The Design and Analysis of Tension Fabric Structures

by

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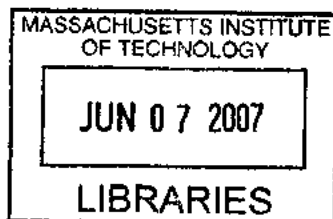
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ABSTRACT

Although tensioned fabric structures are increasingly in demand, since they are comparatively new to the engineering world, there are relatively limited resources available about such structures. This report reviews the topics that encompass the design and analysis of tensioned fabric structures. First, an overview of the conceptual basis of tensioned membranes is discussed, as well as the different shapes that are formed using manipulations of the basic concept. Since the material properties play a key role in the durability of tension fabric structures, the ideal material characteristics, as well as the current available fabrics are described. Both the strength of the employed materials and the load considerations for design are outlined. The report follows by explaining the process of roughly assessing the scope of a project, as well as the variety of non-linear analysis that must be performed and the methods used to perform them. This report concludes with key connection details that must be considered for a successful tension fabric structure.

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INTRODUCTION

Fabric structures have been in existence for thousands of years. However, only in the last fifty years have these "tents" evolved into structures utilizing the inherent structural characteristics of the membrane. While tensioned fabric structures are fascinating to engineers for realizing materials to their fullest potential, they never cease to amaze the architect in its free flowing shape and design.

However, due to the nature of membrane structures, a conventional method of design and analysis does not suffice. Moreover, having a short history of half a century, relatively little information is available compared to conventional structures. Everything from the material selection, load considerations to the analysis method and the structural connections must be designed for the specific needs of the tensioned membrane structures.

In order to get a complete understanding of the aspects of design and analysis of tensioned membrane structures, not only do the conceptual basis and non-linear behavior

of the structure have to be understood, but the material properties and connection detailing between the different elements should also be considered as well.

1.   CONCEPT AND FORM

1.1   Conceptual Development

The use of material is inefficient in bending elements. The interior fibers never reach their maximum stress levels, while always maintaining weight. From this idea, the truss was developed where the inefficient material of the beam was turned into clear space and each truss carried specific tension and compression forces. However, the most simplest efficient structural system is when load is carried by one element that is either completely in tension or compression. While in two-dimensions, this system is a cable for tension loads and an arch for compression loads, in three-dimensional space, this system is a dome and tensioned fabric, respectively. This development is

Figure 1: The conceptual development and effectiveness of tensioned membrane structures (Koch et al., 2004)

outlined in Figure 1. Therefore, terms "membrane structure" and "tensioned fabric structure" not only allude to the nature of the material used in such design, but also the way in which the forces act within the system.

The stresses created are membrane stresses, that is, stresses acting parallel to the local surface and constant through the thickness of the surface. Unloaded, the surface

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prestresses are all in equilibrium. However, when the membrane is loaded, since it can not carry any out of plane stresses, it deforms until all the surface forces find a new equilibrium. Pretensioning of the membrane is necessary to decrease potential deflection. On a loaded pretensioned membrane, the final deflection will be less than a non-tensioned membrane. However, at the same time, the final tension will be higher.

The primary structure, which is usually made up of compression elements, play an important role for it equalizes and maintains forces from the prestressing of the fabric. Not only do they transmit the loads to the ground, but the supporting structure ultimately controls the geometric parameters of the structure.

1.2   Surface Types

There are two categories of membrane surfaces: an anticlastic and a synclastic surface. Anticlastic surfaces have negative Gaussian curvature. This means the two directional forces are in opposing directions such as the cone, saddle or hyperbolic parabaloid. The opposing directional forces that are introduced by prestressing the fabric in both directions counterbalance each other. Conversely, synclastic surfaces have positive Gaussian curvature, that is, curvature in the same direction, such the

Figure 3: The three general saddle surfaces that are dictated by its linear (a), catenary (b) or curving boundary (c) (Huntington, 2004)

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dome. Since the forces are in the same orientation, these forces must be balanced by air pressure. Tensioned fabric structures with anticlastic membrane surfaces will be discussed hereon.

The anticlastic surfaces are also known as saddle surfaces. There are three general types of saddle surfaces. The surfaces are differentiated by their boundaries: linear, catenary or curving, as demonstrated in Figure 3. A combination of saddles made up of different boundaries result in the variety of membrane forms.

2. MEMBRANE TYPES

Membrane structures, encompassing both the tensioned fabric and the supporting structure, can span from 3 to 20 meters to spans more than 200 meters. For spans more than 200 meters, the fabric is supported by cables with steel or air so that unsupported span of the fabric is actually less than 30 meters. There are several systems adopted for tensioned fabric systems. While maintaining the concept of tension fabric design, each system is unique. These systems can be combined with each other to create interesting and even more complex designs. In this section, systems designed for anticlastic-surfaced membranes will be discussed.

2.1 Arch-Supported Structures

The arch-supported membrane shape is comprised of a saddle with one curving boundary and three curving boundaries as seen in Figure 4. This configuration is conceptually very pleasing since the membrane working in complete tension while the arch is ideally working in complete compression. These systems can be designed quite efficiently for spans of about 25 feet.
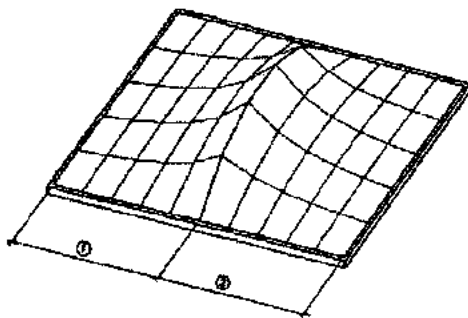
Figure 4: Arch-supported structures composed of a saddle with one curving boundary and three straight boundaries (Huntington, 2004)

The interaction between the membrane and the arch, which create the saddle curvature of the fabric, allows adequate resistance against buckling for shorter span arches. In order to achieve this, the arch must be relatively stiff. Using tubular steel members with low bending stiffness is necessary. Other factors, such as the cross-section of the tubular steel members, the structural geometry and the properties and prestressing of the membrane can highly influence the degree of successful interaction and transmission of loads between the tensioned membrane and the

Figure 5: The stabilizing forces of an arch support structure (Koch et al., 2004)
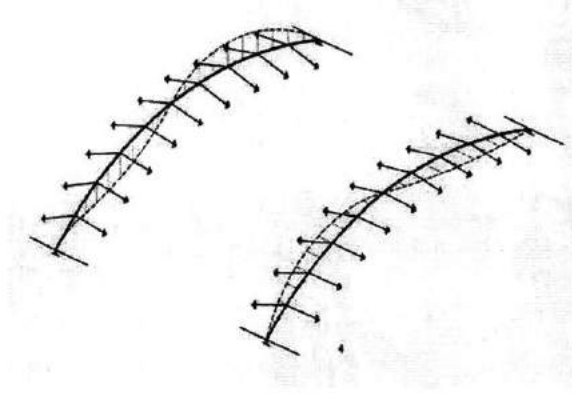
supporting structure in compression. Additionally, keeping the warped (stiffer) direction of the membrane at right angles to the arch and designing for hinged arch supports is essential in this design. A successful design of the membrane and arch structure will result in forces as shown in Figure 5 that will stabilize the arch.

For longer spans, the stabilization that occurs between the two systems is not sufficient. Therefore, arches must increase in rigidity—this is usually carried out by designing multi-chord truss elements. While this increases flexural rigidity, the connection to the ground is hinged so that minor differences with the loading of the arch do not give way to undesired reaction forces.

There are certain disadvantages of larger scale arched roof systems since, for various reasons, the ideal, or catenary, shape can not be realized. First, when form finding, live loads, such as snow and wind loads, that do not always exist are taken into account with the loads from pre-tensioning and dead loads. Also, asymmetric loading that occurs with
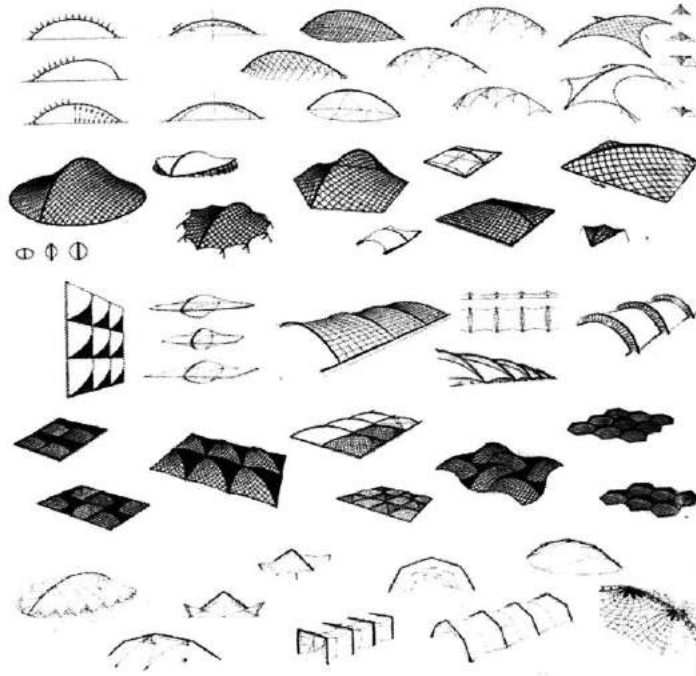
Figure 6: Variations of arch structures studied by Frei Otto (Roland, 1970)

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snow and wind induces bending stresses on the arch. Second, the stabilization of the arched roof is essential and, at times, quite difficult. However, as discussed earlier, the membrane can assist in stabilizing the arch. Therefore, the base can and should be connected as a hinge to avoid high reaction forces at the base that can damage the structure.

2.2   Structures with Primary Supports

Saddle surfaces can also be created in the membrane by primary point supports that, unlike the arch-supported system, do not lie on the same plane. Care must be taken that the cable stays are in tension regardless the loading.

An example of primary point support structures is the simple cone structure that consists of a mast in the center of the membrane. This can be repeated in groups to enclose a larger area of space. Although this can fulfill many applications and provide the greatest range of shapes, the existence of a big structural element in the center of the utilized area can become awkward and obstructive. One solution to this is the king post design. In this design, cables support the bottom of the mast that terminate before it hits the floor. The cables, in turn, transfer the loads upwards to the exterior of the structure.

The funnel membrane form is another example of a primary point support structure, which essential inverts the cone membrane
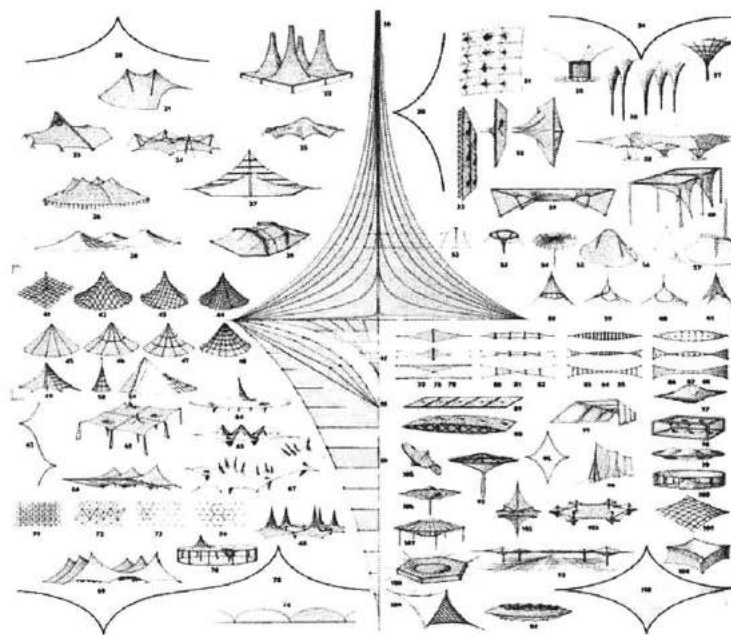
Figure 7: Variation of primary support structures studied by Frei Otto (Roland, 1970)

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form. The high points take on the downward forces and the low points take on the upward forces.

There are key issues to consider when designing this structural system. One, the influences the membrane has on the lateral stability should be reviewed in order to design for any additional needed load bearing support structures. Different loading, especially asymmetric loading, and failure scenarios should be analyzed.

2.3   Ridge-and-Valley Structures

The concept of ridge-and-valley structures are based on the creating of slight saddle by laying cables in an adjacent pattern with opposing curvature. The membrane is created and restrained by the alternating ridge and valley cables.
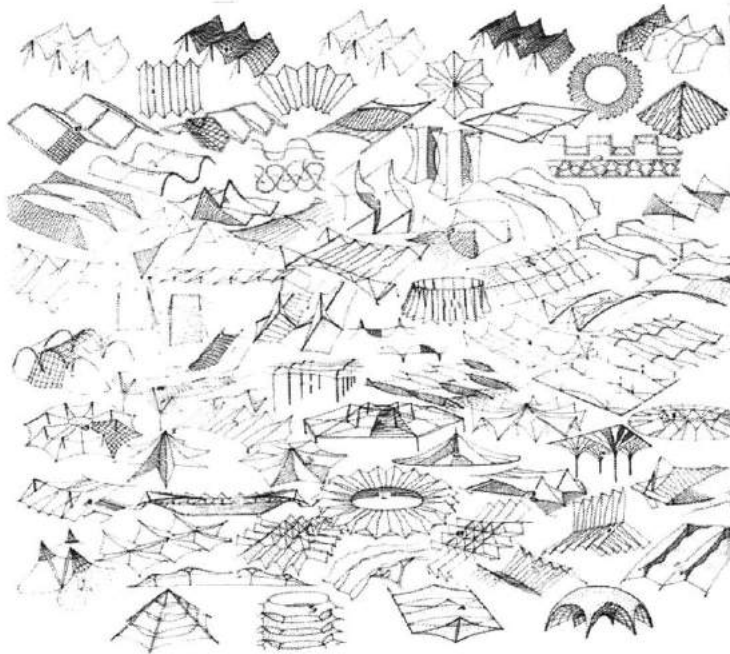
Figure 8: Variations of ridge-and-valley structure studied by Frei Otto (Roland, 1970)

The curvature created is quite small and therefore this type of structure cannot be realized in all situations. Many tests and loading scenarios must be reviewed before deciding the feasibility of this kind of design.

2.4   Mast Structures

In tensioned fabric structures where the supporting structure consists of masts, fabric is suspended from cables hung off masts or other compression elements. This kind of system is ideal for long span roofs. There are many forms of mast structures. The main three forms are the following: masts with hinged supports stabilized with cable stays, masts with hinged supports stabilized by the membrane and masts with fixed supports.
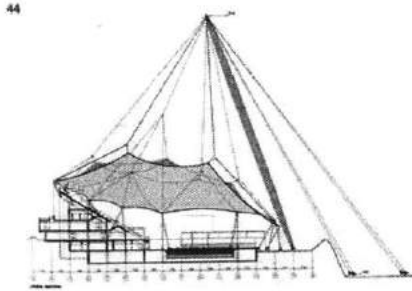
Figure 9: A mast support structure (Koch et al., 2004)

The masts must support both axial loading and lateral wind and dead loads (for angled masts). To resist buckling, which the masts are highly susceptible as a result of the axial forces increasing the moment stresses, the masts are constructed in lattices. The hinged base must be able to initially roll when the masts rotate, but after 2 degrees of rotation, the hinge must be able to slide. Care must be taken through construction and materials to ensure that excess friction does not impede this action.

In order to prevent domino effect-like failures, analytical techniques should be employed. Testing of full scale modules can also be used to confirm the safety of such structure.

An example of a mast system is the Millennium Dome in Greenwich, England which covers 80,000 square meters. It is a single module made up of 12 trussed steel masts from which cables support 72 radial cables lines. Stabilizing cables were attached to the membrane and low points of the mast to resist wind and uplift forces.

Figure 10: Masts of the Millennium Dome (Koch et al., 2004)

3. MATERIAL CHARACTERISTICS

The selection of membrane material is important to the successful design of the tensioned fabric structure. The material contributes to the structural function of the system, as well as other important properties involving durability, insulation, light transmission and fire protection. Also, the membrane component of the structure determines the long term appearance of the structure for it is the most visible element of the structure.

Currently, glass and polyester laminates, composites and fluoroplastic films are most popular. When selecting a membrane, the most important qualities to consider are the mechanical tensile strength and the elastic properties. Due to this, 90% of all weather-proof tensile fabric structure projects have used the following three specific membrane materials: Polytetrafluorethylene (PTFE), polyvinylcholoride (PVC) and ethylenetetrafluorethylene (ETFE) (Huntington, 2004). These materials are preferable in tensile fabric structures for an array of reasons. Not only do they have the structural ability to support such structures, these materials have been in use for the past 50 years and therefore behavior data of these materials are abundant. These materials have become standardized and therefore the ease of acquiring and designing for these materials are higher than others.

3.1 Weave Patterns

The membrane is made up of yarns that are in turn made up of fibers. These fibers, which are generally made of nylon, polyester, glass and aramids, compose the structural component of the membrane. Since single fibers can not sustain themselves as a

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membrane, many fibers are either twisted together or are brought together in parallel. The different fabrication methods of these yarns play a significant role in the ability to extend and bend.

The yarn is then either woven or laid on top of each other to create a fabric. The different kinds of arrangements of the yarn are show in Figure 11. In the plain weave, the warp direction of the yarn is laid taut while the fill direction weaves in and out of the yarn in the warp direction. In the laid weave, the yarns are simply placed on top of each other in a perpendicular fashion. Due to the nature of these two weaves, the plain weave fabric is about three yarn thicknesses, while the laid weave fabric is only two. The warp and fill directions of the plain weave fabric will exhibit different strength values in the two directions, while the strength will be roughly the same in the two directions for laid weave fabrics. The variation in the twisting of the yarn and the different strengths of the warp and fill directions result in different behavior under load. Twisted yarns are more flexible and extendable that yarns that are not. Also, the warp direction of the fabric will stretch under load, while the fill direction will straighten. Therefore, great understanding is needed on the type of fabric being used when designing and analyzing different load behaviors.

Figure 11: The loose plain weave, tight plain weave and laid weave of membrane yarns (Shaeffer, 1996)

For plain weave fabrics, an exchange between the two directional yarns called "crimp interchange" must occur before the fabric can start carrying load. This is when the fill direction straightens out and transfers some of its curvature to the yarns in the warp direction. The negative side to crimp interchange is that the fill direction loses some of its pretensioning in "filling" out its curves. Also, no computer analysis program is able to model the fabric to reflect this interchange in the analysis of the structure.

3.2   Membrane Criteria

There are several parameters to consider when selecting the type of membrane fabric to employ. Of these, the most important are the mechanical properties, durability, light transmission, fire resistance and economic feasibility. For common materials used in practice, such as PTFE and PVC, material behaviors and characteristics have been well recorded. However, for newer materials and innovative applications, there are a wide range of tests that can be performed to get an idea of the properties and qualities of the material.

3.2.1   Mechanical properties

The mechanical properties of most importance to the designer are the tensile strength, which measures the force required to rupture the material, tear strength, which is the resistance to propagate an existing tear, and elastic properties, such as stiffness, which is the relationship between the modulus of elasticity and the area of the cross section of fibers. These properties are measured through a number of tests including, but not limited to the Strip Tensile, Grab Tensile, Biaxial Tensile, Seam Tensile Strength, Trapezoidal Tear, Tongue Tear, Adhesion and the Abrasion Resistance Test.

3.2.2   Durability

The life span of the membrane structure strongly depends on the durability of the membrane fabric. Its durability is greatly influenced by the resistance to degrading from UV radiation and wicking, attacks from organic matter, and the maintaining of seam strength. Vandalism and soiling can also affect the durability of the membrane. For newer materials, the durability can be tested by accelerated weather tests using different environmental conditions, and stain resistance/ clean-ability tests.

3.2.3 Light transmission

When designing a tensioned fabric structure, great consideration is given to the light transmission, absorption and reflection of the structure. This will ultimately affect the appearance and some aspects of the energy behavior of the structure.

3.2.4 Fire resistance

Fire resistance is also an extremely important factor for safety. All materials are required to undergo the following standard fire tests: ASTM E84 Surface Burning Characteristics of Building Materials (Flame Spread Test), ASTM E108 Fire Tests of Roof Coverings (burning brand, spread of flame, intermittent flame exposure, flying brand or rain test), ASTM E136 Behavior of Materials in a Vertical Tube Furnace at 750C (ASTM 1999a) and NFPA 701 Fire Tests for Flame-Resistant Textiles and Films (NFPA 1999).

There are many other criteria that is looked at before making a decision of the material to be used.

3.2.5 Other membrane criteria

While the importance of certain qualities and characteristics depend on the scale and design of individual structures, the above qualities are the characteristics that play an important role in all membrane structures. Other characteristics include the following:

3.3 Fabric Types

The oldest and most commonly used fabrics are coatings or laminates over polyester fabric. Different kinds of coatings are employed for different desired characteristics. For example, neoprene and hypalon are used when opaqueness is desired and reapplying

coats are expected. Urethane coating is used for fabric that will be repeated folded in cold temperatures to prevent cold cracking.

3.3.1   Polyvinylcholoride (PVC) - coated polyester fabric

Polyvinylcholoride (PVC) coated polyester fabrics have been used and tested since the 1960's. The wide use of this material is due to their low cost, as well as their ease of handle. However, their life expectancy is only 10-15 years and fire ratings can be improved. The PVC coated polyester has tensile strength from 350 MPa to 1,200 MPa and a strip tensile strength of 3,100 N/5cm to 5,800 N/5cm for membranes weighing 800 g/m2 to 1,100 g/m2 (Huntington, 2007). The prestress levels of PVC coated polyester fabric range from 1-4 kN per meter (Shaeffer, 1996). The PVC coating helps the material to achieve high tear strength for the soft PVC chains around the fibers at the tear to resist further tearing. PVC also has moderate stiffness as well as moderate behavior to creep. Although this at times requires pretensioning of the fabric, the moderate behavior to creep allows for some flexibility in matching fabricated components and small errors in fabrication will not result in overstress or wrinkles in the fabric.

PVC-coating protects the fabric from UV radiation degradation for roughly 10 to 15 years (Huntington, 2004). Although additional top coats to protect from UV radiation can prolong the life span of the fabric, it is not very effective. PVC coated polyester can achieve light translucency of up to 22 percent and although this fabric is not deemed incombustible, it is classified as a flame retardant. Due to the fact that high temperatures create holes in the material that allow the smoke and heat to dissipate through the membrane, its incombustible nature can add to the overall safety of the structure in a fire hazard.

The most appealing characteristic of PVC coated polyester fabrics is the low cost. In 2003, the cost of this material ranges from $90 to $150/m2. This calculates to $400 to $700/m2 for a complete PVC coated polyester roof structure (Huntington, 2004).

3.3.2   Polytetrafluorethylene (PTFE)- coated fiberglass

Another type of membrane fabric commonly used in practice is Polytetrafluorethylene (PTFE)-coated fiberglass. This material was developed in 1969 when fiberglass fabric was coated with Teflon resin. This new material advancement was a landmark in time for tension fabric structures for it was incombustible, resisted soiling and promised a more durable and therefore longer life span to membrane structures. However, this material was very expensive and had a low resistance to cracking compared to PVC-coated polyester fabric. Therefore, PTFE-coated fiberglass became the material to use in long-lasting iconic architectural applications, while PVC-coated polyester fabric continued to be used for temporary, portable structures that can withstand the effects of being repeatedly erected.

The mechanical properties of PTFE coated fiberglass is 3,500 MPa and the strip tensile strength range from 1,600 N/5cm to 8,800 N/5cm. These strengths allow membranes to stretch long spans with minimal curvature. However, the tear strength of PTFE-coated fiberglass is relatively low, having only 80 N to 550 N of strength to resist tears from propagating. The prestress levels range from 6-8 kN/m, 4-6 kN/m and 1-2 kN/m for heavy, light and light lining PTFE coated fiberglass fabrics, respectively (Shaeffer, 1996).

Case studies have proved that PTFE-coated fiberglass fabric has a expected life span of over 30 years. Structures, inspected at 30 years of age have no need of replacement due to wear and degradation. The several coats of PTFE make the fabric nearly unsusceptible to any damage due to UV radiation as well as chemical attack and wide temperature variation. In one case study of the La Verne structure erected in 1973, pre-stress levels of the fabric remained relatively uniform and near the original levels after 6 years (Huntington, 2004). This shows that the fabric does not creep and distort over time. In fact, the creep was measured to be only a third of its PVC-coated polyester fabric counterpart. However, there are negative aspects of this material. Since PTFE-coated fiberglass fabric have low tear strength, its vulnerability to tears and rips due to vandalism and structural overloading increases substantially. Also, fiberglass is

vulnerable to wicking from edges exposed to water. However, this can be mitigated by water-repellent coating. The cost of PTFE-coated fiberglass fabric is quite expensive. For the full fabrication of a tensioned fabric structured roof using PTFE-coated fiberglass fabric, the cost ranges from $500 to $1,000/m2—five to ten times as much as PVC-coated polyester fabric.

3.3.3 Ethylene-tetra-fluorethylene (ETFE) film

Films are also used to make up a membrane fabric. In actuality, although the films do not depend on any property of the woven fabric in the middle, without it, it can not be considered a fabric. One commonly used film is ethylene-tetra-fluoroethylene polymer (ETFE). The tensile strength of 0.1mm thick film is 225 N/5cm—only 5% of PVC and PTFE-coated fabrics. These films continue to creep under load, unlike the PTFE-coated fiberglass fabric. The film yields after elongating 3% and ruptures at 200% of its original length (Huntington, 2004). This behavior gives ETFE film very high tear strength. It is possible to use composite woven fabric in between the film to increase the overall tensile strength.

Although there are limited tests, films, which exclude the performance of the woven centers, can be expected to endure 15 years facing the environmental elements. However, the durability, as well as the light transmission, fire resistance and cost, all depend greatly on the scale and design of the material and structure.

Table 1a and Table 1b on the following page is a chart of detailed fabric specifications.

Table 1a: Chart of fabric specifications

c	construction	Use in roofes, facades, and building envelopes	special properties	rain-proof	fire rating	UV light resistance	durability (years)	light translucency (%)	light reflection (%)
coated fabric	polyesterfabric w/ PVC coating	permanent – mobile + internal – external	standard material with a wide range of applications	+	+	+	15-20	0 to 25	50 to 70
coated fabric	glass fiber fabric with PTFE coating	permanent – internal – external	high-quality standard material, fabrication is technically demanding	+	++	++	>25	4 to 22	65 to 75
coated fabric	glass fiber fabric with silicone coating	permanent – internal – external	tendency to soil when used externally, but improvable	+	++	++	>20	10 to 20	50 to 70
laminated fine weave fabric	mesh fabric laminated with a PTFE film	permanent – internal – external	good relation of tensile strength and translucency	+	++	++	>25	35 to 65	10 to 20
foil	PVC foil	temporary external – permanent internal	can be used permanently only indoors	+	-	+	15-20 (internally)	up to 90	up to 50
foil	fluorpolymer foil (ETFE)	permanent – internal – external	high quality standard material, mainly used in pneumatic constructions. Due to high UV translucency, self-cleaning and economy an alternative to rigid transparent building	+	++	++	>25	Up to 95	up to 50
uncoated fabric	stainless steel mesh	permanent – internal – external	special manufacture, allows air to pass through, burglar-proof	-	++	++	>50	Up to 95	-
uncoated fabric	polyester fabric	permanent – mobile + internal	light and acoustic fabric for internal architecture sound absorption factor alph w = 0.5-0.65	-	+	+	10-15	30 to 35	60 to 70
coated fabric	glass fabric with fluoropolymer coating	permanent – internal	acoustic fabric with low e-factor <0.4 & for internal architecture sound absorption factor alpha w= 0.5-0.65	-	++	++	15-20	10	59
coated or non-coated fabric	PTFE fabric coated or non-coated	permanent – mobile + internal – external	extremely high quality. Used up to the present in particular for folding membranes and high image projects	+/-	++	++	>25	15-40	50 to 70
coated or non-coated fabric	fluoropolymer monofil fabric coated of non-coated	permanent – mobile + internal – external	extremely high quality. Used up to the present mostly for special lighting projects	+/-	++	++	>25	up to 90	up to 50
coated mesh fabric	mesh fabric coated with PVC	permanent – mobile + internal – external	standard material with a wide range of applications, shading	-	+	+	10-15	>20	20 to 40
non-coated mes fabric	PTFE impregnated glass mesh fabric	permanent – internal – external	diferent open sections and grid dimensions are possible	-	++	++	>25	up to 95	-

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Table 1b: Chart of fabric specifications (continued)

category	colors	self-cleaning property	resistance to chemicals	weight (kg/m2)	tensile strength (N/5cm)	suitability for folding membranes	recyclability	recommended temperature range (C)
coated fabric	large range of colors	+	-	0.6 to 1.55	2,000 to 10,000	+	+	-30 to 70
coated fabric	limited range of colors	+-	++	0.4 to 1.6	1,000 to 8,000	-	-	all temperatures
coated fabric	limited range of colors	-	++	0.4 to 1.6	1,000 to 5,000	-	-	all temperatures
laminated fine weave fabric	standard white	+-	++	0.7 to 1.2	2,500 to 5,000	-	-	all temperatures
foil	standard white and others	-	+	0.2 to 2	300 to 2,000	-	+	5 to 40
foil	transparent, white, prints	++	++	0.05 to 2.0	300 to 600	-	++	all temperatures
uncoated fabric	natural, one-sided painting possible after installation	+	++	3 to 12	2,000 to 30,000	-	++	all temperatures
uncoated fabric	can be colored and printed	0.5 to 0.65	-	0.4	4,000	+	+	-30 to 70
coated fabric	metallic silver	+	++	0.3	3,250	-	-	all temperatures
coated or non-coated fabric	limited range of colors	++	++	0.3 to 0.5	2,000 to 5,000	++	+-	all temperatures
coated or non-coated fabric	transparent, white	++	++	0.3 to 0.5	400 to 1,000	+	++	all temperatures
coated mesh fabric	large range of colors	+	-	0.5 to 1.0	1,500 to 5,000	+	+	-30 to 70
non-coated mesh fabric	limited range of colors	++	++	0.3 to 0.5	450 to 5,000	-	-	all temperatures

3.4   Cable Types

Other than the membrane fabric, the cables used in the structure must also be selected. The strength and durability, as well as the flexibility and bending radii play a key role in the selection process.   In most cases, high-strength steel wire is opted. Typically, 11 strands are wound together, each strand being made of up 19 to 37 wires wound together as shown in Figure 12. These high-strength steel wires are ideal because they have great flexibility while maintaining strength.   Therefore, these wires can be used for membrane structures that are designed with tight radii. Steel structural strand is also another type of cables used when less flexibility is needed.   While the strength of these cables is greater, the ability to bend is quite limited.   Steel tension rods are used, while its usage is limited non-curved applications.
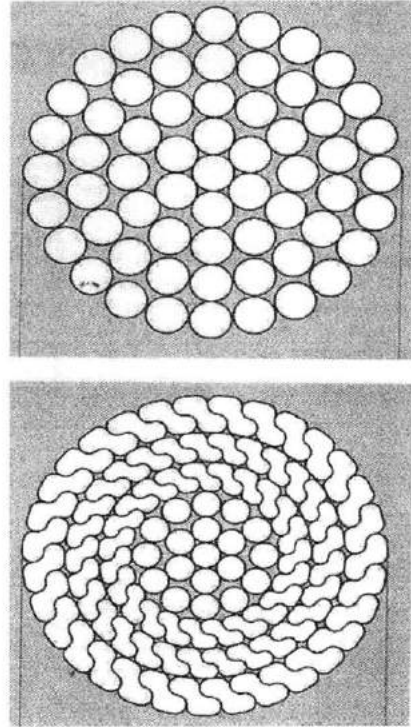
Figure   12:   Typical configurations of a strand made up of wires (Koch et al., 2004)

Corrosion has the greatest affect on the durability of the cables. Protection from corrosion, as well as other staining, is usually provided by galvanizing the wire with zinc coating. A more expensive option is to employ stainless steel.

When selecting cables for a particular design, the following strength criteria should be used. The breaking strength of the cable should be the maximum value of the following:

a. 2.2 * Net tension due to dead load and prestress

b. 1.6* Net tension due to dead load and prestress +

2.7*Change in tension due to live load

c. 2.2*Net tension due to dead, live load and prestress

d. 2.0*Net tension due to prestress, dead, live, wind and earthquake load

e. 2.0*Net tension in cable due during construction

f. 2.0*Net tension due to dead, wind load and prestress

Cables should also be able to prestress at 4-10% of their breaking strength (Shaeffer, 1996). Table 1 and Table 2 on the following page outline the different strengths of cast steel and stainless steel.

Table 1: Strength of cast steel

material no.	strength grade	yield point cold-rolled strip (N/mm2)	tensile strength (N/mm2)	coefficient of thermal expansion (10^-6/K)	remarks
1.4401	235	235	500	16	
	275	275	550	16	weldable to max. 6 mm
	355	355	600	16	
	460	460	600	16	
1.4404	235	235	500	16	
	275	275	550	16	weldable to max. 30 mm
	355	355	600	16	
	460	460	600	16	
	690		800	16	
1.4571	235	235	500	16	
	275	275	550	16	difficult to grind
	355	355	600	16	
	460	460	600	16	
	690		800	16	
1.4462	460	460	600	13	compression loading only to 355 N/mm2
	690		800	13	

Table 2: Strength of stainless steel

materials	cast steel with enhanced welding properties and impact resistance		high-strength cast steel with good welding properties		cast stainless steel
reference no.	GS20 Mn 5 V		GS18 NiMoCr 3 6 V		G-X 5 CrNiMo 16 5 V
german standard	DIN 17182		SEW 520		SEW 410
materiao no.	11.12		16.759		14.405
thickness (mm)	<100 mm	<160mm	<80mm	<150mm	
yield point (N/mm2)	300	280	700	630	540
tensile strength (N/mm2)	500-650	500-650	830-980	780-930	760
breaking elongation (%)	24	22	12	12	15
notched bar test (ISO V test)	min. 50 J	min. 40 J	min. 40 J	min. 40 J	min. 40 J

4. DESIGN ANALYSIS

Like designing any innovative and high-precision structure, thorough analysis of the design must be carried out for tensioned fabric structures. Multiple load scenarios must be analyzed to ensure the structural integrity of the system in all situations. While all structural analysis is performed by computers, physical modeling and two-dimensional hand calculations are still employed to give a sense of possibilities and ideas. Non-linear form-finding and load analysis are imperative to conduct simultaneously as an integral part of the designing stage for a successful design of a tensioned fabric structure.

4.1 Load Considerations

Although ASCE has developed standards, loading standards for tensioned fabric structures fall under the specifications of building code requirements. This can be deceiving for these loads did not consider the deformability and flexibility of the membrane structure. However, a good understand of load considerations specifically for membrane structures can assist in the analysis.

Wind loads are the main consideration for membrane structures. In order to resist these loads, the membrane must have sufficient tensioning and curvature. While load coefficients are easily assessable in most places, other tests such as a wind tunnel test may be necessary for larger and more complex structures to determine loading distributions. The possibility of aeroelastic effects that occur when the structure is vibrated with its natural frequency must also be considered. This is especially true if the natural frequency of the structure is significantly longer than one second. In such cases, further investigation of the aerodynamic instabilities should be carried out by using models that reflect the real-life mass and flexibility parameters of the structure.

While wind is usually the most significant of loads for the membrane structure, in areas of colder climate, snow and snow drift loads can also be substantial. Again, while snow

load coefficients are available, physical model testing may be required for complex structures. Snow drift loads can be analyzed by the Finite Area Method, where the snow drift is modeled as a thin layer of particles moving with a mass flux related to the wind velocity.

Point loads should be avoided on the membrane component of the structural system. The necessary heavy point loads should be set on the supporting compression structure at all times possible.

There are several loads that are negligible in membrane design. The self-weight of the membrane is usually negligible, but often included in the analysis. Moreover, due to the negligible weight of the membrane, seismic loads are also usually insignificant and not incorporated in the analysis. Rain loads are also rarely considered since water will be designed to shed rapidly to avoid ponding. Live roof loads can also be significantly reduced for it usually accounts for building material during construction, which is irrelevant in the case of membrane structures. Lastly, as of yet, temperature gradients of the membrane have not produced accountable loads for the fabric.

Although there is no set safety factor for the strength of the selected fabric, conventional practice is to use a factor of 4 for short term load cases and a factor of 5 for live load cases (Huntington, 2004). In order to mitigate the fact that these factors do not take into consideration many imperative aspects, ASCE is currently developing a methodology obtaining more reliable safety factors.

4.2   Physical Models

In the early stages of tensioned fabric structure design, there was heavy dependence on physical models. These models consisted of soap film for minimal surface finding, wire and stretched fabric. Famous for such works is Frei Otto based in Germany who pioneered patterning and initial form data for later computer analysis. His greatest

innovation was in his work with soap models like the one shown in Figure 13. Soap bubbles stretch between supports and the final shape of a soap bubble is one having the least potential energy, minimizing the tension in the system. This is of particular interest for at this precise state, the tension stress is equal at every point of the bubble and the minimum surface area is found. Frei Otto correlated this to membrane structures and was able to find the most stable and uniformly pre-stressed form of a membrane between any set of arches and masts.

Although physical models are used for conceptual phases, especially at the initial designing stages for tensioned fabric structures, currently, form-finding, load behavior and patterning is undertaken by computer analysis. Additionally, the soap bubble models use have uniform stress levels in both the warp and fill direction of the

Figure 13: A soap arched membrane

membrane. Although this is highly reflective of nature and quite aesthetically satisfying, in practice, the warp and fill directions can have variable stresses, allowing for more variety and choices in the designing process.
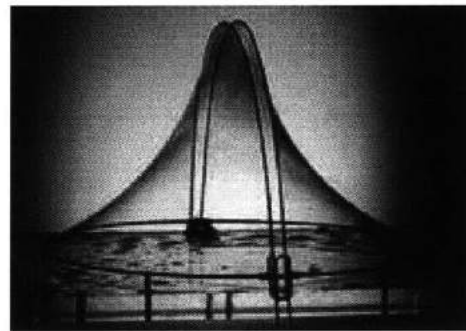
4.3   Two-Dimensional Preliminary Analysis

Simple two-dimensional hand calculations, based on a few assumptions, can be performed to get an initial idea of scope and feasibility in the design stage. By using these calculations in critical locations of the structure, one can deduce the overall behavior of the structure. The cable follows the characters tics of a membrane, having no compression, shear or bending and the tension forces must be balanced.

The following is an example of a simple analytical procedure using the idea of a uniformly loaded cable to obtain rough estimates of the reaction forces and end

parameters of the membrane. The membrane under vertical load is approximated as a parabola, although circular arc approximations are also valid.

The original arc length of the cable in its catenary shape is:

$$A = 2 \times \left(\frac{L^2}{4} + \frac{4h^2}{3} \right)^{1/2}$$

The vertical reaction at the end of a cable under uniform live load is:

$$V = \frac{wL}{2}$$

where w is the vertical load per unit length and

L is the length of the cable

The horizontal reaction force is:

$$H = \frac{wL^2}{8h}$$

where h is the height of the sag

The force in the cable is:

$$F = \left(V^2 + H^2 \right)^{1/2}$$

The tension force can be approximated to equal H if the sag ratio (h/l) is 0.2 or less.

Under lateral loading, the tension in the cable is:

$$F = \frac{w\left(L^2 + 4h \right)}{8h}$$

where w is the lateral force per unit length

Now, the change of arc length under load is:

$$\Delta A = \frac{F \times A}{E}$$

where E is the modulus of elasticity

Therefore, the new arc length is:

$$A' = A + \Delta A$$

Knowing this, the updated sag of the membrane is:

$$h' = \frac{\sqrt{3}}{4} \times \sqrt{A'^2 - L^2}$$

Using the value of h prime, and value for F, the tension of the cable should be updated. Several iterations are needed in order to converge to a relatively constant value. This is imperative since final results can greatly differ from results calculated after a single iteration.

Although this and other simple calculations were used from geometries from physical models, with the development and availability of analysis computer software, these calculations are used only at the conceptual stages to sense out initial design, feasibility and scope.

4.4   Types of Analysis

With the increasing of innovated materials and demand for more complex designs, it is even more imperative that thorough non-linear numerical analysis be conducted. Having low shear stiffness and no compression force carrying capabilities, the membrane carries load by making significantly large displacements and movements. This results in a unique non-linear behavior since the displacements are not proportional to the applied

loading. Thus, many iterations of analysis with updated stiffness values must be performed to get accurate results. Also, time sensitive scenarios, such as the membrane wrinkling or the cables relaxing must be assessed.

If the supporting structure is rigid, the primary and membrane structure can be analyzed separately, making non-linear analysis needed only for the membrane component of the structure. However, if the primary structure is flexible relative to the membrane structure, the entire structure should be analyzed together in a non-linear form. In this discussion, only the non-linear analysis for the membrane is considered.

In addition to analysis for form-finding and behavior under load, non-linear analysis is performed for material patterning and construction sequencing. Due to the importance of high-precision in the construction of such structures, accurate fabrication membranes for all materials must be provided through patterning by numerical analysis. Additionally, an analysis of the sequence of construction may be necessary to ensure that none of the components of the structure are overstressed during the construction phase.

4.4.1 Form finding

Warp:Fill stress ratio

1:1   2:1   3:1   4:1   5:1

The ideal form of the tensioned membrane has uniformly or constant varying stresses in both the warp and fill directions of the fabric. The shape is directed and formed by both the geometry of the supporting structure and the prestress introduced to the membrane. Ultimately, the warp and fill directions of the fabric should coincide
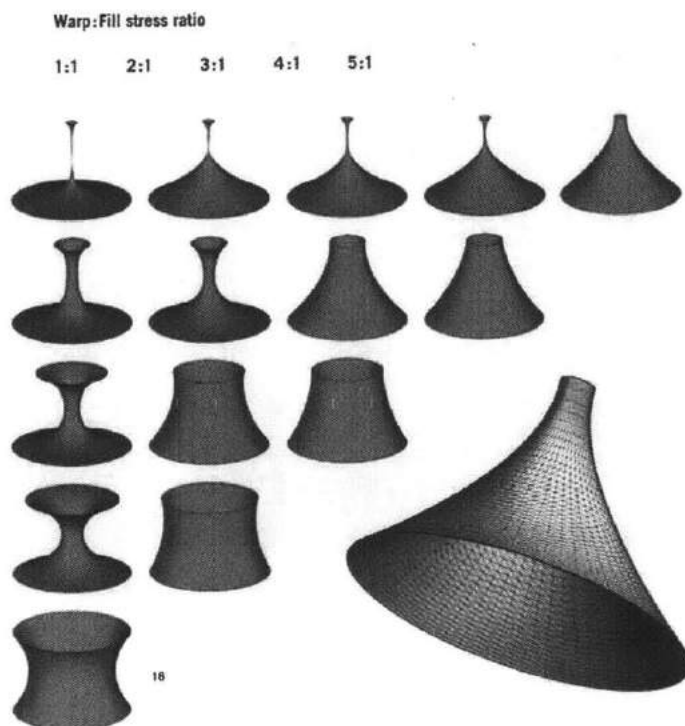
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Figure 14: Varying membrane forms resulting from different preset stress values in the warp and fill directions and slightly altering geometries (Koch et al., 2004)

with the main curvature of the membrane to optimize the stiffness of the tensioned membrane.

With computer-run numerical processes, the given prestress values and geometry calculate the forces induced at each element. To assist in aligning warp and fill directions with the principle curvature, a line is super-positioned over the model to trace the shortest distance between boundaries. As the optimum shape is being found, by changing geometry and stress levels, the forces and shortest distance paths are continually updated. Of course, there are times when the given prestress values will not result in any feasible shape. It is also important to note that during this time, no material properties are taken into consideration.

The analysis of a simple conic shape in Figure 14 demonstrates the range of outcomes with varying structural geometries and preset stresses. As the upper ring is decreased, the allowed stress in the vertical direction must increase. If there is not enough allowed stress in that direction, the shape will be deemed unattainable, as portrayed in the top-left images of **Error! Reference source not found.**. When the upper ring of the same conic shape is replaced by a cable, the cable deforms to make up for the increased stress that is needed in the vertical direction.

4.4.2   Load and load carrying behavior

The non-linear behavior of the membrane under a variety of loads must be considered as well. As mentioned earlier, both the curvature and loading affects the stress on the membrane, as shown in the following equation:

$$stress = radius * load \text{ (all vectors)}$$

Therefore, when loading is applied to the membrane, equilibrium is regained by changes in both the geometry of the membrane as well as the change in stress. Other structures, such as beams, have shear and flexural stiffness and therefore can resist the loads without significant deflection. However, membranes, which lack both shear and flexural stiffness, must "make up" for this by big deflections.

Furthermore, the stress levels vary depending on the direction and position of the membrane. An example of this can be demonstrated by a membrane stretched across two masts with the warp direction between the two points. Accordingly, the warp direction has an upper curvature and the fill direction has a downward curvature. As shown in Figure 15, as the
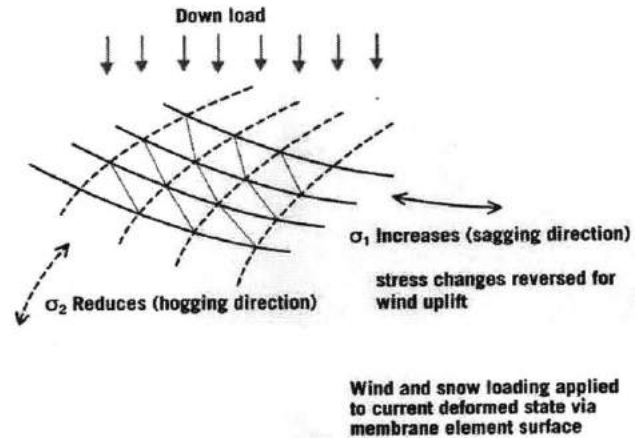

Figure 15: The change in stress in the sagging and hogging directions of a membrane under vertical load (Koch et al., 2004)

downward load is increased, the stress in the warp direction is increased and the stress in the fill direction is decreased. Conversely, as an upward load is increased, the stress in warp direction is decreased and the stress in the fill direction is increased.
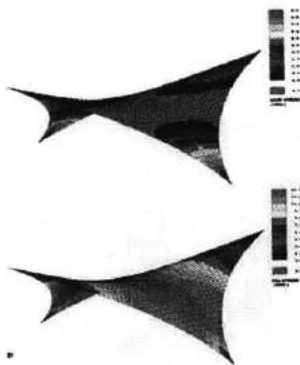

Figure 16: Analyzed membrane structure in Error! Reference source not found. (Koch et al., 2004)

An iterative analysis between form finding and load carrying behavior is carried out to ensure that both structural (warp and fill stress ratios, geometries, strength) and logistical (adequate head room, avoidance of ponding, constructability, etc) issues are equally resolved. Table 1 shows a load case study of a membrane with different warp-to-fill stress ratios under varying loads. The search of finding a form with sustainable load carrying behavior is quite complex for every

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decision affects all aspects of the analysis. This dynamic process involves, but is not limited to, the highly varying loads, warp to fill pre-stress ratios, geometries and fabric orientation.
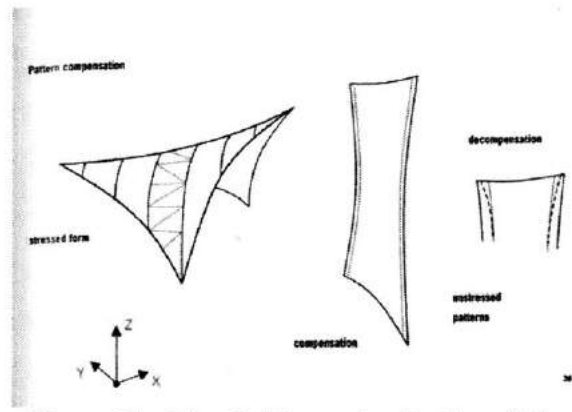

Figure 17: The dividing and adjusting of the membrane that are entailed in patterning (Koch

Table 1: Load case comparison of membrane shape in Error! Reference source not found. with varying warp-to-fill prestress ratios (Koch et al., 2004)

warp to fill prestress ratio	direction	max membrane stress under load			
		unloaded	1 kN/m^2 down	1 kN/m^2 up	2.1 kN/m^2 up
1:1	warp	1.0	9.0	3.4	5.8
	fill	1.0	3.4	9.2	18.0
2:1	warp	2.0	11.8	4.7	8.1
	fill	1.0	2.2	7.3	14.7
3:1	warp	3.0	13.6	5.4	9.1
	fill	1.0	1.7	6.6	13.4

4.4.3   Patterning geometry

In order to fabricate the membrane, the membrane may be divided into triangular pieces from the two-dimensional area derived from "unfolding" the three-dimensional membrane model. The tracing of the geodesic seam lines must be an integral part of the form-finding and load behavior analysis to reach the optimal solution.

The difficulty lies in compensating for the final prestressed geometry when patterning. The final model represents the geometry of the membrane after it is pre-stressed and loaded and thus stretched. Therefore, when "unfolding" the membrane for fabrication patterning, the actual fabric will be slightly reduced, as illustrated in Figure 17. Biaxial testing on the material being used determines the elastic properties that are needed to calculate the compensation required.
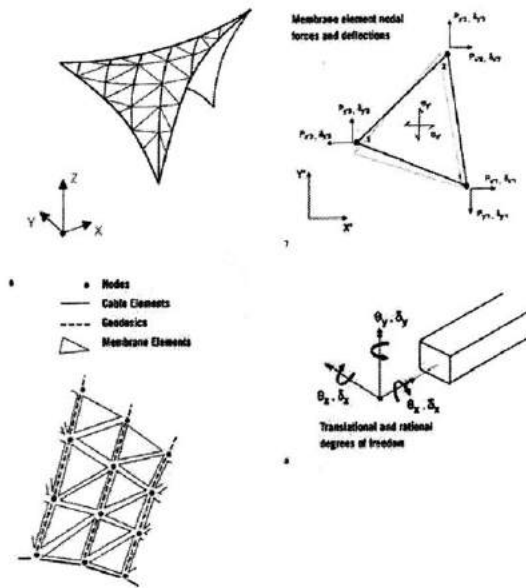
Figure 18: The finite element make-up of the membrane (Koch et al., 2004)

4.4.4 Construction sequencing

At times, an in-dept analysis of construction sequencing should be considered. This is particular so when the supporting and membrane structure are not stable until the final stages of construction. These kinds of studies are done by going backwards in the construction sequence. Initially, the pre-tensioning of the membrane can be slowly reduced to see the non-linear behavior of the overall structure. Then, the different components of the structure can be deleted in the reverse order of construction.

4.5 Analysis Methods

The numerical analysis is done by the finite element method. The basic concept of finite element is to divide a model into a finite number of elements, made up of nodes. In the finite element method, the nodal stresses are calculated through equilibrium equations related to stiffness. Once the nodal deformations are obtained using the stress/strain relationships, compatibility is approximated for the entire structural model to a pre-set tolerance. This is a complex iterative process involving thousands of nodes and calculations, and at times, no solution can be found.

When using analytical computer programs, it is imperative that the engineers know and comprehend the method of analysis of the program and how the program operates. This includes knowing the algorithms implemented in the analysis, as well as how the program responds to inputs and the method of feedback. Understanding how the program reacts in

certain situations, such as local instability and infeasible geometry, is vital. Having a physical model to compare analytical results will help in examining the validity of the results.

The program selected to perform the analysis should also have full range of capabilities to alter the model in geometry, stress and load. This is particular imperative for the design phase of the structure. If there are limitations, having a clear understanding of them will be useful in evaluating the various responses of the program.

Although specialized programs are being created to address the analysis of membrane structures, none of the methods available take into consideration the fabric behavior of crimp interchange, which was discussed in an earlier. Conventionally, a value of the stiffness for both the warp and fill directions are used that approximate the average stiffness throughout the life of the membrane.

4.5.1   Matrix method

Programs that are designed specifically for the design and analysis of tensioned fabric structures are based on of two different finite element methods: the matrix method and the vector method. The matrix method uses the Newton-Raphson method where the tangential stiffness of the entire model is incrementally solved to a convergence point.

4.5.2   Force Density method

A method called the Force Density method is implemented in the form finding segment of the analysis. This method is particularly attractive 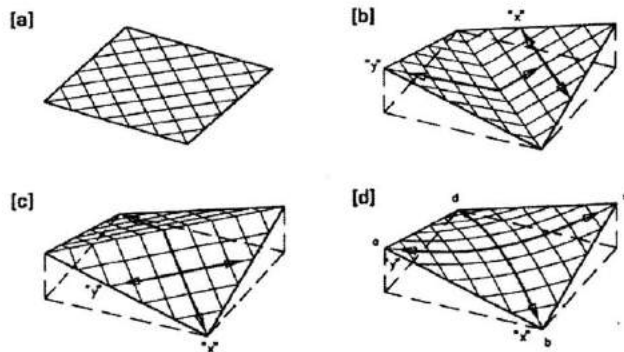because it is a linear method. In the Force Density method, the stiffness of membrane strips is modeled as a grid of cables (Figure 19a). Using linear methods, the shape that stores the least total potential energy and uses the minimum length of cables is found. Since linear methods are used, the shape is quite irregular and extreme, modeling some cables with infinite stiffness (Figure 19 b and c).

Figure 19: The concept behind the Force Density method (Huntington, 2004)

However, this is resolved by applying a constant force density to the entire model, resulting in a shape between the extremities (**Error! Reference source not found.**d). This method was later updated to use triangular surface methods, rather than cables and is know as the Surface Stress Density method. The weakness of these methods is that the final stress distribution is not very smooth and thus sometimes difficult to replicate in practice. Although this can be mitigated by carrying out multiple iterations, the method ceases to be a simple linear analysis.

4.5.3 Dynamic Relaxation vector-based method

Vector methods are more popularly used than matrix methods for membrane form finding and load analysis. Vector methods keep the equilibrium and compatibility relationship separate a convergence point is met with the equilibrium equations. The nodal stiffness is also not integrated with each other until the end of the process.

The vector-based Dynamic Relaxation method is the most widely accepted method used today. In this method, the form-finding and load analysis are solved using dynamic analysis methods, which involve mass and damping coefficients and time steps. At each time-step, the forces at each node of the finite element model are calculated. The net

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forces in the model are then attributed to the acceleration of the model at that time-step. As the model comes to rest, the forces causing the acceleration will shape the surface of the prestressed equilibrium state at that increment. This method is popular for its ease of use and capability to analyze successfully the great variations and configurations of structures. Even when initial estimates are extremely rough, the Dynamic Relaxation model can easily "come out" of any unstable or infeasible configuration since the unbalanced forces are all attributed to acceleration. The most difficult part of implementing this type of analysis is the defining of dynamic properties such as the damping, mass and time-step. Unwise decisions on this matter can result to slowly converging or even non-converging analysis.

4.6   Design Analysis Approach and Strategies

In order to perform the different types of analysis mentioned above successfully, comprehension of the concept of membrane structures, as well as experience is needed. Knowing the fundamental concept of tensioned fabric structures, one can create functional efficient and beautiful shapes structures while maintaining economy and structural reliability. During the analysis phase, there are strategies to mitigate obstacles and dead end situations that are accumulated through much experience and knowledge. The following are situations that can cause a design of a tensioned fabric structure challenging or impossible to realize and their mitigation strategies:

Inadequate fabric curvature- The stress that occurs under the load of the fabric is inversely proportional to the curvature of the shape. Therefore flat/large curvature radii will compensate under load by curving more until it hits equilibrium. But this is an inefficient way of load bearing. This mechanism should be left to canopies less than 10m long. The span: sag ratio should be kept at less than 15. With increased spans, lower ratio and/or cable reinforcement is needed.

Inadequate cable curvature- Cables should curve along with the fabric since it is sensitive to curvature like the fabric. The ridge, cable or other cables should curve with the fabric curvature. It is considerably more economical if the span to sag ratio is lower than 15.

Inadequate mast termination- The fabric loads must be transferred to the mast top without overstressing the fabric. Therefore, a ring located below the top of the mast is needed for the transfer, unless there are radiating cables that help transfer the load to the top of the mast. [refer to book for deeper calculations]

Excessive Aspect Ratio- Large aspect ratio, although it increases curvature, also increases the exposure of lateral wind loads to the roof, increases fabric material, increases the amount of air needed to be temperature controlled and increases the height of the compression members. All things must be considered when wanting a high aspect ratio.

Long Compression Members- Long compression members increase the change of buckling. Therefore, the longer the compression members, the larger and heavier the cross sections will have to be. Also, this will increase aspect ratio, which the consequences are discussed above.

Reversal in curvature- There can be overstress or over deflections at point of inflections since this decreases fabric curvature (curvature=infinite).

Unstable supporting structure- Until perfectly reliable fabrics are made available, the fabric should not be used to stabilize masts, arches, and other members. Cable nets in the plan of fabric, guy cables to connect masts/arch to ground or self bracing is used. Moment supporting member base connections can be used, but are expensive.

5. CONNECTION DETAILS

Connections and detailing of tensioned fabric structures are significantly more complex than conventional structures for many of the connections must be made in angles and moveable and, since most connections are left exposed to the pubic eye, the aesthetics of the connections must be kept in mind. Additionally, there is very little available on codes and standards for these types of structures. However, connections between cables and its supporting structure follow the conventional design methods, and therefore will not be discussed. Although there are many ways to specify a connection that fulfills the structure's need, the most successful are the connections that transfer loads in a simple and direct path so that the flow of forces are visually clear. In practice, designing connections for the heaviest and complex load paths first may make way a clear and simple overall detailing.

5.1   Fabric Connections

5.1.1   Fabric joints

Adjoining pieces of the membrane together is usually a process done off field to ensure the accuracy of such joints. These joints are usually welded together. However, there are times when on-site adjoining is necessary due to the logistical situation of the structure or construction. For these connections, roped membrane edges are connected together with clamp plates. When significant pre-tensioning is necessary, a wider base plate is used.

5.1.2   Curved membrane end-connections

When the structure terminates with fabric hung by a cable, the cable is joined to the membrane by a cuff that runs along the cable. In order to avoid
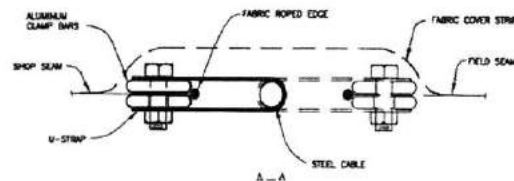

Figure 20: U-strapping at curved membrane end-connections (Huntington, 2004)

wrinkles, small slits are cut to increase flexibility. At the ends of the cuffs, the cable and membrane are secured together with U-shaped clamp plates or a "stud end" is attached to one end of the cable to resist it from slipping through the cuff once tension is applied (Figure 20).

5.1.3 Supporting structure end-connections

When the membrane must be joined to the support structure, clamp plates are most commonly used.

5.1.4 Corner end- connections

Corner membrane connections are the most difficult for all the slight angle and size errors show up in this process. This can be understood by illustrating this with bed sheets. Tucking the last corner of the fitted sheet is the most difficult for the alignment of all the other corners converges at that one corner. For the tensioned fabric structure, this is especially hard to accomplish, especially for the effects of all the slight error in angles and tensioning of the entire membrane are realized at this phase.
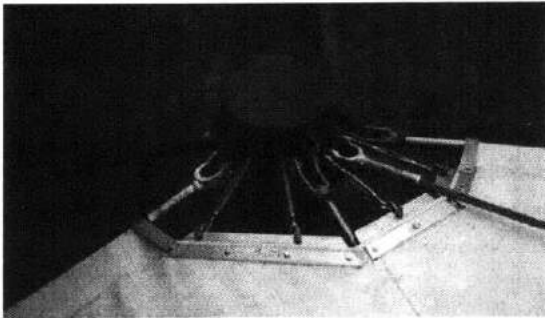

Figure 21: Turnbuckles used for adjustable corner terminations (Huntington, 2004)

There are three methods in approaching the connections of these corners. First, turnbuckles are utilized for connections. As seen from Figure 21, the membrane is trimmed back and connected to clamp bars which are then connected to multiple turnbuckles. These turnbuckles are in turn connected to the support. The negative aspect of this kind of connection is the bulky appearance. To avoid this, instead of using turnbuckles, a cable is looped into the trimmed corner of the fabric and connected to the cable with a swaged stop. Although this allows for some flexibility in making the corner connection, it is not as adjustable as the turnbuckle connections. The third method entails running the cables through a flat webbed edge that is attached alongside the edges of the

membrane. The webbed edges have openings that reveal the cables. At these points, the cable is connected to a support using turnbuckles or other devices.

5.2   Cable Connections

5.2.1   Cable to support connections

In tensioned membrane structures, cables usually terminate at a mast by an ear plate. When designing for such connection,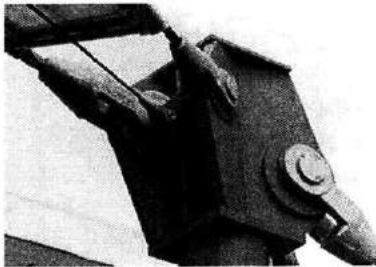 the bearing failure of the connecting pin, shear and tension failure of the plate and the bending failure of the pin should all be considered. The bending failure is usually solved for by adding a washer-like plate between the ear plate and the connector to prevent the movement of the pin as seen in Figure 22. Another factor to consider is the bending of the mast created by the perpendicular pull of the cable to the axis of the mast by the cable. Sometimes, the ear plate is completely sliced through the center the mast, instead of being welded simply on the top. This allows both sides of the tubular mast to resist the bending force, cutting the force into half. Usually this is not enough and a circular ring plate is welded around the mast and onto the top and bottom of the ear plate to almost eliminate the bending force
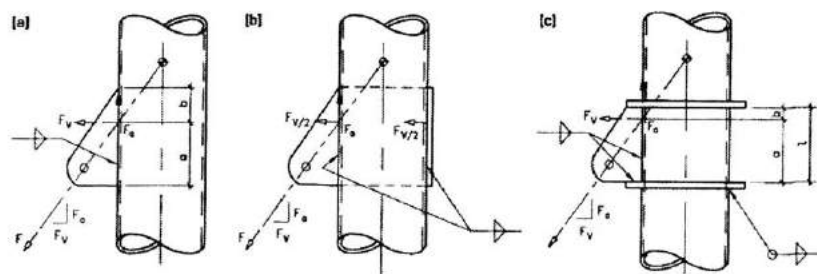

Figure 22: Detailing the cable to support connection to prevent bending failure (Huntington, 2004)

Figure 23: The different measures to resist bending force of the support structure (Huntington, 2004)

entirely. Figure 23 illustrates these three designs. Lastly, unnecessary moments created by the different directional pulls of the cable are avoided by orienting the line of forces of the cables to a single point on the mast.

There are several factors to consider when selecting the type of cable terminations for a structure. One, tension forces must transfer completely to the connected structure. Two, although the cable length can be either fixed or adjustable in length, the orientation of the cable should be flexible.

The eye loop is a connection that addresses all the above concerns, while being very workable on-site. Although being the most economical of all cable connections, its less than elegant appearance and potential improper installation of these types of connections hinder some designers from specifying th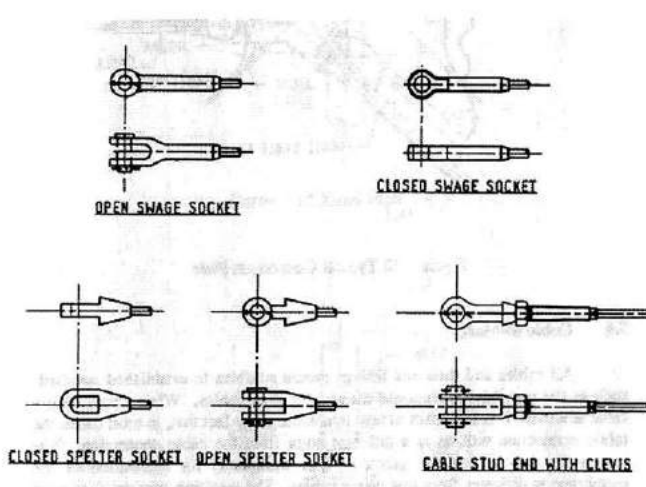ese. Since looping the cable causes a tight bending radius, the cable strength must be reduced 10 percent for cables 25 mm or greater in diameter and 20 percent for cables smaller than 25mm.

Figure 24: **Swaged and speltered sockets for cable termination connections (Shaeffer, 1996)**

Another type of cable terminations are the swaged and speltered terminations as shown in Figure 24. These terminations can have either stud ends, jaw ends or eye ends. Swaged and speltered terminations, although more costly, are more refined in appearance.

A connection called a turnbuckle is used to split a cable so that the length can be adjusted. Pipe buckles are the more aesthetic alternative.

5.2.2   Cable saddle connections

At saddle points of the tensioned membrane structure, particular consideration of the detailing is entailed since it is the point where cables intersect with other cables and supporting members, sometimes with a change of angle.   While designing for cable saddle connections, the orientation of the cable in its unloaded and variable unloaded states must be addressed.   The range of its orientation will determine the amount and direction of force that is transferred to the supports and connecting cables that are in different angles.   Also, the tension forces may vary on the different sides of the saddle. This will cause forces that move the position of the cable.   When the net difference in force is relatively minimal, just a few bolts or pins can suffice.   However, when these forces are large, steeper measures, such as cable sleeves should be taken to insure the cables are secured in place for minimal sliding.

An important consideration in detailing cable saddle connections is the size of the cable that should be used.   The cables at the saddle point, having to bend relatively more than other parts of the membrane, must sometimes be significantly more flexible and therefore, have smaller bending radii.   At the same time, however, increasing the curvature of a cable causes the cable to lose considerable strength.   According to the ASCE, the full strength of a cable can only be relied upon when the bending radius is over 15 times its own diameter.   The ASCE also limits the saddle bending radius to be no less than 10 times the diameter of the cable, at which the strength of the cable is considered to be reduced by 25 percent.   Therefore, a balance should be taken when selecting the size of a cable for a more flexible cable will lack in strength, while a cable with a larger bending radius will look aesthetically bulky.
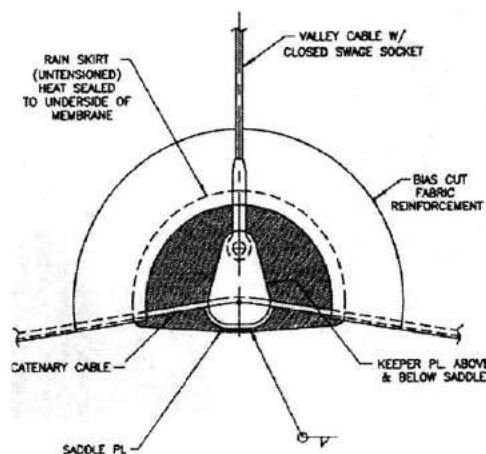
When crossing the saddle point, the cables can either continue over the saddle or terminate on both sides. Figure 25 illustrates the use of both cable crossings in one connection. The valley cable is terminated into a swaged socket, while the catenary cables continue through the keeper

Figure 25: Cables both continuing and terminating   at   a   saddle   point (Huntington, 2004)

where the swaged socket is connected. In most cases, the flexibility and location of the cable, as well as the need to change cable sizes and aesthetic considerations usually dictates what method is used.

5.3   Pretensioning

Pretensioning of the structure can be performed through direct tension of the fabric, cable tensioning or support mast tensioning. In all cases, the mechanism for pretension should tension the fabric in deliberate amounts that result in the smooth surface of the membrane.

5.3.1   Direct tensioning

Direct tensioning is commonly reserved for smaller-scale structures that do not need precise nor large prestress forces to be induced onto the membrane. These structures usually do not have supporting masts nor exterior cables so rely solely on tensioning at the edge of the membrane. A modified version of the typical fabric-to-support connection that includes an extra base plate with extra holes is used to allow for manual pulling of the fabric.

5.3.2   Cable tensioning

Cable tensioning is generally preferred over direct tension for both its aesthetic value and effectiveness. Only a few points of cable tensioning suffice to tension the entire membrane, as direction tensioning implies the continuous tensioning around the edges of the membrane. This can be done in both the interior and exterior cables. One way is to
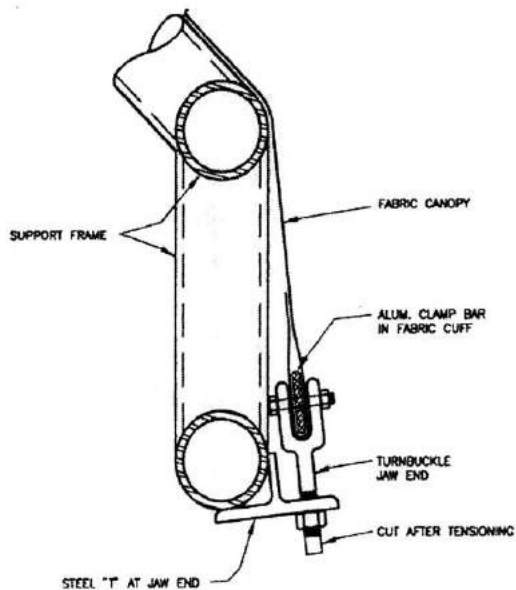

Figure 26:   Pretensioning at exterior tie-back cables (Huntington, 2004)

tension the membrane at the tie-back cables at the exterior of the structure. Figure 26 illustrates how tie-back cables can be tightened by adjustable turnbuckles that cause the support structure to pull back, which then causes the interior cables to tighten, causing the entire membrane to follow suit. This method may be restricted depending on the location of the tie-backs. In other cases, cables at key points can be tensioned using the adjustable cable-to-cable connections.
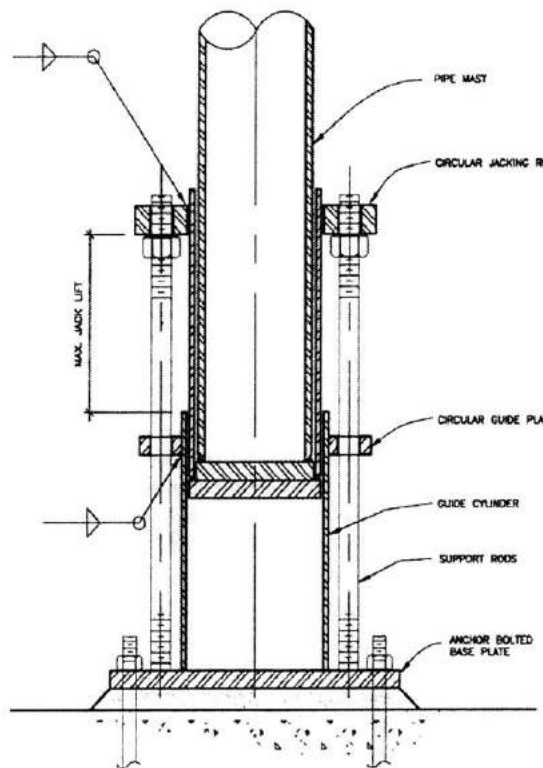
5.3.3 Support structure tensioning

Figure 27: Support structure base pre-tensioning (Huntington, 2004)

Tensioning at the support structure, through mast-jacking, is more versatile since it can be implemented no matter the location of the catenary cables and the mast itself. Like cable tensioning, only a few key points of mast-jacking are needed to induce the needed tensioning of the membrane. Masts can be jacked at either the top of bottom of the structure. Other than aesthetic issues, the difference between the two methods is that mast-jacking at the top only requires one hydraulic jack while the bottom requires multiple jacks. However, the actual tensioning of the hydraulic jacks is significantly harder from the top and the construction of the masts become significantly difficult since cranes must be employed to construct the mast.

CONCLUSION

Although tensioned fabric structures are relatively new in the engineering field, a lot of innovation has already occurred. However, there are still many concerns and limitations with these structures. First, with such a short history of existence, the complete behavior of tensioned fabric structures is yet to be known. Second, although current computer programs do an adequate job of form-finding and load analyzing, there are no programs that take into consideration all the specificities of the non-linear behavior of membrane structures. These include the effects of "crimp interchange." Lastly, the limiting factor of tensioned fabric structures lie within the fabric itself. Although tensioned fabric structures claim to be "permanent" as well as temporary structures, some will argue that the durability of the current fabrics do not allow for long lasting structures.

However, the field of designing for tensioned membrane structures will only continue to grow and reach new levels. As more case studies and behavior data records are compiled, more will be known of the behavior of these structures. Also, currently there are many studies and research taking place in the field of computer analyzing and durability of tensioned membrane structures. As time goes by and design and analysis for such structure advance, tensioned membrane structures will only capture more fully the amazing structural design by means of their inherent qualities.

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