticlastic surfaces have their principal curvatures in opposite directions. This geometry allows the surfaces to resist a given loading condition in any direction, whereas a dome or synclastic surface can only resist loading in one direction (e.g. positive pressure in pneumatic structures). This principle is illustrated in Figure 4.1. Figure 4.1a and 4.1b show how the cable geometry is only stable for loading in one direction, but becomes unstable if the load direction is reversed. In Figure 4.1c, the system remains stable under any loading condition.

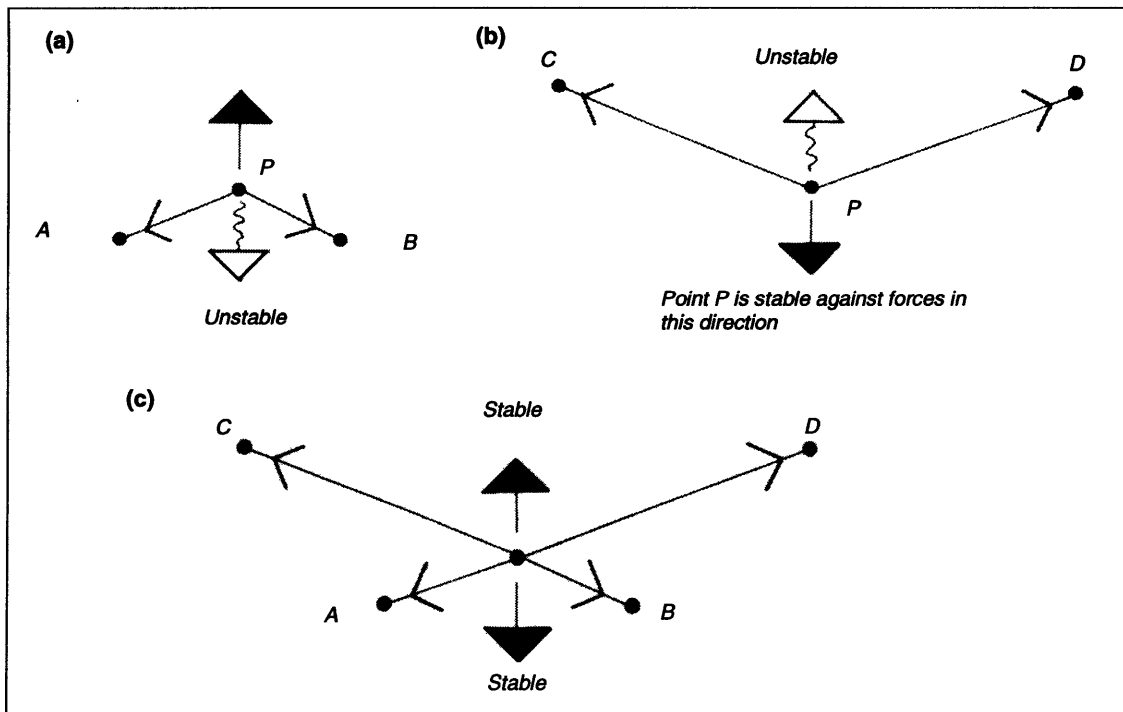


Figure 4.1 Point P is stabilized against external forces from all direction is restrained by two tension members A-B and C-D acting in opposing directions [16].

The simplest example of this principle is the saddle shape membrane structure, such as the music pavilion in Figure 1.3, where a square membrane is stabilized with two high points and two low points. A schematic of this structure is given in Figure 4.2.

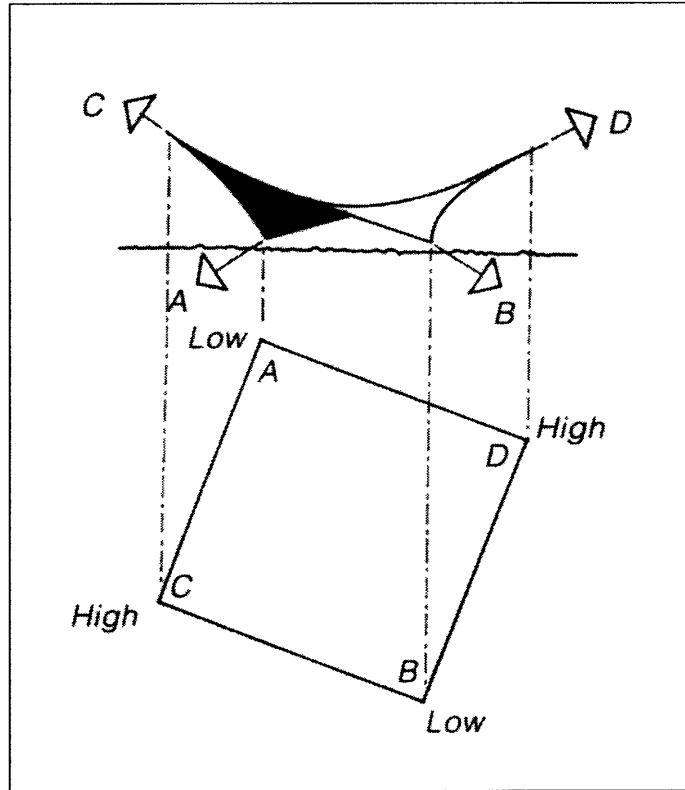


Figure 4.2 A four-point saddle shape created by two high points, and two low points.

When deciding on the geometry of the membrane structure, the following guidelines should be considered [16]:

- The greater the curvature of a given surface, the more effective the pre-stressing becomes at providing surface stiffness and preventing flutter.
- Counteracting the previous point, excessive curvature can make for practical difficulties in pre-stressing, especially with stiff materials such as PTFE-coated fiberglass membranes. These fabrics resist deformation and do not allow the fabric to redistribute local overstressing.
- Curvature distribution across the entire membrane should be relatively uniform, as large variations can lead to “soft” areas in some places, and stiff areas in others. This

could lead to excessive flutter of some areas, and even membrane failure under certain loading conditions.

GENERAL DESIGN PROCEDURE

Although the design of membrane structures cannot be reduced to a strictly linear sequence of tasks, the following general stages should be included in the design process [16].

- Finding a suitable geometrical form.
- Deciding a workable pre-stressing method.
- Testing the proposed structure for stability under all loading conditions.
- Dimensioning the parts (fabric and cables) for manufacture.
- Finalizing choice of materials and finishes.

For the conceptual design of membrane structures using both physical and computer modeling, the flowchart in Figure 4.3 is very effective. These steps will be explained in detail along with examples, but only general aspects of the steps that follow the conceptual design of a membrane structure (patterning, joint design, etc.) will be discussed. Using the design criteria mentioned in this section, the method of form-finding a working membrane shape and pre-stress can be done by physical and/or computer modeling.

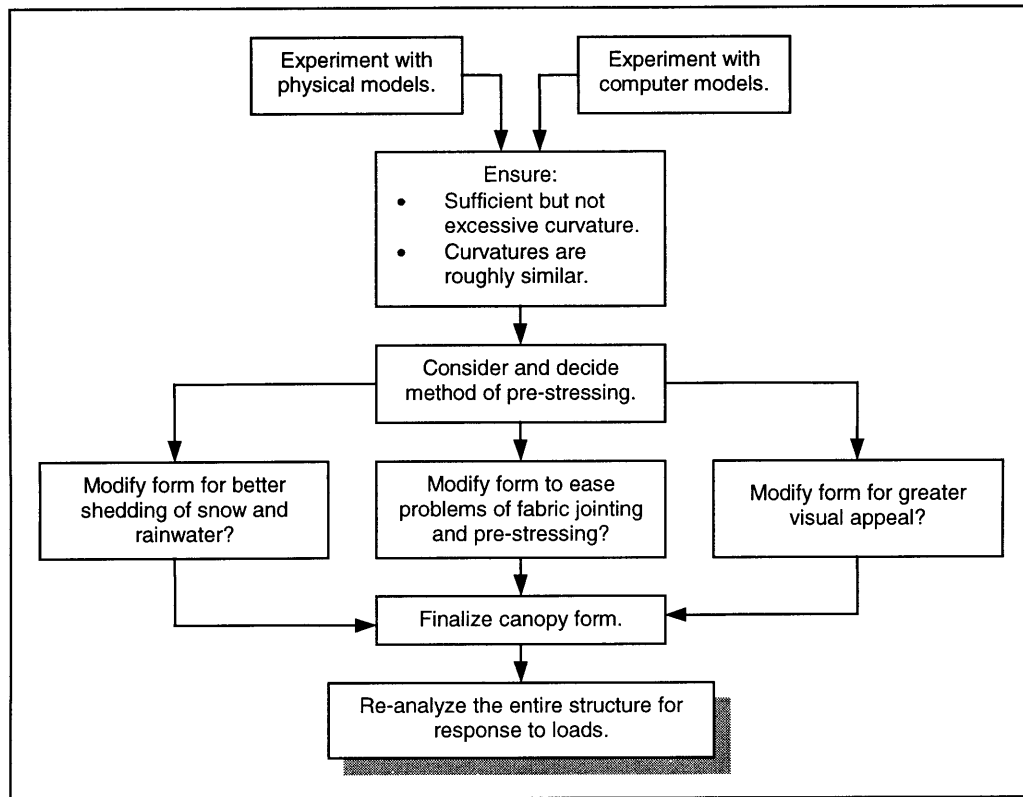


Figure 4.3 Stages of a conceptual design process for a tension structure [16].

4.2 *Physical Modeling*

Unlike traditional framed structures, membrane structures are not easily drawn or sketched on a sheet of paper due to their complex geometry. The lack of a principal projection coordinate for stressed membranes makes it very difficult to experiment with forms on a two-dimensional plane, which is why 3D modeling is essential to the design process. Physical models are still a key part of the design process for membrane structures, although computer models are gaining popularity and reliability. With physical modeling, the designer can investigate the possibilities and limitations of tensile structures. However, to obtain a meaningful understanding of the actual behavior, the physical model must mimic the behavior of the prototypical structure [12].

Most tension structures have a near-uniform pre-stress throughout their membrane. For the special condition of uniform tension throughout the membrane, there are no shear stresses in the membrane, and the surface is minimized for a given set of

initial conditions. However, the “minimal surface” approach to designing membrane structures is not always practical. This is because a minimal surface is only an “ideal” solution for a specific set of loading parameters and pre-stressing, whereas the real structure will be subjected to a variety of static and dynamic loading conditions, and stress concentrations.

Soap and liquid plastic films are a minimal surface modeling media, and are very useful in investigating the limitations of uniformly stressed membrane surfaces. Liquids have tensile capacity, but no shear capacity. Soap films in wire or string frames will form the anticlastic shapes or pre-stressed structures, and the range of possible shapes with a uniform stress field can be explored by stretching the boundaries. Once an adequate shape has been found, photographs can be taken for measurement and scaling purposes. Figure 4.4 shows a typical soap film model.

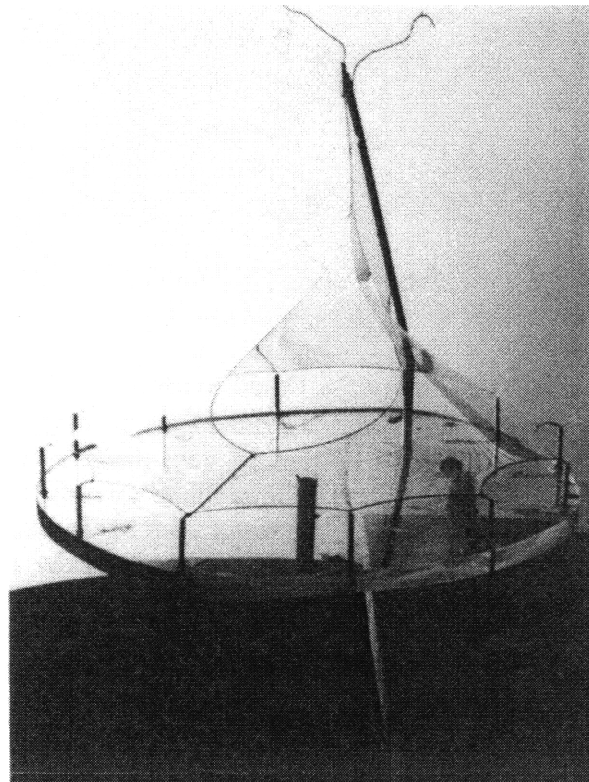


Figure 4.4 Soap film model with an internal support.

Films can also be used to observe the performance of the membrane under applied loads by simply blowing on the film. The shape of the film will change in order to

maintain equilibrium. If a sufficiently high load is applied, the film will become synclastic and resemble a pneumatic structure. Threads can be used with soap films to model cable boundaries, the shape of which are determined by the length of the thread and the stress field of the film [12].

Nylon or other stretchy fabrics can also be used to model membrane structures, supported by thin cables or rigid masts. These materials will not have a completely uniform tension throughout their surface. The implications of high local tension can be studied by noting how uniformly the fabric is stretched, and how loose or wrinkled the fabric is in areas of low tension.

Both modeling materials are useful in exploring the range of possible shapes for a given set of boundary conditions, but should only be used for experimenting and not for final shape determination. This is because there are several significant differences between the models and the actual membrane materials used in tensions fabric structures. Structural membranes are not as flexible as liquid films, or even nylon fabric, and thus the final shape may be significantly different than that of the model.

4.3 Computer Modeling

Stemming from the need for more accurate form-finding of membrane structures, computer models have become increasingly popular. Currently, only a few software companies sale their code, and most membrane designers retain their programs as a market advantage. This report focuses on a commercially available membrane design and analysis program, called “EASY,” sold by the German software company Technet-Gmbh.

INTRODUCTION TO COMPUTER MODELING

The analysis of tensile structures is a non-linear problem, and the stress-strain relationship of membrane materials is also highly non-linear. Fortunately, the stress-strain relation is nearly linear within the allowable stress range of most structural membranes [12], and are ignored in the analysis process. The deformations associated

with a given loading condition and pre-stress usually influence the resolution of those same forces, thus making load analysis a geometrically non-linear problem. Thus, the two stages of computer modeling can be summarized as follows:

- **Formfinding:** Formfinding is the process of determining the initial equilibrium shape for a given pre-stress condition. The computer finds a form that a 'pure' membrane would assume if stretched between the proposed boundaries with uniform tension in all directions.
- **Analysis:** The physical characteristics of the proposed membrane material and applied loads are fed into the computer, producing a modified equilibrium form. Stress and deflection magnitudes can then be checked.

Computer analysis of tensile structures is based on the assumption that it is possible to approximate the behavior of smooth surfaces by defining the geometry, material properties, and applied loads at discrete locations of the structure. As with most computer modeling, cables, membranes, compression struts and beams are divided into finite elements. These elements may correspond to the entire structural component or a portion of it, and are joined at nodes. The nodes are used to define the spatial geometry of the membrane, and may be restrained from translating or rotating. The individual elements are defined to have a certain elastic behavior, which can be defined to preserve a certain length or a certain force.

Because the thickness of membranes is very small relative to its other two dimensions, membrane structures are usually modeled using two-dimensional elements with different properties in the warp and fill directions. Uniaxial elements are much simpler to formulate and analyze than biaxial elements, and thus cable elements are usually used to model the membrane. There are several analysis techniques that utilize this uniaxial simplification (e.g. non-linear stiffness analysis, dynamic relaxation), but the Force Density method has proven to be extremely accurate, fast, and generates a smooth surface for practically any set of boundary conditions. EASY utilizes the force density method in its formfinding program, and non-linear stiffness analysis for its load-analysis program.

FORCE DENSITY ANALYSIS

The force density method is an analytic technique used to linearize the form finding equations for a tension net. Although it may be used in the analysis of a tensile structure under applied loads, the resulting geometrical shape is an ideal in that it does not take into account the stiffness characteristics of the materials. Thus, programs such as EASY use this method only for identifying the equilibrium shape for a given pre-stress force.

Given a set of boundary conditions, topology, and force density ratios (cable force divided by cable length), the force density method generates an equilibrium mesh. This mesh contains the geometrical characteristics that would result from a tensile structure utilizing either cables or a membrane. The method is independent of the initial location of the free joints, and takes into account each of the four elements that frame into each joint. In a computer model, the shape of the mesh can be fine-tuned by simply varying the force density ratios. The method is numerically robust, has a physical feel, and finds equilibrium shapes for determinate, indeterminate, stable and unstable structures [12].

The force density method is extremely efficient for computer applications because for positive force densities, the system of equations is positive, definite, and always has a solution. No iteration is required for formfinding, saving time and guesswork. The higher the force density ratio, the shorter the element for a constant force. This can be visualized as a rubber band constant, in which the larger the ratio, the stronger the rubber band linking the nodes [12].

FORMFINDING WITH EASY

The program package EASY makes experimentation with forms and spaces of simple structures almost as easy as playing with a nylon fabric and some wires. For complex structures and boundary conditions, the use of nylon or other physical models is quite cumbersome and time consuming. Using EASY, the time required to solve the single system of equations from the force density method takes about the same time as a simple structure (once the designer is familiar with the somewhat complicated interface).

The formfinding process in EASY consists of the following general steps:

1. Define the boundary conditions.
2. Define the net parameters.
3. Run the mesh and surface generating programs.

The above procedure will now be illustrated for the simple case of a square membrane with two high points and two low points. Figures 4.5 and 4.6 show the front-end window of EASY (called FRONTEND), used to generate the data needed to run the mesh generation software. All parameters in EASY are “unitless,” so consistency in the values entered is critical in obtaining meaningful results. The boundary lines drawn in FRONTEND can be straight, sagged to a certain value, and even “pulled up” to form arches or other 3D shapes.

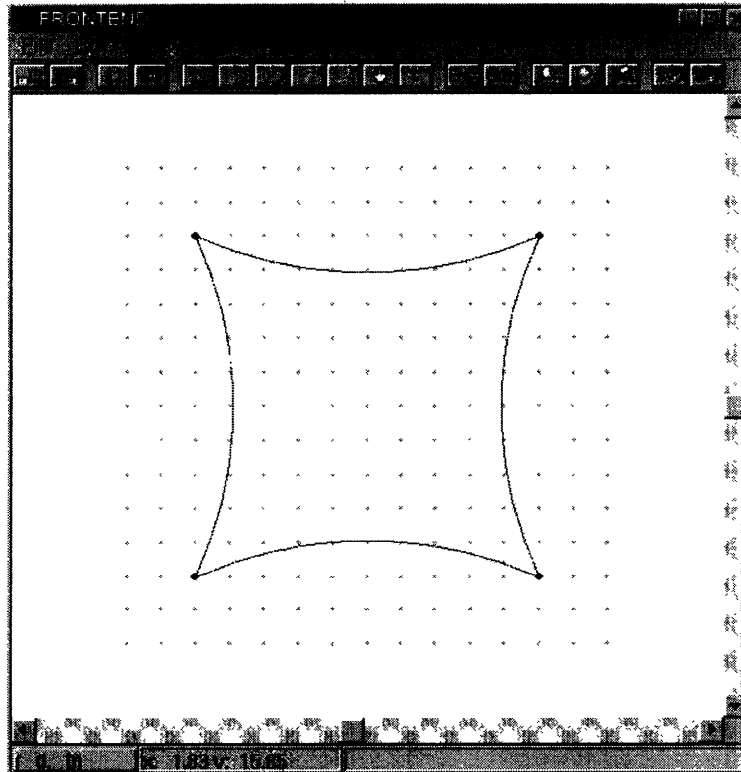


Figure 4.5 Plan view of the boundary cables for a four-point membrane structure.

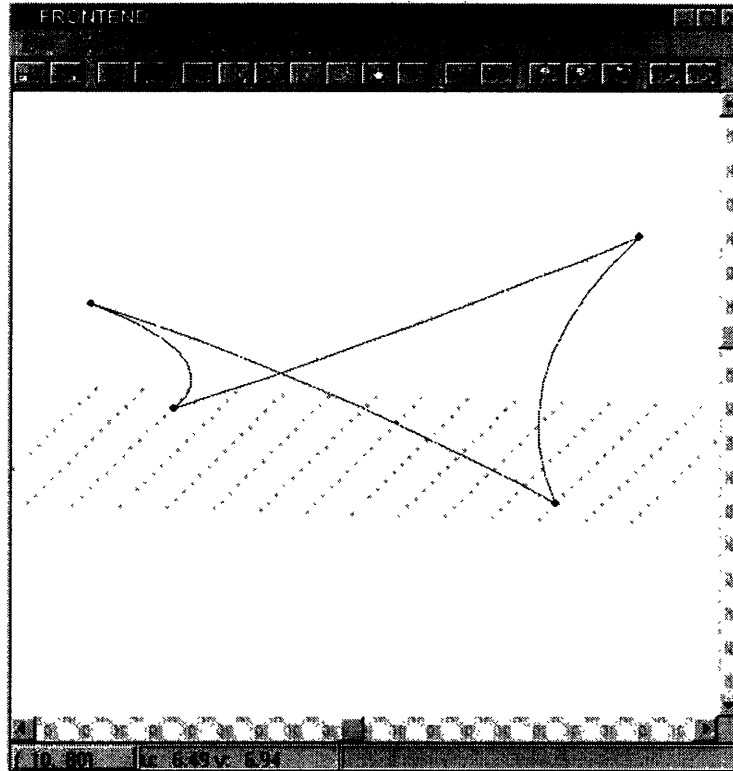


Figure 4.6 Isometric view of the boundary cables for a four-point membrane structure.

All tensioned membrane structures must have a continuous boundary. This boundary need not be straight, but must be without breaks of any kind. This requirement can be demonstrated by the soap-film model, in which any break in the frame that holds the film will cause instant rupture. The boundary geometry plays a pivotal role in defining the shape of the membrane structure, and serves as the location where the loads are taken out of the membrane and transferred to the rigid structure [16]. The boundary may be rigid or flexible, but most membrane structures have flexible edges formed by a perimeter cable or belt in a continuous edge pocket (see Figure 4.7) or running outside the membrane and connected to it by loops (see Figure 4.8). The most important considerations for boundary design are sag or curvature, and movement of connections. The shallower the perimeter curve the higher the tension in the perimeter cable must be. Higher tensions add greatly to costs and may require unpleasantly heavy-looking restraining systems. Perimeter connection points require careful attention to movement in order to avoid wrinkling or tearing of the membrane [16].

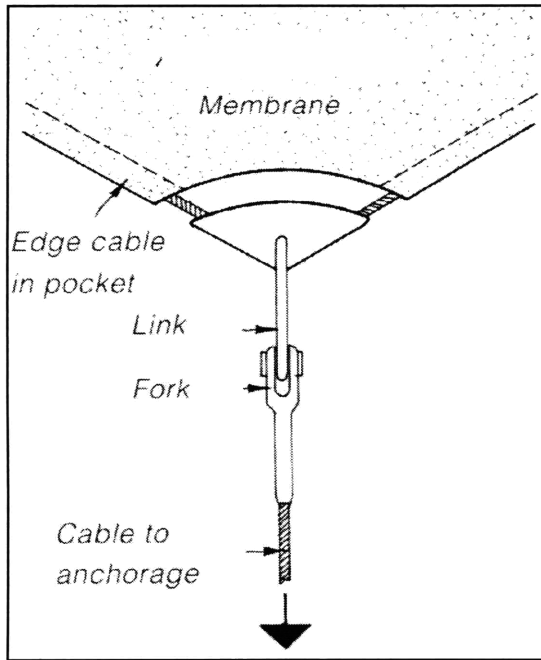


Figure 4.7 Typical edge cable detail at one of the perimeter locations where stresses are taken out of a membrane into the surrounding structure.



Figure 4.8 Tendon terminations at Il Grande Bigo, Genoa.

The boundary cables drawn on FRONTEND are initially straight, but can be given a certain radius of curvature, a pre-stressing force, and broken into a finite number of elements that will be used to compute the curvature (the higher the number of segments, the finer the curvature). Figure 4.9 shows the boundary-editing window in FRONTEND. Here, the stiffness value input box is simply a “place holder,” in that the formfinding software does not read this value when computing the surface geometry. The stiffness values for boundary members or cables can be entered here for use in the analysis program or, as is more efficient, defined once the surface geometry has been finalized and is ready to be analyzed with non-linear stiffness methods.

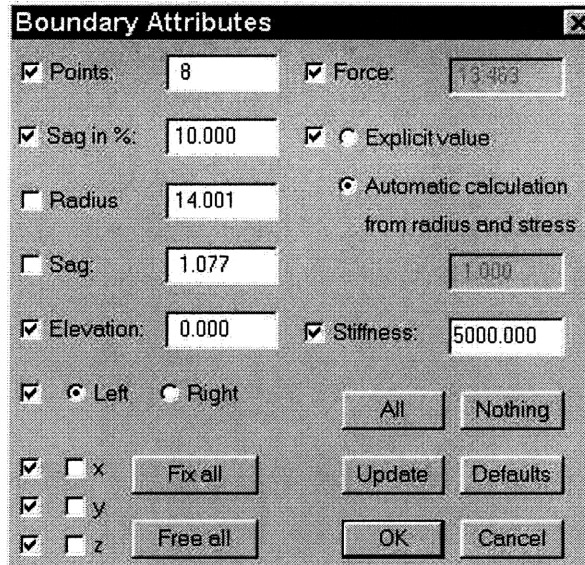


Figure 4.9 Dialog box for editing the boundary lines in FRONTEND.

Before running the mesh generating programs in the formfinding package, the net parameters must be set. If the parameters are not changed, the defaults shown in Figure 4.10 will be used. Several net structures can be generated simultaneously, and parameters for each of the nets set individually. The force density (labeled “stress” in the dialogue box) can be set different in the warp and fill (weft) directions. Also, the Net Parameters dialogue box allows the designer to generate either regular or radial nets (for conical shapes), and vary the angle of the membrane “cables” with respect to the global coordinates.

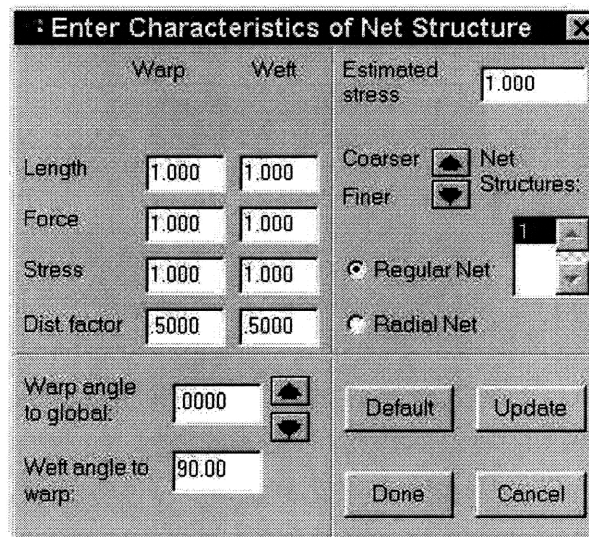


Figure 4.10 Net parameter dialogue box in FRONTEND.

Using the default values for the net parameters, the mesh generation package produced the surface geometry shown in Figure 4.11. Reducing the length and force values in each of the membrane directions (warp/fill), while maintaining the desired force density ratio (stress) can generate a finer mesh. Figure 4.12 shows the same surface geometry, but with a mesh with twice as many “cables.” Once a suitable shape has been obtained, material properties can be given to the entire membrane, an individual cable, or any combination in between. The following chapter describes this process, as well as the how loads are applied and analyzed in EASY.

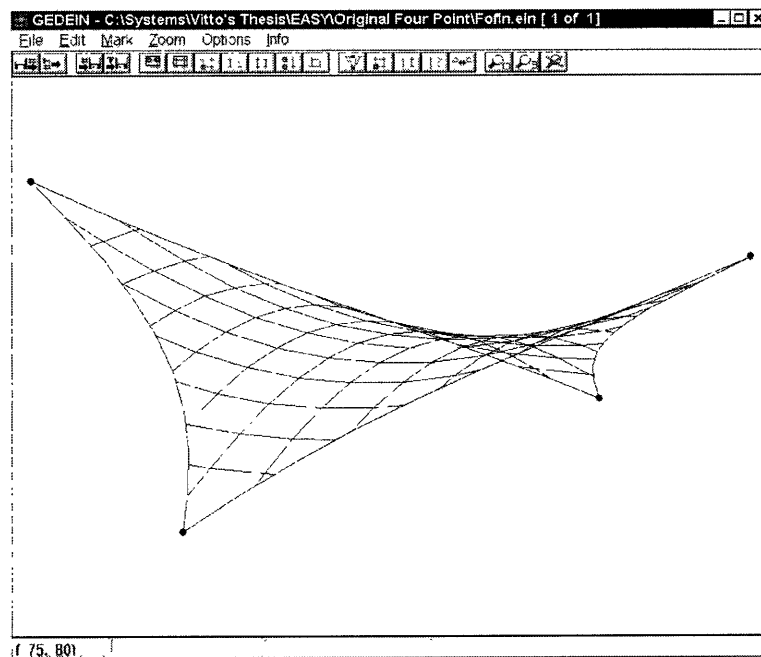


Figure 4.11 Isometric view of the four-point tensile structure.

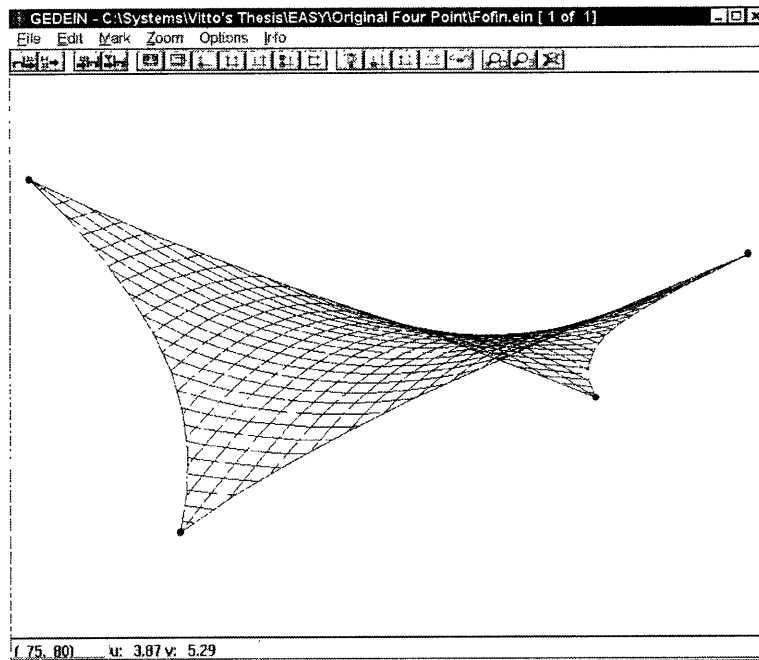


Figure 4.12 Isometric view of the four-point tensile structure with a finer mesh pattern.

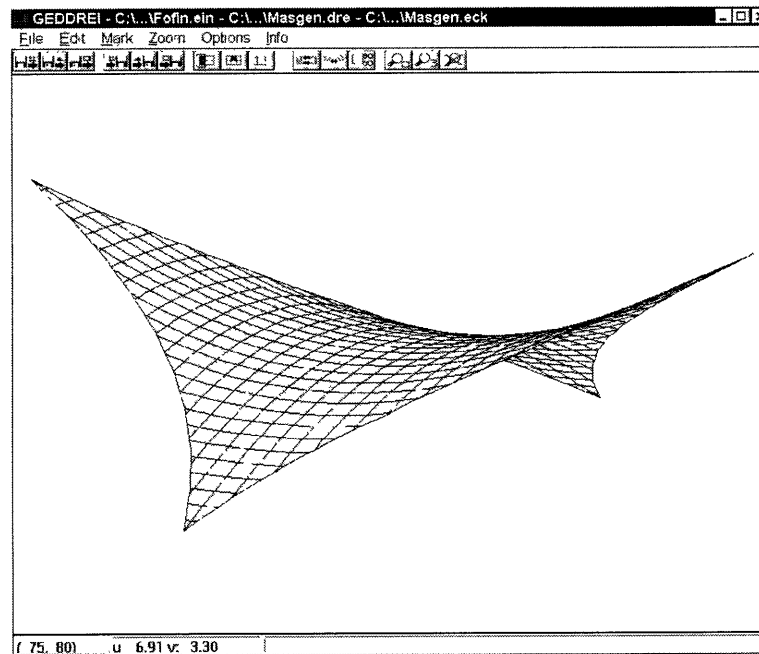


Figure 4.13 Isometric view of the surface generated by FRONTEND.

CHAPTER 5

ANALYSIS & DESIGN

5.1 *General Parameters*

CODES AND STANDARDS

Although standards for membrane structures are not as common or as comprehensive as for many other types of construction, several agencies and industries have addressed some of these concerns [2,7,10,13 & 15]. In the near future, ASCE will publish a document that outlines suggested design and analysis guidelines for membrane structures [12]. Nonetheless, the regular building codes and guidelines are useful in determining loading conditions, and in the design of the supporting structure.

SAG TO SPAN RATIOS

As discussed earlier, the load carrying capacity of a membrane structure is very sensitive to the curvature of its surface. As the distance between the supporting boundaries of the membrane are increased, the available curvature typically decreases. This reduces the membrane's load carrying capacity (i.e. the load carrying capacity of a membrane structure is proportional to its curvature). Intermediate cables may be used to help define the form and to reduce the effective span of the membrane. However, as the number of supports is increased, the cost of the structure is likely to increase as well. Membranes with sag to span ratios of 1:8 to 1:20 are typically the most viable structures [12].

PRE-STRESSING FORCES

Membranes are normally stressed to a uniform biaxial level, responding to applied loads with an increased stress in one principal direction and decreased stress in the other. The direction of the membrane which experiences a reduction in tension as transverse loads are applied to the structure, should not be allowed to lose all of its tension. Once the

membrane loses tension, it may bag or wrinkle, which is highly undesirable and even dangerous to the stability of the structure. Also, dynamic load conditions that could suddenly detension/tension or snap the membrane can be very destructive [12]. For these reasons, the pre-stress level is generally set high enough to remove any looseness on the pattern form and prevent zero-tension levels under applied loads. The level of pre-stress depends on the strength and stiffness properties of the membrane being used, as well as the range of applied loads that are expected to occur in the structures life span. Typical levels of pre-stressing for common materials are:

- 4-10% of breaking strength for cables
- 6-8 kN/m (0.41-0.55 kip/ft) for heavy PTFE/glass membranes
- 4-6 kN/m (0.27-0.41 kip/ft) for light PTFE/glass membranes
- 1-2 kN/m (0.07-0.14 kip/ft) for light lining PTFE/glass membranes
- 1-4 kN/m (0.07-0.27 kip/ft) for vinyl coated polyester membranes

SUPPORTING STRUCTURE

The deflections of the members of the supporting structure are usually very small relative to the movement of the tensioned membrane surface, and may safely be ignored in the analysis. However, this criteria should be evaluated for each structure, as there may be situations in which the equilibrium or movement of the supporting structure is directly dependent of the movement of the membrane. An example of the latter would be a non-restrained mast supported structure (see Figure 5.1), where the model should allow for rigid body motion of the mast. If the top of the mast is stabilized with external cables or other such restraining members, then the top of the mast may be assumed to be fixed.

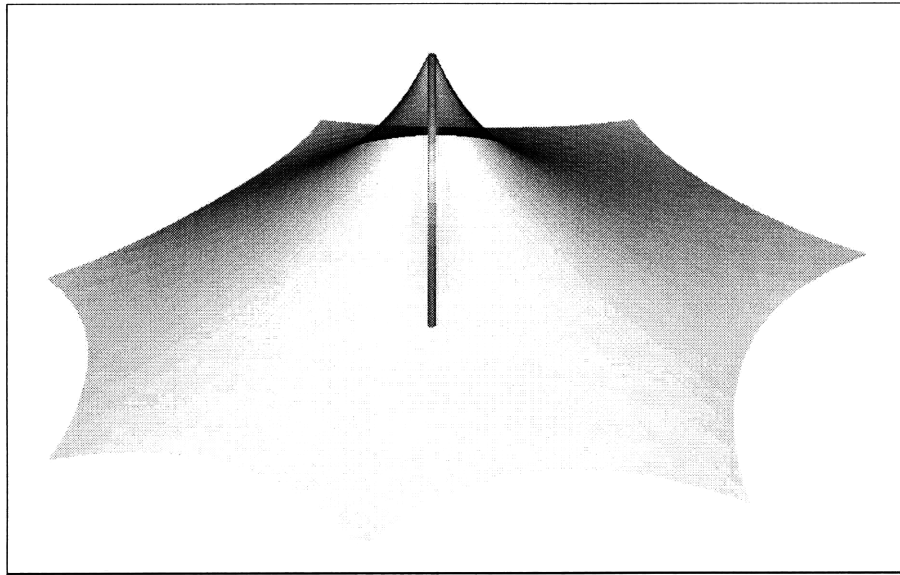


Figure 5.1 Sample membrane structure with an unrestrained mast (shown here in equilibrium).

ANALYSIS TECHNIQUES

As mentioned earlier, the magnitude of the design live loads can be obtained from the appropriate local building regulations. However, establishing the appropriate pressure distribution across the membrane can be quite challenging. Wind tunnel testing is common for final dynamic analysis of large membrane structures, and CFD models will most likely be used in the future along with finite element programs such as EASY. The large deflections that result in membrane structures due to applied loading require the solution by non-linear methods. The complexity of non-linear solutions requires the use of a computer to obtain a solution, with most programs utilizing algorithms that include biaxial membrane elements. Faster convergence to the non-linear systems is achieved with EASY because the elements are uniaxial (cables). Analytic models used to design tensioned membrane structures simplify the problem to a system of coincident elements with loads applied at nodes, which may not be representative of the physical system. The large design forces in tension structures make even minor deviations from presumed concentric work points significant, and should be checked by the designer [12].

FACTOR OF SAFETY

The strength of membranes is usually measured prior to fabrication, shipping and installation. The allowable design loads for membranes vary greatly with the type of material used, consistency and quality control of manufacturing process, the duration of the applied load, long-term weather degradation, fabrication techniques, and potential damage during construction. These factors tend to reduce the initial available strength of the membrane, and the consequences of in-service membrane failure range from incidental loss of weather protection to catastrophic structural failure. The latter has resulted in designers using factors of safety of 3 to 8 for membrane structures. Generally, the supporting structure is designed to withstand the maximum loads transmitted from the membrane, and to remain stable in the event of membrane failure.

5.2 *Analysis Using EASY*

In comparison to physical models used to analyze the performance of membrane structures under applied loads, the time required using EASY is negligible. Physical modeling requires complex scaling procedures, most of which are extremely time consuming and expensive. Frei Otto used soap film photogrammetry to predict the minimal surfaces generated for a variety of boundary curves, and most membrane designers have built physical models for wind tunnel testing before fabrication [8,9]. Programs such as EASY have dramatically reduced the time and cost of analyzing the stability of tension structures.

EASY allows the designer to alter the cable-mesh generated in the formfinding program, specifying the material properties, applied loads, supporting structure, and degrees of freedom at each node. With this amount flexibility, almost any tensile structure can be modeled. Returning to the sample membrane structure described in Chapter 4 (10x10 m four-point membrane), Figure 5.2 shows the altered model with defined stiffness properties and supporting struts and cables. The location and orientation of the struts was chosen based on the direction of the unbalanced forces at the previously fixed nodes of the membrane. This assures that under only pre-stressing forces, the strut

will experience minimal bending forces. However, the in-service force resultants at the connection points between the membrane and the supports will depend on both the prestressing forces and the applied loads.

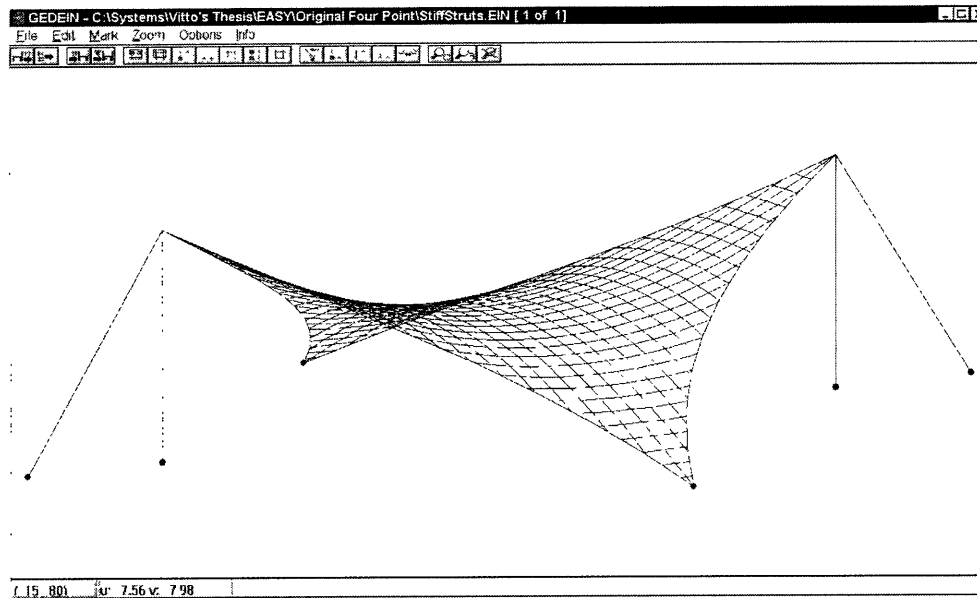


Figure 5.2 Modified four-point membrane structure, showing supporting struts and cables.

The analysis output files can be read using a spreadsheet program, or graphically using a visualization packages in EASY. The deflections can be visualized by superimposing the original structure with the deflected structure in GEDEIN. For stress distribution in the membrane, cables, and struts, STRESSVU is used. Figure 5.3 shows the stress distribution for the membrane without external loading using STRESSVU. The different stress levels can be shown by use of color gradients, line thickness gradients, or both. Although the stress variations may seem to be significant from the thickness variations in Figure 5.3, the difference from the maximum stress to the minimum stress is only 0.04 kN/m (2.7 lb./ft). As expected, the higher stresses occur near the supports.

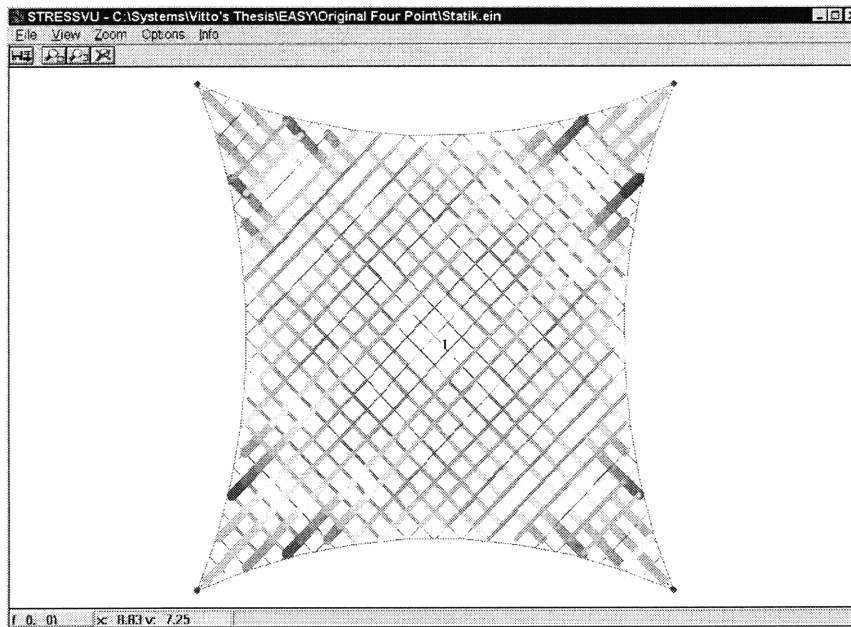


Figure 5.3 Stress distribution (plan view) of the four-point membrane with no external loads applied.

As can be seen in Figure 5.2, the curvature of the membrane is not significant, especially near the center of the structure. When external loads are applied to the surface of the membrane (e.g. a uniform snow load), Figure 5.4 shows the excessive deflection of the membrane under the applied loads. This is caused by both a low pre-stressing level and a small radius of curvature throughout the surface of the membrane. The most efficient solution to excessive deflections in tensile structure is to increase the curvature as much as possible, without compromising constructability or the aesthetic criteria of the architect. If curvature alone is not sufficient to obtain the desired deflection performance, higher pre-stress levels can be implemented.

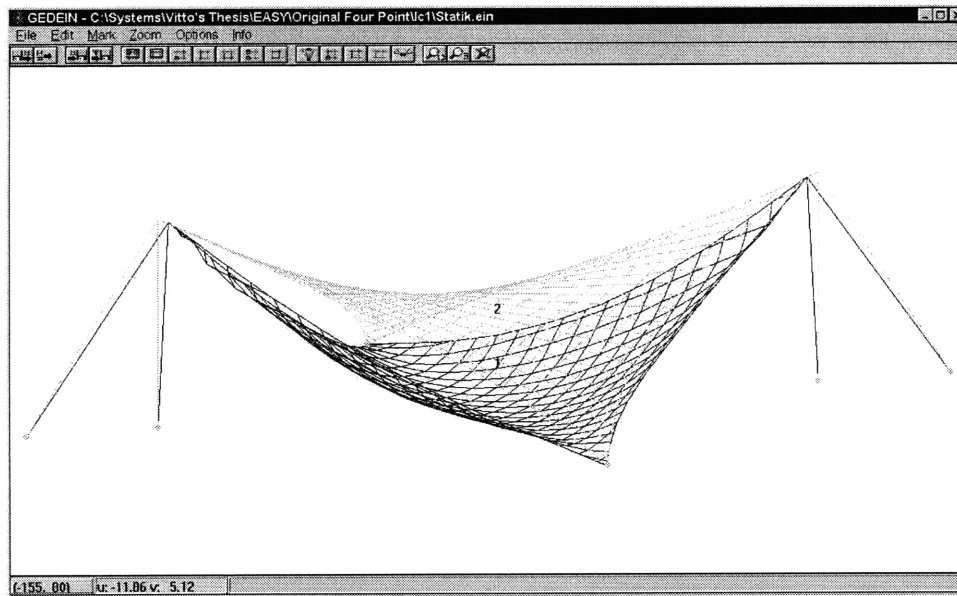


Figure 5.4 Deformed (solid) and undeformed (gray) shape for four-point membrane under a of 1.4 kN/m^2 (30 psf) uniformly distributed load (to scale!).

The curvature of the structure described in Figure 5.2 can be altered by simply raising the two high points. Figure 5.5 shows how the geometrical alterations have increased the effective stiffness of the structure, reducing the maximum deflections dramatically from 135 cm (53 in.) to 6 cm (2 in.). The latter values are reasonable, considering the long, unsupported span of the membrane in both directions, and the flexibility of the membrane fabric. Because of the high magnitude of the applied loads, the pre-stressing was also increased to 4 kN/m , in order to maintain tension throughout the membrane. Figure 5.6 shows the stress distribution in the membrane under the heavy snow loads, with the maximum stress occurring near the boundary cables (5.05 kN/m). The minimum stresses in the membrane are around 0.05 kN/m , which is still high enough to avoid any wrinkling or ponding during heavy snow loads. Various loading cases should be considered in the same way as the snow loading from this example, especially for the situation of strong wind forces acting on the structure.

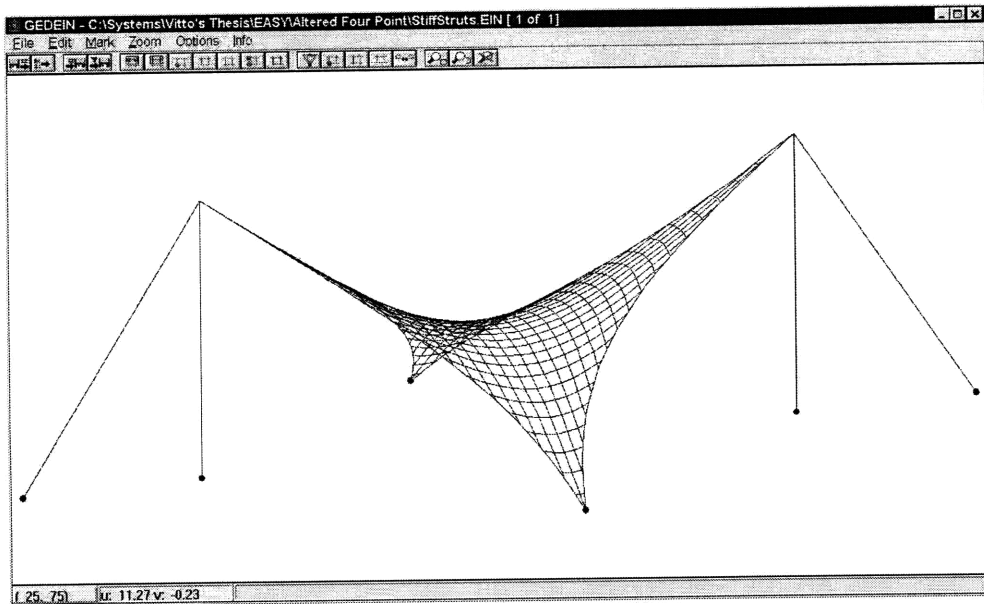


Figure 5.5 Deformed (solid) and undeformed (gray) shape for four-point membrane with increased high-points, a 4 kN/m pre-stress, and subjected to a of 1.4 kN/m² (30 psf) uniformly distributed snow load.

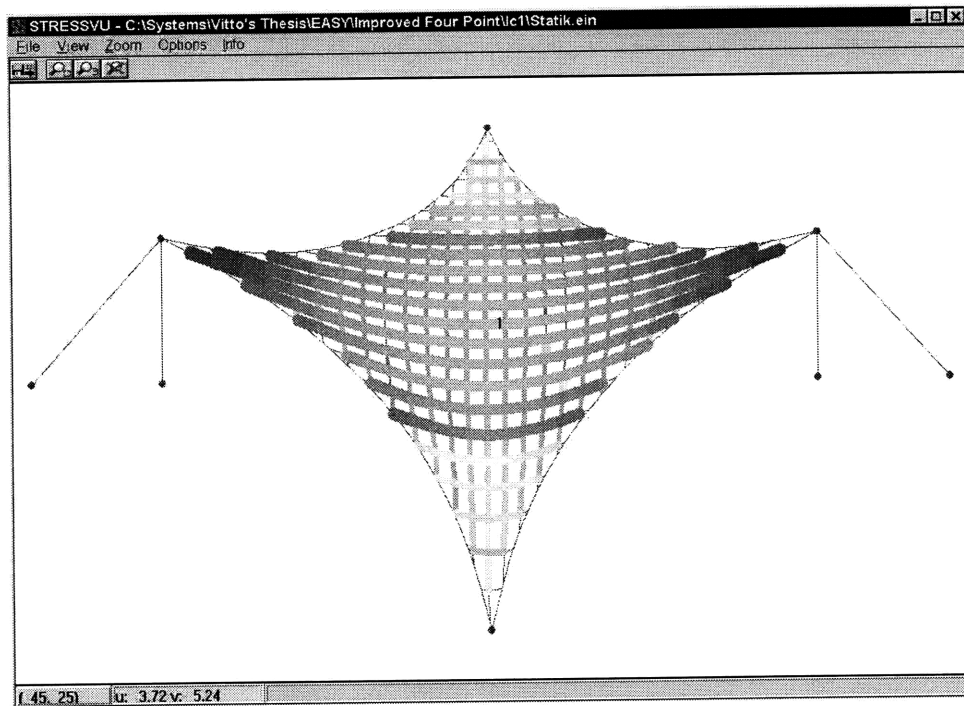


Figure 5.6 Stress distribution for the new four-point membrane structure under uniform snow load of 1.4 kN/m² (30 psf).

The 1.4 kN/m² (30 psf) is a substantial load, and the span of this simply supported membrane is over 30 feet. If lower pre-stressing in the membrane is desired or required,

supporting cables can be placed under the membrane at certain intervals. In EASY, this is done by simply increasing the stiffness properties for the desired cable (i.e. change the equivalent membrane cable to an actual cable).

CHAPTER 6

PATTERNING & FABRICATION

6.1 General Patterning Information

The final design stage of membrane structures involves working out the precise fabric cutting patterns that are to be manufactured. The entire three-dimensional curved shape cannot be flattened out, but rather requires that single sections be cut out of flat membrane material and then sewn or welded together. Therefore, the three-dimensional geometrical shape defined by the designer must be translated into two-dimensional cutting patterns.

The most important aspect of fabrication and installation of membrane sections is that they reproduce in the constructed project the prescribed surface geometry at the prescribed pre-stress level, as established by the designer [12]. Up until the early 1970's, most fabric patterning was done using approximate hand calculations and/or physical models. The use of hand calculations has greatly diminished with the increased use of computers. Physical models are still widely used in the design of membrane structures, but more for overall system evaluation and education of clients than for actual patterning and fabrication purposes. Ideally, the fabricator will utilize the latest form-generation technology and possess a thorough technical understanding of the stress-strain properties of the material being used. Also, it is very important that the installer monitor the geometry of the structure as it is being erected, as small discrepancies can lead to excessive deviations from the pre-stressing forces prescribed by the designer. The difference in pre-stressing can lead to an incorrect aesthetic shape, membrane wrinkling, or even failure due to excessive in-service stresses.

COMPUTER MODELS

Fabric patterns should be derived directly from the equilibrium membrane surface shape as described by the three-dimensional geometry given by the designer [12]. When finite-element computer programs have been used to generate the surface geometry, these elements must be collected into a series of “strips.” These strips can then be “flattened” by the computer program, and the fabricator can then use these dimensions to produce the physical membrane strips from a flat fabric sheet. Figure 6.1 shows an example of a fabric-cutting pattern used in the Buckingham Palace ticket office in London. However, it should be kept in mind that the fabric sections cut using a two-dimensional pattern only approximate the original mathematical model of the structure. While the individual fabric panels will lie flat on the floor or ground, the final assemblage of panels will not [12].

The density of the model elements used to generate the fabric strips should not be too sparse or too dense. If there are not enough elements in the patterning model, local stress concentrations could develop and cause trouble in the membrane in service or during construction. Also, the patterns could end up being wider than the width of the fabric roll from which the patterns are cut. If the density of the fabric membrane elements used to describe the surface shape is too dense (i.e. there are too many elements in the patterning model), the result could be unnecessary fabric waste. This waste is due to not taking full advantage of the width of the fabric roll or width. Minimizing the fabric waste is a crucial aspect of controlling the cost of fabrication [12].

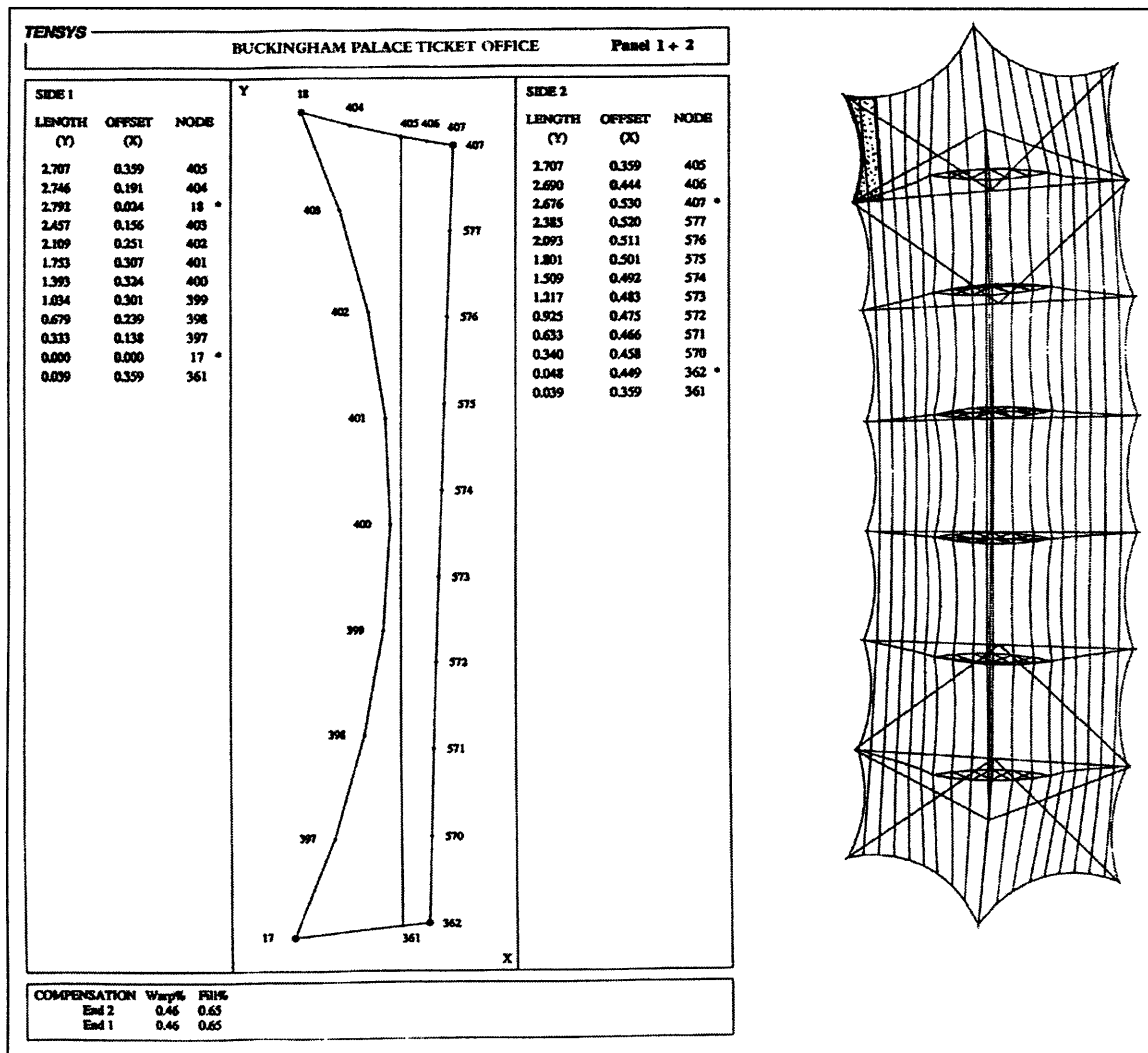


Figure 6.1 Example of a fabric cutting pattern: the Buckingham Palace ticket office in London by Sir Michael Hopkins and Partners [16].

The software package used in the previous design examples, EASY, has the capabilities to generate patterning data and graphics for practically any membrane structure. As mentioned earlier, the inherent curvature in membrane structures makes their fabrication possible only by the use of narrow strips of fabric. The boundary lines for these strips must be found from the 3D surface generated in the design phase. EASY generates these strips from geodesic lines on the surface, resulting in very small distortions and relatively straight strips when flattened to a 2D plane. EASY allows for a “quick and dirty” patterning method using the geodesic lines, and a final strip calculation obtained by creating a strip on a developable surface close to the given surface. This surface may then be trimmed and flattened out without distortion. Thus, EASY allows

the designer to explore the most efficient patterning schemes before the fabricator and installer take over a given project.

COMPENSATION

Once the fabricator has converted the three-dimensional surface to two-dimensional fabric sections, careful attention must be given to the stress-strain properties of the particular fabric being used. This is because during installation, in order to develop the prescribed pre-stressing forces, the fabric must be stretched a certain amount. The stretching requires the fabric sections to be cut and assembled smaller than their final installed size. The difference in size from the cut and assembled fabric section is proportional to the amount of biaxial strain that each of the warp and fill directions of the fabric undergoes when loaded to the specific pre-stress level. The general process of making the fabric panels smaller than the final installed size is known in the industry as “compensation.” [12]

ACCURACY

Dimensional accuracy must be tightly controlled during the fabrication of the membrane structure, from cutting to assembly. This is because the development of the proper pre-stress level in the finished structure is dependent on very accurate sizing of the fabric assembly [12]. Otherwise, the actual pre-stress level in the membrane may end up being too high or too low, which could lead to undesirable performance and visual appearance.

The issues mentioned so far regarding patterning are, necessarily, simplistic. In practice, these phases of the fabrication process can be extremely complex and require the attention of highly qualified, thoughtful, and meticulous engineers and/or technicians [12].

6.2 Tendon Selection and Specification

Structures which require high stiffness and corrosion resistance, and especially in external situations where the client is not likely to carry out regular maintenance

inspections, solid rods are likely to be the most effective tendons. High tensile steel tendons are available for use in membrane structures in diameters ranging from 4 to 35 mm (0.16 to 1.38 in.), and can be subjected to higher loads than cables of the same diameter [16]. However, the cost of a solid rod may be as much as two-and-a-half times that of a cable, making a larger diameter cable the most economical solution in some cases.

Where flexibility, curving geometries, and a high strength-to-weight ratio are important, a spun cable is more effective. However, careful consideration by the designer should be given if the cables are to be subject to the environment, as corrosion is likely to occur in cables. Regular inspection and maintenance are critical when using cables in external situations. There are many types of spun cables, with the best performance for a given diameter being the compact or tightly wound cables with as few strands as possible. However, in terms of flexibility, the exact opposite is true.

The choice of tendon material and finishes are extremely important for the long-term performance and appearance of the structure. Tendons are available in various types of steel, and it is up to the designer to select the best balance between cost, corrosion resistance, strength, and appearance. For solid rods in highly corrosive environments, stainless steel or Nitronic 50 steel are the best choices. A rod made from Nitronic 50 steel will be stronger, stiffer, and more expensive than one of equivalent diameter in stainless steel [16]. Cables in highly corrosive situations can utilize stainless steel, or use steel treatments, such as PVC coating, galvanization, or zinc impregnation during spinning, in order to increase their durability. Stainless steel is the most durable solution, but also the most expensive in initial cost.

Finally, when determining the flexibility required of tendon, the bending radius should be selected carefully. If the cables are curved too tightly, they lose their strength and may even come apart. The degree of risk varies between cable types and expert advice should be sought when finalizing the design of tendons. As a rule of thumb, the bending radius should be at least 500 times the diameter of the individual wire strands [16].

6.3 Connections

GENERAL

The design of connections in membrane structures is critical in ensuring that the working stresses of the fabric are smoothly transferred to the cables or other reinforcing materials, and into the supporting structure. Design forces, especially in cables and steel supports, are often high, and the connections to these members provide the load path onto the sub-structure. In detailing these connections, care must be taken to ensure [12]:

- Proper flexibility exists in the connection for the expected displacements and rotations.
- The connections are sufficiently rounded in areas of fabric contact to prevent abrasions, lacerations, or development of stress concentrations in the fabric.
- The connection joint will remain sufficiently watertight for the intended application.

Creep, or the elongation of a member over a period of time under constant stress, is characteristic of some membranes and should be considered in patterning and in the connection design. Creep results in loss of pre-stress, which if significant can lead to undesirable performance and aesthetic conditions in the membrane structure. Factors influencing creep include the duration of the load, magnitude of the load, humidity, and temperature. Fiberglass fabrics and some vinyl-coated polyester fabrics exhibit little or no creep compared to other fabrics. If the effects of creep are not accounted for, connections may develop unbalanced loading and unwanted displacement. If creep is expected to be a problem in the membrane's lifetime, the connection should be designed to be adjustable. Adjustable connections can be accomplished by using slotted or offset holes in clamping, turnbuckles on cables, etc. [12]

Finally, corrosion is an important consideration when designing connections. Depending on whether the connection is exposed to the exterior environment or not, various means of corrosion protection are available for consideration by the designer. Some of these are stainless steel, aluminum, galvanized steel or painted connections.

However, post-installation inspection should be performed when galvanized or painted connections are used, to restore any portions of the coating that may have been damaged during construction.

FABRIC-TO-FABRIC

Fabric membranes are supplied in rolled form of varying widths. Patterns are then cut from these rolls and assembled at the edges by several methods. The three principal methods for joining woven fabrics are [16]:

- **Sewn Joints:** These are the strongest types of joints, but the thread is susceptible to degradation. Sewing is suitable for PVC-coated polyester where it is normally combined with heat sealing for maximum strength, and in external situations the joint should be protected with a PVC layer. Sewing is not suitable for PTFE-coated glass fabrics due to the brittleness of the yarn.
- **Heat Welded Joints:** Heat welding is done by heating the seam of the fabric above its melting point and then letting it cool while applying pressure. The heating can be done by a jet of hot air, by contact with heated elements, or by radio-frequency electromagnetic radiation. Heat welded joints are suitable for both PVC-coated polyester and PTFE-coated fiberglass fabrics. However, in the latter case an interlayer of a different material must be used, because the PTFE does not itself melt.
- **Mechanical Joints:** Although sewn and heat welded joints can be performed on site, they are best made in a workshop. Mechanical joining is often preferred for on-site construction. The three most common types of mechanical joints are:
 - 1) The roped edges of two sheets of fabric are clamped between plates (see Figure 6.2a). The plates should be discontinuous to allow for movement.
 - 2) The roped edges of two sheets of fabric are held in an extruded aluminum “double clamp strip” (see Figure 6.2b). Again, the plates should be discontinuous. This method is less waterproof than the one above.

- 3) The simplest method is to connect a series of scallops at frequent intervals by means of shackles. This kind of joint is easily and quickly assembled on site, but is not waterproof.

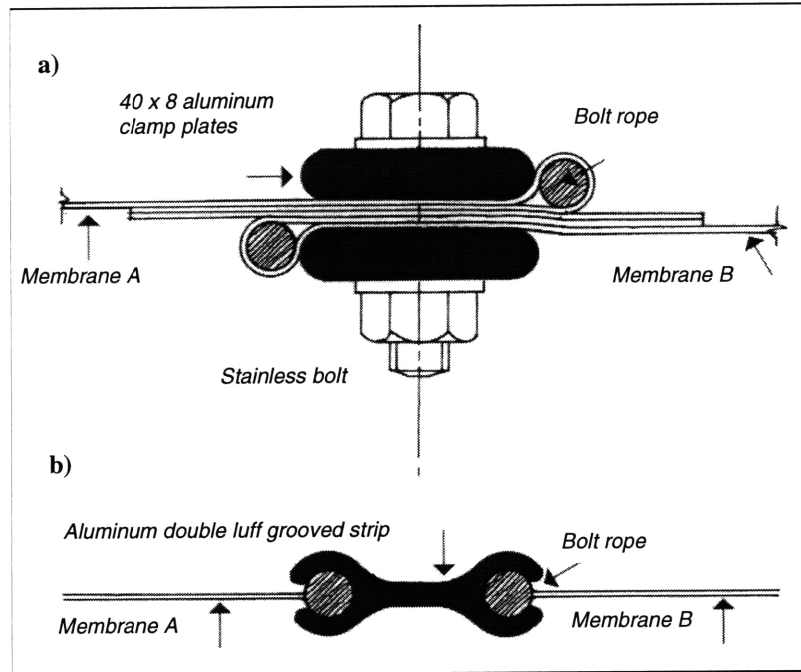


Figure 6.2 Typical mechanical joints for membrane structures [16].

Consideration should be given to providing a fabric seam strength adequate for short term (wind) and long term (snow) loading under all anticipated environmental conditions with applicable safety factors. Seam strength is primarily a function of coating adhesion (for glued and welded seams) and seam width. Typical seam widths are 25 to 50 mm (1 to 2 in.) for PVC materials and 50 to 75 mm (2 to 3 in.) for silicone and PTFE [12] (see Figure 6.3). Patterning of the membrane should be done so as to minimize fabric seams and splices, and “bias reinforcing” patches should be incorporated in corner and other areas of possible stress concentrations.

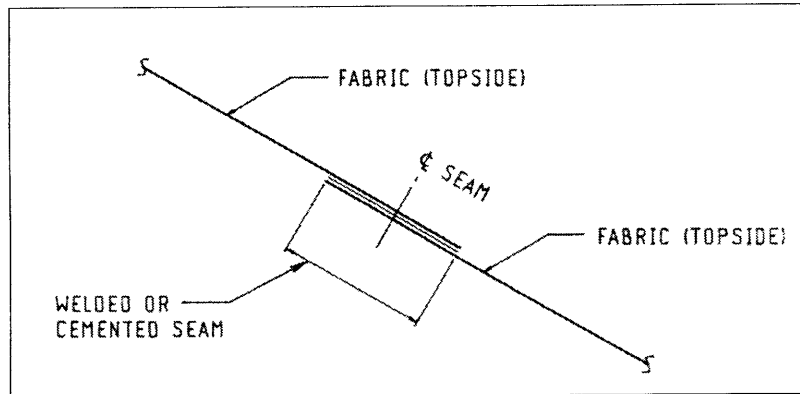


Figure 6.3 Typical seam width arrangement [12].

FABRIC-TO-RIGID FRAME

The most common form of attaching a membrane to a rigid edge condition, such as a concrete or steel curb, is by the use of a fabric roped edge and clamping hardware (see Figure 6.4). The fabric roped edge is compressed between the base plate and the clamp bar, with the bearing of the roped edge against the clamping hardware providing the fixity of the membrane to the rigid edge.

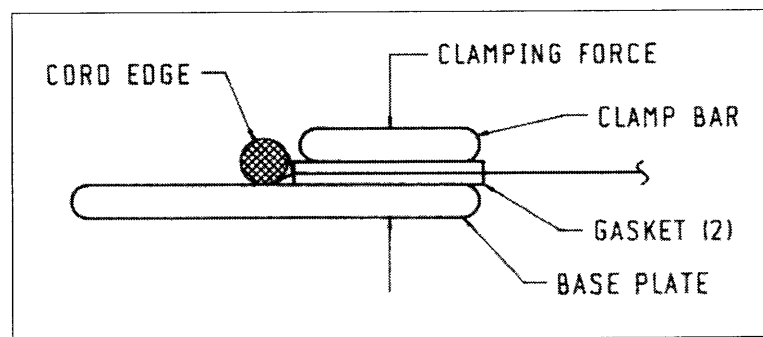


Figure 6.4 Typical clamping arrangement [12].

The clamping arrangement should be continuous, as shown in Figure 6.5. The components of the clamping hardware should be rounded and padded, in order to avoid stress concentrations or abrasions during service. The fabric clamp system should be designed to withstand the stresses established in the design of the fabric envelope, without any deformation or distortions that could lead to undesired stress levels in the membrane.

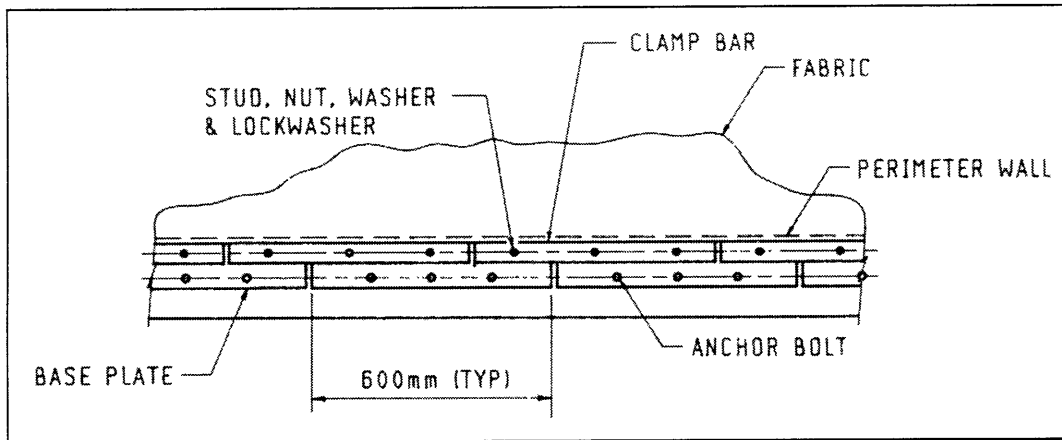


Figure 6.5 Plan view of a typical perimeter connection scheme [12].

In situations where the membrane is supported by a cable or a steel tube, the membrane is usually carried, but not attached to, by the member [12]. Usually, the seam is located above the member, in order to minimize the seam's visual impact (see Figure 6.6). The supporting members are usually coated with plastic in order to reduce the amount of abrasion at the interface. Also, if the analysis of the membrane structure indicates that the membrane might lift off the supporting structure (e.g. under certain loading conditions), the membrane may be attached with a cuff or by clamping the fabric along the arch to control deflections and membrane stresses (see Figure 6.7).

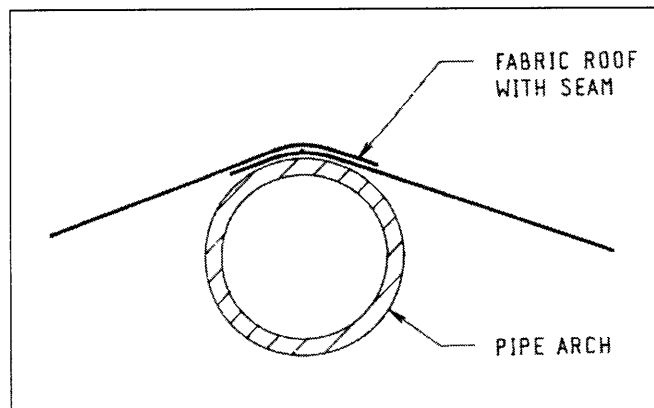


Figure 6.6 Sketch of a pipe arch supporting a membrane seam [12].

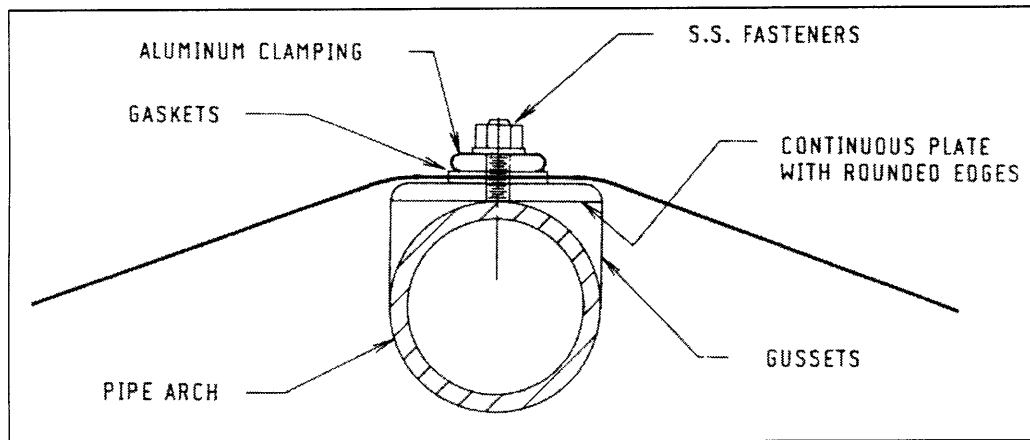


Figure 6.7 Steel pipe support with a fixed fabric [12].

FABRIC-TO-CABLE

Termination of a fabric membrane at a cable location can occur under two conditions: termination of the fabric at a cable catenary edge (a one-sided connection), and termination due to the sectionalizing in a fabric membrane where the fabric is terminated on both sides of the cable [12]. In both cases the membrane should be secured continuously to eliminate any free edges.

There are several methods that can be used to connect a cable to a fabric membrane. Figure 6.8 shows how the cable can be enclosed within a fabric cuff, where the membrane stresses are transferred directly. Friction along the cable prevents slippage of the fabric. Figure 6.9 shows a different connection, in which the roped edge can be compressed between clamping hardware, with the clamping hardware attached intermittently to the cable by means of straps. Finally, Figure 6.10 shows how sectionalizing of the membrane can be accomplished by the use of clamping hardware. In general, care must be taken to design a cable connection that will withstand the stresses from the membrane, as well as the fabric stresses from only one side (as is the case during construction or if one membrane fails) without permanent distortion [12].

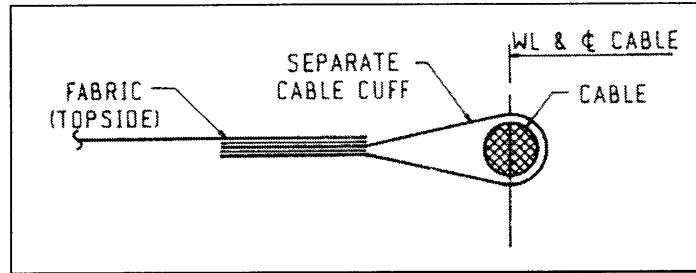


Figure 6.8 Cable cuff arrangement.

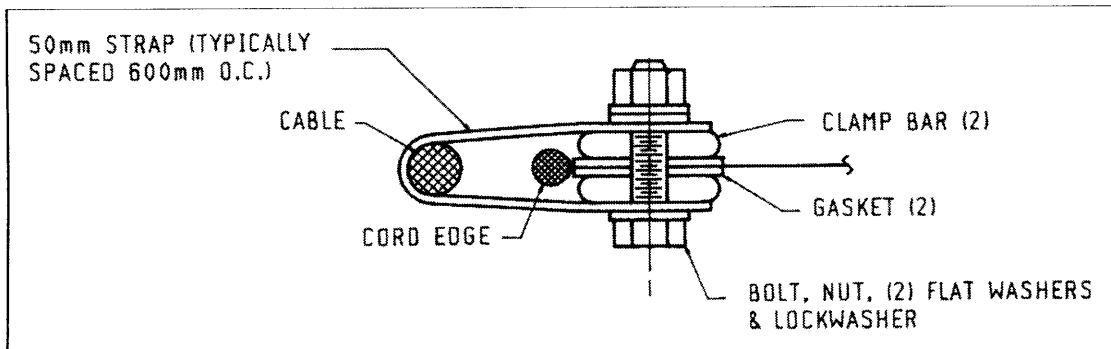


Figure 6.9 Cable clamping arrangement.

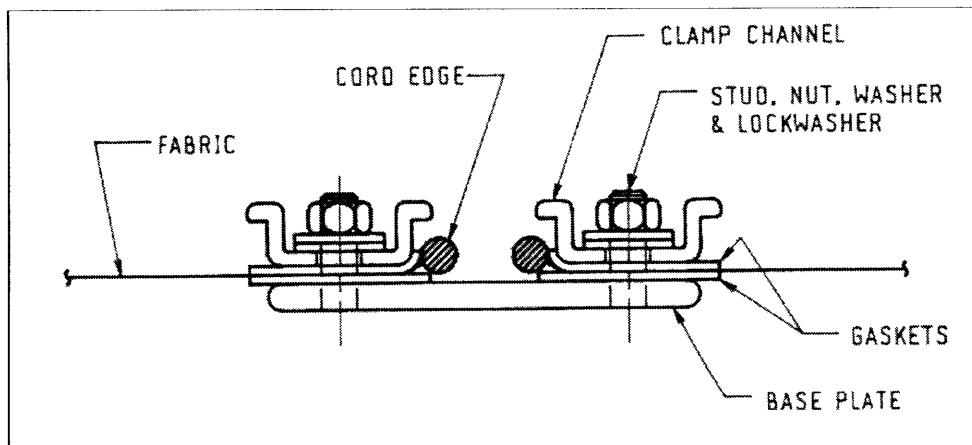


Figure 6.10 Sectionalizing details.

CABLE-TO-CABLE

Cable terminations and joints can add to the aesthetic properties of a membrane structure by coordinating the fittings to give a coherent appearance. When cable tendons are used (as opposed to rigid bars), then proprietary rather than custom designed terminations are

virtually obligatory [16]. The most commonly used fittings are shown in Figure 6.11, and the determination of the termination type will depend on the following criteria:

- Whether the tendon is of fixed length or needs to be adjustable.
- What is considered the most convenient method of adjustment.
- Tendon length and diameter.

Due to the large deflections and movement inherent in membrane structures, most cable terminations are of adjustable length. If adjustable length is not a requirement, then solid rods can be used with each end swaged or welded to an eye or fork (see Figure 6.11a). For fixed-length tendons, the designer must exactly specify the pin-to-pin distance, as significant on-site adjustments are not possible. If cables are used instead of solid rods, pre-stressing techniques can be used to cut the cable to the equivalent in-service length after “constructional stretch” has taken place.

Adjustable-length tendons are much more common in tensile structures. By rotating a threaded component in the axis of the cable, adjustments can be performed on-site. As shown in Figure 6.11b-d, adjustable-length cables can allow for no rotation, or rotation in one plane. Also, Figure 6.12 shows how rotation in two planes is also possible for situations where out-of-plane movement may occur. The designer must consider the rotation of the cable terminations in order to avoid any bending stresses in the cable.

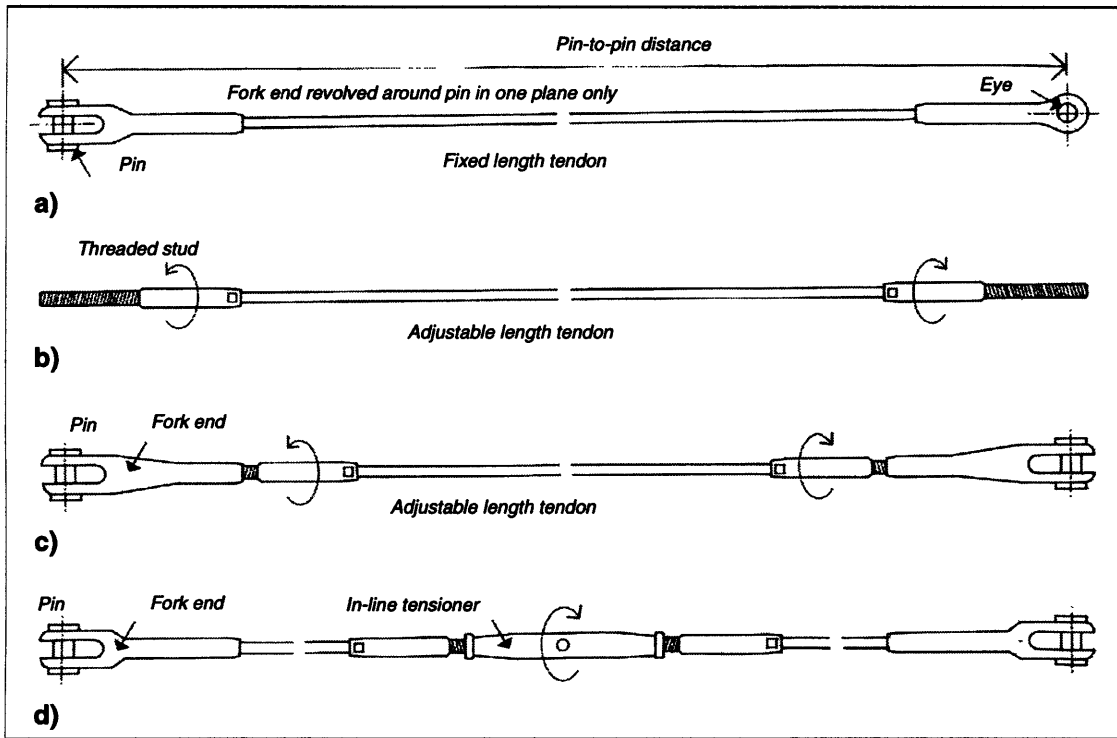


Figure 6.11 Common methods of tendon terminations [16].

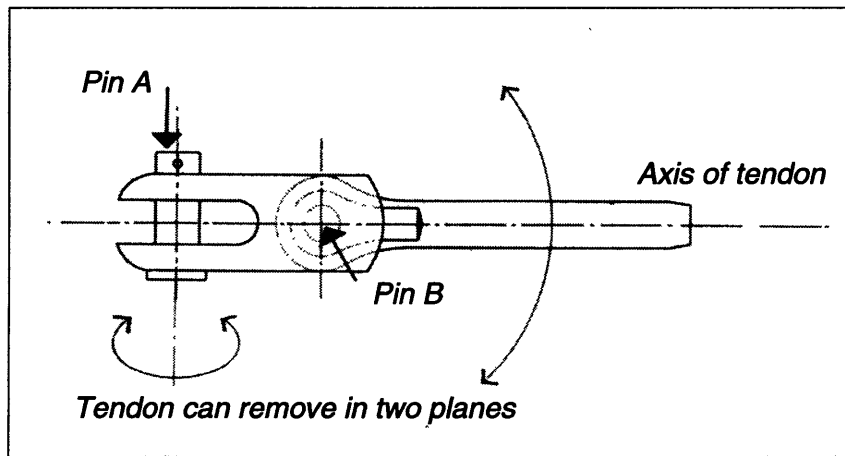


Figure 6.12 A toggle fork that allows movement to occur in two planes without transmitting bending stresses to the cable [16].

6.4 *Fabric Handling and Installation*

Proper fabrication and construction of membrane structures is as important as their accurate design. Even minor fabrication and/or construction errors, such as a membrane that is too small, can lead to inaccurate pre-stressing magnitudes. Most membrane structures cannot be pre-assembled in the workshop for testing. The assembly of perhaps hundreds of parts on site is both the first and the last opportunity for discovering any discrepancies from design to reality. The best way to avoid any major mistakes is to have an experienced team of designers, fabricators, and installers working closely until completion of the project.

HANDLING

During fabrication and shipping phases, the membrane fabrics are usually subject to harsh environments and treatment, which may lead to permanent damage of the fabric. Most of the recommendations for preventing damage to the fabric during these phases are dictated by common sense. The most obvious examples include proper fabrication conditions, packaging, and shipping. Fabrication should be done in a clean area, and free of objects or machines which could damage the fabric. When walking on the fabric is necessary, soft-soled shoes should be worn and care taken not to step on folds. Fluids and chemical agents should be kept away from the fabric, unless the manufacturer approves the type/quantity of the fluid.

Packing and shipping the fabric involves careful attention to the folding, shipping conditions, and unpacking at the site. At the site, the fabric should not be placed on the ground without having removed any damaging objects and placing a soft cloth or layer such as polyfilm [12]. Because the fabrics are very light, wind gusts may damage the unrestrained membranes, and rain may penetrate the membrane through the unsealed edges. In all, careful planing of the above conditions can reduce the chances of damage to the fabric prior to its installation.

INSTALLATION

The installation procedure should be a part of the early design phases for membrane structures, as it may dictate the size of the fabric strips or location of the membrane connections. Therefore, the installation plan should answer the following questions throughout the design process [12]:

1. How large an assembly can be reasonably managed at a time? In other words, does the fabric roof have to be broken up into several pieces in order to be properly installed?
2. Does the choice of direction of warp and fill of the fabric make the job installation any easier or harder?

The installation procedure can be broken down into three general steps: layout, fastening, and tensioning. In the layout phase, the fabric and accessory items are unpacked and placed loosely over the supporting structural elements. The supporting structural elements may be masts, arches, cables, etc. It is in this phase of installation that the fabric is most vulnerable to weather-related damage. Fabric can be severely damaged at this time if caught in a windstorm, and even workers may be at risk if the high winds occur while they are holding or standing on the fabric. It is generally recommended that the fabric be installed during wind velocities of no more than 25 km/h (15 mph) [12]. In addition, once fabric installation has begun, it should not be left vulnerable to damage due to inclement weather. In this phase the fabric is usually tied down with ropes but not fastened with the permanent hardware.

A commonly used technique during the layout phase is to loosely (i.e. without stretching) attach either the warp or the fill direction (usually the warp direction) of the fabric assembly to its boundaries. Once this is accomplished, the fabric is reasonably under control should inclement weather occur. Then the system is pre-stressed by pulling only in the orthogonal direction.

In the fastening phase of installation, the fabric is anchored to its permanent attachment system. For example, cable end fittings are attached to the collector fittings, fabric is attached to clamp bars, etc. Significant tensile forces may be developed during

this phase as the fabric begins to stretch when pulled to its attachment locations. Any evidence of improper fitting or size of fabric strips should be immediately addressed, as such misfits will probably become more of a problem as tensioning proceeds. The misfits are not purely cosmetic (e.g. wrinkles), but may produce improper structural response in the system when subjected to service loads. When the fabric goes slack, that portion or a certain direction of the membrane is no longer taking its share of the load.

During the tensioning phase, the fabric is stretched to its final boundaries. Pre-stressing forces should be developed gradually, in stages, and uniformly around the entire structure. Final tensioning should have the objectives of developing the desired stress field in the membrane as well as removing any wrinkles [12]. In the case of very complex structures, the structural engineer for the project should assist in determining when the appropriate level of tensioning has been achieved.

REFERENCES

1. Buchholdt, H. A. *An Introduction to Cable Roof Structures*. Cambridge University Press. 1985.
2. *Design and Standards Manual*. Air Structures Institute. 1977.
3. Irvine, H. Max. *Cable Structures*. The MIT Press. 1981.
4. Krishna, Prem. *Cable-Suspended Roofs*. McGraw-Hill, Inc. 1978.
5. Leonard, John W. *Tension Structures: Behavior & Analysis*. McGraw-Hill, Inc. 1988.
6. Levy, Robert. *Analysis of Geometrically Nonlinear Structures*. Chapman & Hall. 1995.
7. *Manual for Applications of Steel Cable for Buildings*. American Iron & Steel Institute. 1973.
8. Otto, Frei. *Tensile Structures: Volume 1*. The MIT Press. 1967.
9. Otto, Frei. *Tensile Structures: Volume 2*. The MIT Press. 1969.
10. *Recommendations for Air-Supported Structures*. International Association for Shell and Spatial Structures. 1985.
11. Schueuermann, Rudi. *Tensile Architecture in the Urban Context*. Bath Press Colourbooks, Great Britain. 1996.
12. Shaeffer, R.E. *Tensioned Fabric Structures: A Practical Introduction*. American Society of Civil Engineers. 1996.
13. *State-of-the-Art Report on Air-Supported Structures*. American Society of Civil Engineers. 1985.
14. *The Massachusetts State Building Code: User's Guide to 780 CMR* Sixth Edition. Commonwealth of Massachusetts.
15. *Uniform Building Code*. Chapter 55. International Conference of Building Officials. 1991.

16. Vanderberg, Matriz. *Soft Canopies*. Academy Group Ltd., Great Britain. 1996.
17. Vilnay, Oren. *Cable Nets and Tensegric Shells*. Ellis Horwood Limited, Israel. 1990.