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ABSTRACT

ARCHITECTURAL CONCEPTS FOR CIVIL ENGINEERING ROOF SYSTEMS

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Civil engineering roof systems for outdoor environments find use in bazaars, car park areas; outdoor sport facilities and places have been built to protect people or their goods from environmental effects such as sun and heavy rain. Therefore, in this thesis shown architectural concepts for such roofing systems which have great amount of application and each country spends huge volumes of materials to build these roof systems to improve life quality of people in cities. Thus, it is evident that further research on these civil engineering structures has the potential to decrease the cost of these roof systems and build more efficient ones. This study investigates a novel concept in the world called as “tensile structures” used to cover wide outdoor areas. This concept actually combines civil engineering designs and some architectural aspects. Instead of using materials with high stiffness, tensile structures adapt membrane materials to cover wide areas. Cable elements accompany those membranes to transmit the internal forces and stresses to structural columns or ground. Although membrane materials have lower strengths compared to steel, these structures offer flexibility in use, light coverings, lower costs and faster construction time. In order to investigate opportunities of these structures and present some possible configurations of tensile roof systems, special commercial software is used in this thesis, the software named FORTEN 2000 program.

Keywords: Tensile structures, roofing, architectural design, structural mechanics

ÖZET

İNŞAAT MÜHENDİSLİĞİ ÇATI SİSTEMLERİ İÇİN MİMARİ YAKLAŞIMLAR

ALSHAREEF, Alaa Tareq Shukri

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İnşaat Mühendisliği çatı sistemleri dış alanlarda pazarlar, otoparklar, spor tesisleri gibi yerlerde ve ayrıca insanları ve eşyaları güneş ve yağış gibi çevresel etkilerden korumak için kullanılmakktadır. Bu tez çalışması, birçok alanda uygulaması olan ve bütün ülkelerin şehirlerde yaşayan insanların hayat kalitelerini artırmak için büyük miktarlarda malzeme harcadıkları çatı sistemlerini mimari yaklaşımlarla incelemektedir. Bu inşaat mühendisliği yapıları üzerinde yapılacak araştırmaların çatı sistemlerinin maliyetini azaltıp daha etkili yapılara olanak sağlama potansiyeli açıkça görülmektedir. Bu çalışma dış alanların kapatılmasında kullanılan ve dünyada yeni bir yaklaşım olan çekme-germe yapılarını araştırmaktadır. Bu yaklaşım, aslında inşaat mühendisliği tasarımı ve mimari yaklaşımları bir araya getirmektedir. Yüksek rijitliğe sahip malzemeler yerine çekme-germe yapılar geniş alanları kapamak için membran malzemeler içerirler. Kablo elemanları membranlara eşlik ederek iç kuvvetlerin ve gerilmelerin kolonlara ya da zemine aktarılmasına yardımcı olurlar. Membran malzemeler çelikle karşılaştırıldıklarında düşük mukavemete sahip olmalarına rağmen kullanımda esneklik, hafiflik düşük maliyet ve hızlı inşa imkânlarını sunarlar. Bu yapıların sunduğu fırsatları incelemek ve çekme-germe çatı sistemlerinin bazı konfigürasyonlarını sunmak için bu çalışmada özel bir bilgisayar yazılımı kullanılmıştır, bu yazılımın adı FORTEN 2000.

Anahtar Kelimeler: Çekme-germe yapılar, çatı kaplama, mimari tasarım, yapısal mekanik

To My

Father and mother which they span there live for me and my beloved husband who give the time and support to reach this level from the knowledge

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I cannot forget to recall with my heartiest feelings, the never-ending heartfelt stream of caring and blessings of **my Father** and **my Mather**, to support me with everything since my early childhood till reach high education, They were always denying themselves for supporting and pushing me to every success.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF SYMBOLS

SYMBOLS	
V	Vertical reaction
H	Horizontal reaction
W	Distributed load to the cable
L *or* S	Length of cable (m)
h *or* d	Maximum vertical deflection
R	Approximate circular *arc* (radias)
T *or* F	Tension in the cable
T_o	Initial pretension
k	Axial stiffness
E	Young's modulus of elastisity in the cable
e	Extension o the cable
A	Cross-sectional area in the cable
f_1	A natural frequency fundamental of tensioned cables
m	Mass in (kg)
q	Force-density ratio
Q	Force-density matrix
X	Nodal displacement stiffness
σ	Bending stress
P_{in}	Internal forces
$K_{\mathrm{i+1}}$	New stiffness matrix
$\Delta\delta$	Incremental displacement vector

CHAPTER 1

INTRODUCTION

The term tension structures covers a colossal group from structures, that contains fabric membranes, pre stressed cable grids , and cable beams on a shape for trusses and girders. They are being used either as roofing forms, or bridges structures, and now a permanent feature of modern architecture, showing their potential for exploitation as efficient structures and aesthetically pleasing art forms.

Tension structures can greatly extend architects imagination because of their lightweight characteristics by making use of tensile materials, cable and/or membranes. This kind of structure can achieve the desired geometrical configuration and capacity of resisting external loads by the introduction of pre stress. The last few decades have seen a quick expansion on a growth for number and range from application of them [1].

The tension structure has been recognized as an efficient and practical configuration for achieving various structural and architectural objectives. Therefore, such roofing systems have great amount of application and each country spends huge volumes of materials to build these roof systems to improve life quality of people in cities. Thus, it is evident that further research on these civil engineering structures has the potential to decrease the cost of these roof systems and build more efficient ones. Generally these roof systems are manufactured employing structural steel material. As is well known, steel has promising mechanical properties such as high strength and high stiffness which can be exploited in structures that expected to receive very high magnitude of loadings, such as earthquake resistant buildings. However, there also exist some disadvantages of completely using steel in these roof systems. For instance, due to unit weight of material the roofs manufactured using steel are very heavy. The primary goal in the design of a tension structure is to select and arrange the structural components so the loads are carried primarily in tension and the number of compression members is held to the minimum necessary to main stability. So, construction process requires significant labour and time. Also steel construction is an expensive process considering measure of covered area for outdoor roof systems. Moreover, these kinds of roofs manufactured using completely steel are not flexible in use, that is to say, when it is unnecessary for some period of time it is not possible to remove the roof covering and re-cover it when it is necessary again. This paper investigates a novel concept in the world called as "tensile structures" used to cover wide outdoor areas. This concept actually combines civil engineering designs and some architectural aspects. Instead of using materials with high stiffness, tensile structures adapt membrane materials to cover wide areas. Cable elements accompany those membranes to transmit the internal forces and stresses to structural columns or ground. Although membrane materials have lower strengths compared to steel, these structures offer flexibility in use, light coverings, lower costs and faster construction time. Since these structures are built utilizing membrane materials and cables which support tension forces only, conventional stress office methods are not capable of handling their analyses and designs. A design achieved by extensive use of high strength tension members with relatively small cross sections can offer advantages over a more conventional one. The potential for significant weight reduction is probably the most important, however, since, more often than not, weight is a limiting or controlling factor when a tension structure design is an alternate candidate to perform a specific function.

A common example of the use of tension structures is in the design of roof systems to span large areas enclosed by modern structures such as stadiums and shopping centers. Networks of slender cables provide the strength necessary to support the tremendous loads involved and the same time afford the architect the opportunity for imaginative creation. Space activities provide further applications for the tension structure concept since weight is a principal factor in determining feasibility [2].

1.1 Classification of Tension Structures

Kim [3] proposed a simple figure where various structural systems can be classified with ease, as in Figure 1.1. In this figure, early we can cluster in to two portions according to materials. The early one is the hard structures that are made by underpinned concrete, steel structures and so on; early structural forms below unloading have been ambitious to be a fixed form. The supplementary is the soft structures that are made by fabrics, cables and so on ; early structural forms below unloading have not been ambitious . These two structural arrangement expose disparate behaviors. In the preceding, structural stability adjustments from stable to precarious as the external burden level gets higher and reaches a precise critical point . But the last displays the opposite phenomenon, namely from precarious to stable in an un-tensioned state. In structural design, consequently, the hard structures demand to check the critical burden due to the bucking phenomena, but the soft structures demand form discovering due to the introduction of early stresses.

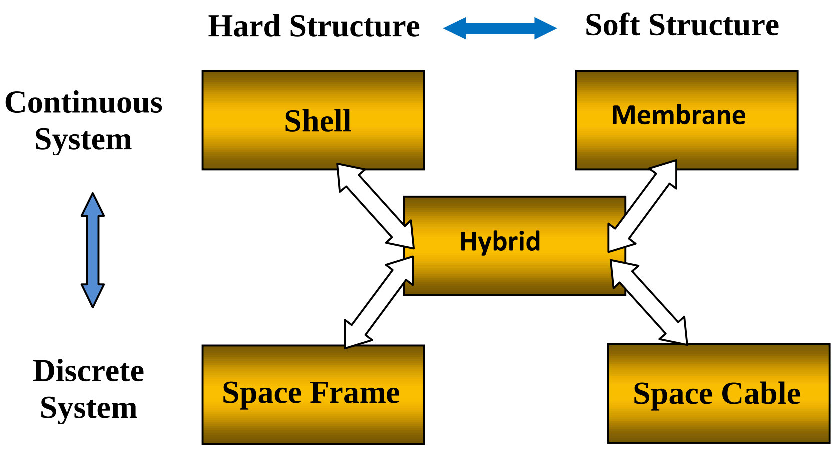

Figure 1.1 Classification of spatial Structures [3]

Secondly, the spatial structures is gathered according to how to assemble; the one is crafted by constant arrangement such as casings and membrane structures, and the others is discrete arrangement such as space structures and space cables. Tensile structure is made of tensile materials, cables and/or membranes, in that there is neither arcing, compression nor tension but merely tension forced/stresses exist. It is normally utilized as a colossal-span structures because of the light-heaviness characteristics of the structural materials and nonexistence of agents that could have buckle. Across tension structures come in fluctuating scale, size, form and form, they consists of the alike frank parts:

- The handy and elastic fabric membrane, tighten for stabilization and normally utilized such the roofing unit.

- Flexibility linear agents like ties for cables, that are usually utilized on borders and edges.

- Solid upholding associates that as masts, constructions, ring, arches and frontier bar, that normally carry loads in compression. These rigid supports are normally made from established constructing materials such as steel, concrete, and timber.

The last two decades have seen the quick expansion on a growth for the number and range from applications of tensile architecture [4]. Structural engineers and architects the design of lightweight structures is mysterious [5]. Most frequently, tensile constructions are utilized for a melodramatic result above presentation and outdoor exhibition spans, theatres, music periods, entrance driveways, parking spans, walkways, stadia, domes, airports. Designed as permanent or demountable canopies, they act as a foil for lighting and the projection of images, and can also be used for protecting audiences from the elements [6].

They are variety at ways into categorize tensile membrane structures. Lewis [7] they classify in to three major groups: Pneumatic or air supported structures, Boundary tensioned membranes, Cable-nets and cable-beams.

1.1.1 Boundary tensioned membranes

The pre stress level in the external have to be of an appropriate level, to safeguard opposing a probable defeat of tension across the existence span of the construction on one hand, and to permit the physical to stay inside the flexible scope of deformations on the other. Below imposed loads, such as wind and snow the stress in the external can rise 6-8, even 10- crease design of tension membranes is aimed at keeping the early prestress at concerning 1/20 of the breaking strength of the cloth [7].

Boundary tensioned membranes are stressed by stretching the external to encounter the frontier made of flexible, tension cables, or a rigid frame/beam. The frontier agents are an vital portion of the tension construction as they ascertain the form and nature of not just the frontier but the external as whole. The former has zero excess pressure between the outer and inner surface [7, 8].

1.1.2 Pneumatic or air supported structures

Pneumatic constructions or “air houses” are slender membranes stressed by inner air pressure generated by fans. Their form is extremely powerfully altered by the difference amid the external and inner pressure, that change continually, as a consequence of temperature variations, wind and snow burden condition. The Air dome is the one example of pneumatic structures which used in different place of the world for many uses like swimming pool and tennis poole as shown in Figure 1.2. Air houses are projected to uphold an inner pressure amid 0.2 KN/m^2 and 0.55 KN/m^2 [7, 9, 10].

Figure 1.2. Air Dome (air supported structures)

1.1.3 Cable – nets and cable beams

Cable nets can be stressed undeviatingly employing rigid supports such as compression ring beams, or flexible frontier cables alongside upholding mast and tie backs. They can seize the form of suspended construction stabilized by way of a heavy rooftop cladding, or can be encased in concrete. The opportunity for crafting new structural form is immense. If a prestressed cable net constitutes a portion of a concrete casing, it is no longer a handy tension construction and the supremacy of flexible is lost. Though , because of their seeming discernible lightness, the form of cable net constructions are duplicated in to rigid forms, as was the case alongside concrete “tents” crafted in the Middle East in 1991 [7,11,12].

The main difference amid cable nets and fabric constructions, from the structural think point, is that fabric structures are capable of sustaining membrane shear forces whereas cable nets are not, due to the deformability of the surface [16].

1.2 The Advantages and Disadvantages of Tensile Membrane Structures

The producing attention in tension constructions can be attributed to pursuing advantages:

- Provided appropriate and well designed structural forms are utilized these structure can become very attractive architectural landmarks.
- Many fabric architectural constructions are projected so that the fabric can be removed if there is danger of a hurricane. This helps stop damage to a construction in a method that is not probable alongside roofed constructing structures. It additionally helps stop damage to encircling property from hovering shingles or metal roofs.
- Adapts its own, exceptional shape. Because of their uniqueness and primarily, fabric constructions can appeal supplementary attention to a business. Adding appealing signage and logos to aid promote businesses.
- They are light heaviness and can be transported at moderately low cost.
- These constructions can be utilized to cover colossal spans at extremely competitive prices each constituent area.
- These structural forms consequence in constructions that can be fully stressed as there is no demand to ponder arcing or buckling that aftermath in extremely effectual use of the materials used.
- These structures may be prefabricated and can be manufactured in the most efficient method [13, 15].

On the other hand, tensile membrane structures have a little disadvantages. These are:

- Cannot take heavy weather conditions.
- Creep (stretch extremely slightly).
- Short economical life span of structures.
- Loss of tension is dangerous for stability.
- Thermal values limit use [14].

1.3 Goal of the thesis

This dissertation is established on factual findings, past references, the globe expansive web and two individual case study. It is composed as an introduction, to the magnificent an varied globe of tensile membrane architecture. The early half seizes a brief retrospective gaze at the past progress of tensile membrane constructions, commencing alongside the tent, advancing to knowledge and across to the industrially produced elevated tech membrane constructions we discern today. Briefly documenting the work, motivations and research of a little of the most vital architects and builders encompassed alongside the progress of this exceedingly technical method of constructing across the twentieth century and beyond. The realization and consecutive understanding of this dissertation should be fruitless lacking the frank understanding of the past outlook of tensile architecture. It is undoubtedly the understanding of the past that escorts us towards a extra notified opinion concerning the future.

The subsequent half of this dissertation presents the analysis and design of two tensile membrane constructions employing business package program. The design of tensile membrane constructions is grasped out in four steps. These are conceptual design, form finding, structural scutiny and cutting patterning. This dissertation is not meant to be a definitive engineering escort, but merely meant as an eye opener for an or else lesser understood method of constructing assembly that has been producing in popularity and rationality for countless years.

1.4 Thesis content

The pending contents of this thesis are coordinated as follows:

Chapter 1 introduced tensile structure and membrane, classified the tension structure, boundary tensioned membranes, the advantages and disadvantages of tensile membrane structures, objective of the thesis and the containt of thesis.

Chapter 2 gives the factual findings and past references. The early portion of the thesis presents pictorial references that are encompassed to enable a larger discernible understanding of the subject matter. The past reference studies are selected firstly for their architectural relevance; secondly for their difference to every single supplementary, and thirdly; for this design technology. The subsequent portion of the chapter debates progress in the design procedure and its constituents such as form discovering, analysis etc.

Chapter 3 presents the design procedure and numerical methods for form discovering, analysis and cutting pattering.

Chapter 4 presents design of three tensile membrane structures. These constructions are sunshade of shopping and car park . The steps of every single design are given in detail.

Chapter 5 concludes the discover and gives a little discussions of upcoming discover on the design of tensile membrane structure, and give some recommendations.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The historical human need of roofing since the dawn of our on this planet, human kind has inhabited its self alongside the conception of shelters. This is, of sequence, an in- crafted human instinct as a reply to the great variations in meteorological conditions and as a defensive barrier protecting us from predators or unwanted intruders. It might additionally be believed honest and harmless nesting locations for our youthful and loves ones. This instinctive demand for the conception of protection has, above countless thousands of years, lead to countless constructing methods, styles, principles and technologies being past down from creation to creation, from sophistication to sophistication and state to country. This obsession with building has been prevalent in just about every period of history and this obsession is now affectionately called architecture [17].

Light, no permanent and main tensile design produced out of the rambling or nomadic existence styles of the main savage people. These people industrialized handy, demountable constructions that were adequate for their physical, communal and frugal needs. The technical attainments of these main constructions whereas perhaps underestimated in the past, by the bulk of architectural biographers, but luckily the importance of these easy, light prefabricated and handy dwellings can style proposal nowadays designers inspiration. Tent architectural evolved out of a shortage of constructing materials and the believed of immovability or non-permanentness, made the humble tent the flawless protection for spans whereas lack of resources negated a nomadic existence style. These kinds of tensile textile constructions additionally have an adaptability, that made them flexible to changing situations and conditions, and can uses for different times and place accordingly human needs.

So to briefly sum up the qualities of these early primitive is like including a present brief for a present prefabricated housing project: Economic, flexible, manipulated physical custom, prefabricated, transportable, environmentally approachable physical, use of usual light, connection to the encircling landscape and low power consumption.

2.2 Tent

The black tent is plausibly concerning as aged like the kibitlea take shape and likes it yet far utilized nowadays as in the Figure 2.1. The tent have been the house on the one shape or one extra of maximum nomadic dwellers for a Ice Era into a present. Vegetation permitting, the maximum area supports of tents were tree splits or the trunks of saplings. A minimum profile and shallow hills for a black tent make it resistant to the desert winds. For a three basic forms the black tent is the only one in that the shape is not completely assigned to by its supporting framework [19].

A membrane tent is plausibly the subsequent most antique constructing form in human past afterward caves. Evidence of mammoth bones and tusk used as supports for animal hides has been found at sites verified to be more than 40.000 years old in the Ukraine region [13,18].

In north America innate tribes rambled and were able to hold their tents to new locations as the periods dictated. Of the three basic take shape the conical image is oldest and saw widespread use over north Europe, Northern Asia and North America. A conical shapes “kibitlea” is shown in Figure 2.2, shape dates to B.C. or earlier and has been the world’s most popular dwelling form [19].

The past of membrane structures in the late nineteenth century and main twentieth century is related to the progress of circus tents. The biggest wall of tents were the travelling cirque “big tops” accepted at the U.S. for main 19 Century. In the 1950s these reached their maximum size covering more than one hectare [13,19].

Figure 2.1 Black tent [19]

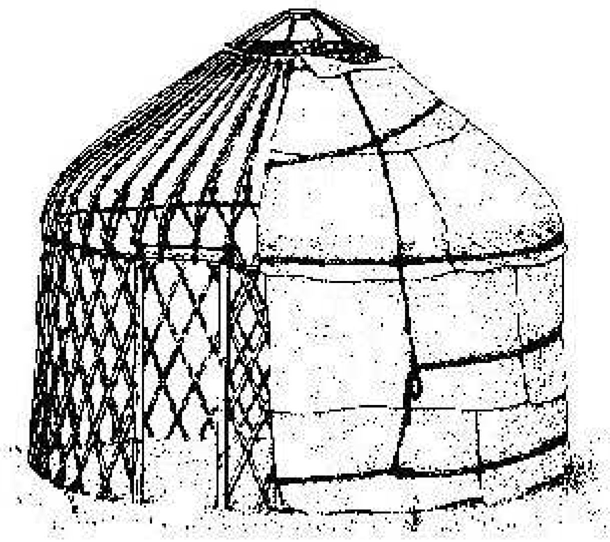

Figure 2.2 Kibitlea tent [19]

In the late nineteenth century the ‘breakthrough’ came as larger constructions were required in a post-industrial society, Many significant developments took place, after the second world war in the design procedures, materials, construction and erection methods, and of course computation [13].

2.3 Structural Developments

There are elegant, light and efficient structures, the taking applications variation between big stadium roofs and light-increase walls of building to pneumatic furniture or aerospace tools. Since the 1950's Frei Otto's pioneering doings in that structures (both membrane and cable structures) presents a important research of field in engineering and architecture. The design of the structures is integrated to their analysis, in a operation that contain steps for form finding patterning and load analysis. Several references about the design from taut structures are Haber and Abel [20], Knudson [21], Tabarrok and Qin [22], Moncrief and Topping [23], Barnes [24] and Pauletti and Pimenta [25].

Engineers and architects should be works jointly, to meet the objective requirements. It is extensively recognized which architects are concentrated on the geometric shape form for a membrane, when engineers are concerned distressed alongside the inner stress allocation of the membrane. Both methods are undeviatingly related, as the geometric form from a membrane depended in a given early prestress at the membrane.

2.3.1 Form finding developments

Though prestressed structures such as tents known on a first human-made structures, a few has familiar on a analytical modelling on their load deflection behavior. Prestressed cable-nets and textile membranes are qualified by the ingrained interaction between they geometry and stress distribution. This relationship between a shape and forces makes it impossible to immediately design this structures same as is the case for classical structures[26].

When at 1967 the German Pavilions on the Montreal EXPO was built, no functional analytical solution technique was obtainable to set the cable-net shape and behavior under external load. Which on that time the only path of the design and a investigation of this nets was to use physical models [26].

Determining a feasible shapes necessarily a determination for the character of equilibrium of interior forces and loads of a structure. Thes normally obtain results on a doubly curved roofs. Mathematically this surfaces might merely be almost approximated by differential equations. As doubly curved surfaces cannot be flattened without deformation, the generation of accurate cutting patterns is required of fabrication. Finally the structure will experience big deflections under expressible loading conditions whose means that analytical methods would have to be able to cope with that [26].

The design the cable-net roofs at the 1972 Munich Olympic Games stadium. Frei Otto establish exact physical samples that were infectious into be the grounding of information for all relevant data. Linkwitz counseled into measurement the sample precisely requesting close area photogrammetric methods that should statement for a simultaneous determination of the 3D-geometry of the model without touching it. It has realized but that the models were by no means exact enough to derive the cutting pattern of an equal mesh cable net made of steel [26].

A photogrammetric measurements for a physical models had into be adjusted on quest into fulfill a constraints for equal unstressed mesh-width and for enjoy equilibrium in each node. An analytical solution of these task has achieved through applying the method of least square to the measured nodal coordinates [27, 28] discerning the boundary conditions above. Applying this method, the cutting pattern of the stadium roof was created at a time consuming however successful step using all the computer force available during that time [26]

At 1971 Linkwitz and Schek [27] discovered the first formulation for a figure of equilibrium from forces, the force-density shape. They comprehended that this was more convenient for solving the problem, especially that of finding good initial geometry..

A design procedure from pre tensioned structures this such cable nets and membrane structures is affected through a progress of computational methods. However the first styles for form finding have been physical modelling together that fabric, wire nets or soap films, today some numerical methods for form finding are progressing developed based at [29]:

- Conjugate Gradient / Force Density [28, 30]
- Dynamic Relaxation [31, 32]

- Modified Stiffness
- Principle of negligible surfaces [33, 34]

Or supplementary ways in pathological a three dimensional balance.

Method of Force Density used the analytic method into linearize a form finding equations of the tension net. Thes linearization makes the method independent of the material properties for a membrane. Force density proportion (force of cable divided by length of cable) want to be enumerated of every any element, and various proportion award dissimilar equilibrium forms. A process is numerically strong, separate for the initial places from the nodes and the equilibrium form is established easily. The force density resolution into applied loads is non-linear and requires iteration [35].

Method of Surface Stress Density can be believed like the popularization for linear force density mode into a bi-dimensional status and part to account an shear stress. these case, a surface stress density proportion is given by the stress divided by the area for the element.

Method of Dynamic Relaxation resolves an geometric nonlinear problem via equating it into a dynamic problem. Basics from dynamic are utilized into resolve the analysis. A suitable dynamic properties requirement to be defined, such as a mass and damping characteristics of the membrane. A equilibrium for forces is made on each node, presenting the residual force that produces the movement for a node in the way of these force, according into a dynamic behavior for the net. New position of a nodes are examined until the final equilibrium form is reached. At this point the residual forces are sufficiently small [35].

Developments in mainland Europe have mostly used Conjugate gradient/force density solvers, Britain has pondered on dynamic relaxation, and Japan and the USA have mainly used the modified stiffness method. Two element types are usually used to model textile roofs. Cable net models employing link agents have been accepted in Conjugate gradient/force density arrangement, as triangular continuum agents have been normally utilized in vibrant relaxation and adjusted stiffness systems. It is vital to highlight that the prevalence of employing particular agents alongside particular solver algorithms does not have a hypothetical or computational basis. Conjugate gradient/force density arrangements alongside triangular continuum agents are utilized after appropriate and adjusted stiffness and vibrant relaxation arrangements can additionally use like agents to ideal textile [5].

Whole method include at public while no physical regulations are vital discovering a balance for a three dimensional form of offered stress allocations, frontier conditions and supports. This forms of balance ought to safeguard at the crafted construction a uniform allocation for a tension stresses. In fact a physical deeds, procedure of cutting outlines, producing and pre tensioning in locale affecting the stress allocation, wrinkles and spans for above stress are seeming, can be perceived and measured [29].

2.3.2 Analysis

Generally in the structures the membrane requires non-linear geometric technique. A general analysis consists a membrane tensioned directly egther extremely fixed solid structural elements as (beams, walls, posts or braced frames) or cables. A mechanical characteristic for cables and fabric as nonlinear nature that could be divided to two groups [36]:

- Nonlinear nature because of big displacements (rotation and translation).
- Nonlinear nature because of the fabric and the cables can not be affected by compression loads.

When the strain of the fabric and cables is believed small, Therefore, they do not give any compression stiffness. The fabric materials are having orthotropic linear flexible properties. For the cables itself proposition is made. Finite membrane and cable elements have been requested of a progress from procedures ambidextrous to resolve the mechanical behavior from a tensile structure below disparate constant extern loads [36].

Were studied two mechanical aspects:

- The first is instituted on form-finding out of given stress or load fields. In that study, only the geometry can usefull to a stable in state of balance. A problem is then predestined statically. Equilibrium no longer depends on the rheologic properties of the fabric. This procedure has been extensively adopted and uses two kinds of design [37]:

- Reinforced cable elements modeling: In that methods vector of the conditions of balance and compatibility are decoupled till assemblage for an balance solution. The most general of that are Dynamic repose [37, 38], the Scaled joint Gradient Method [39], and Force density method, qualified primarily by Scheck [39], equal cable net models [40]. The former has obtained the most convention on a analysis for tensile membrane structures because of its apparently physical analogy and easiness of application of the necessary controls and constraints. Individual element solidity relations are held separately, whose greatly eases the specification of stress controls at form-finding and non-linear, stress following, elastic properties beneath analysis. It is similarly unsophisticated into introduce a wide framework of boundary conditions that can themselves be dependent upon the current disfigured state of the structure [4]

- The module of finite elements are triangular and quadrilateral membrane: These method has initially developed via Ishii [41, 42], Haber [43, 44], D'Uston [45], Tsubota [46] and Nouri-Baranger [47, 49].

➢ A second parts is established at the nonlinear elastic in big deflection analysis and believes strain elements. Great deflections and stress factors contain the list from parameters, that developed through a some iterations. These aspect has accomplished at 1974 via Argyris et al. [37, 50, 51]. Though, it is effective, it is the generality complicated of a designer to behavior [37]. The procedure evolve in this sense can be established within fabric modeling through a network at cables (Argyris [36], grundig [52], Nishino [53] and Frei [54]). A disadvantage for these steps comfort on its inability into reproduce the existing behavior for the fabric: stress state, wrinkling, deface, distort and weft direction leading according of the pattern cutting. A alternative operation uses modelling via triangular or quadrangular membrane finite elements. A nonlinear matrix methods are typically the implementation for more standard nonlinear structural analyses this as a Newton-Raphson method [55]. A structure comprehensive tangent stiffness matrix is solved incremental till convergence is acquired. Specific controls limiting the maximum incremental deflections and nodal residual forces may be required. These stress / strain connection of the individual component are connected within a equilibrium and compatibility requirements from the complete structure [4].

Many tensile structural arrangements are strain hardening. A collection of public tensile structural arrangements are primarily strain softening and being to display to strain hardening deeds after adequate burden is applied. Consequently, non-linear resolution strategies that anticipate strain hardening have been retained alongside accomplishment and can speed convergence in a expansive collection of usually encountered problems. There are momentous exclusions, such as a class of “tensegrity” kind constructions that come to be strain softening as burden is increased. The vibrant relaxation method is additionally utilized alongside accomplishment for the finished scutiny of geometrically non-linear setbacks [56]. Most architectural/structural fabric materials display non-linear deeds, as a consequence of being woven composites. Nearly all architectural or structural fabrics in use nowadays are coated composites. Though, physical non-linearity is scarcely modeled.

Coating properties additionally have an result on the composite’s mechanical deeds, albeit at a lesser extent than the properties of the center cloth. Fabric is usually modeled employing linear steady strain agent (finite agent methods or a web of thread elements. Both of these modeling ways have been extensively utilized alongside accomplishment as every single has attendant limitations that the analyst have to consider. Membrane agents that larger simulate the non-linear deeds of woven composites have been industrialized [57]. As the fabric physical non-linearity is normally no modeled, it will probable clarify to be functional after the technicians of fabric wrecks are larger understood and utilized quantitatively in a check state design way [56].

2.4 Architectural Developments

Tensile membrane structures nowadays yet posses the alike frank qualities of competent coverage and fast assembly, but have evolved in to colossal scale area undertakings, capable of protecting huge crowds instead of tiny relations units.

Table 2.1 Some examples of tensile membrane structures constructed in the world

Year	Structure	Architecture & Engineers	Design Style
1952	J. S. Dorton arena Raleigh, NC. US	Matthew Nowicki (arch) William Dietrick (arch) Fred Severud (engr)	First large cable-net structure
1958	French pavilion, World's fair Brussels, Belgium	Rene Sarger (arch)	Early cable net roof
1967	German pavilion, Expo Montreal, canada	Frei Otto (engr) Rudolph Gotbrod (arch)	Tensile membrane structures
1970	US pavilion, World's fair Osaka, Japan	Davis and Brody (arch) David Geiger (engr)	Air-inflated vinyl-coated fiberglass
1972	Olympic stadium Munich, Germany	Behnich and Partners (arch) Frei Otto(engr) Leonhardt &Andra (engr)	Tensile membrane structures
1979	King Abdul Aziz university sport hall	Buro Happold (engr) Rudolph Gotbrod (engr)	
1982	Munich ice skating rink Munich, Germany	Jorg Schlaich	Cable net and trussed arch
1985	A King Fahd Stadium Riyadh, Saudia Arabia	Ian Fraser, John Roberts (arch) Horst Berger (engr)	288 m diameter plan
1986	Canada place Expo Vancouver, Canada	Zeilder/Roberts Partners Horst Berger (engr)	Ridge and valley design
1992	Georgia dome Atlanta, GA,US	Weidlinger Assoc (engr) Walter Bird (const)	Largest cable dome to date
2002	Stands roofing, Fenerbahce stadium / Turkey	Teschner, Kosel	PES/PVC fabric
2005	Stands roofing Formula I ring -Istanbul Turkey	Teschner, Kosel	PES/PVC fabric
2010	Members of the Medina Haram Piazza project	SL-Rasch is the architect, A German umbrella manufacturer Liebherr and Japanese manufacturer Taiyo Kogyo	High-yield steel structure, PTFE-membrane

Table 2.1 catalogs a number of notable tensile membrane constructions crafted Turkey and World. Every single undertaking brings alongside it a new set of design

necessities and challenges. The pursuing is brief for chosen structures and those constructions at the advancement for tensile membrane construction designing and constructions.

2.4.1 Dorton arena

A J.S.Dorton Arena that is shown in Figure 2.3. (Familiar into its architect such like a Paraboleum) is a 7610-bench multi-purpose arena at Raleigh, North Carolina, in a fields of the North Carolina State Fair. It has opened in 1952.

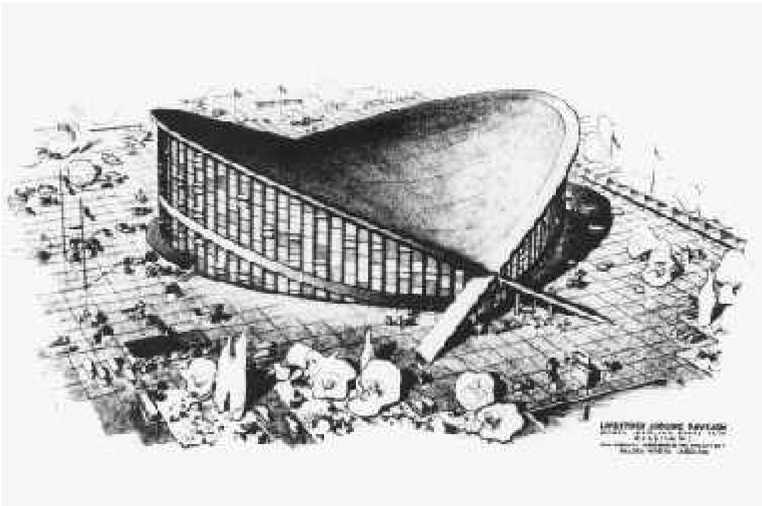

Figure 2.3 Dorton Arena

The arena's brave parabolic design was conceived by Matthew Norwicki, a gleam architect who helped layout the repairing of warsaw pursuing Globe Fight II. Norwicki additionally assisted in arranging the United States convoluted in New

Tork. Native architect William Hanley Dietrick supervised of completion for the arena employing Nowicki's change design. Its design features the steel cable upheld saddle-shaped roof on tension, service up via parabolical concrete arches on compression. The arches section about 20 feet above ground level and keep underground, where the ends from a arches are held jointly through more steel cables on tension. The outer walls at the arena support next into no weight at all [58, 59].

2.4.2 French pavilion at the Brussels universal exhibition

Explicitly projected into rapid France's dynamism at a anxious era, these colossal pavilion alongside its convoluted shapes undeniably remarkable the 1958 Universal Showing as shown Figure 2.4.

Figure 2.4 French Pavilions at the Brussels Universal Exhibition

The finished take shape of the rooftop is offered by twain united lozenges on hyperbolic shape stable through an oblique mast, proceedings it probable to covering 12000 m^2 lacking each inner support. The rooftop itself is encompassed of slender metal piece upheld through a double web for tensioned wire. More at an skilled on concrete, Guillaume Gillet whom was building the Royan cathedral on the time, opted to involve steel in this instance (Architecture: Guillaume Gillet, Consultant Engineers: Jean Prouve &Rene Sarger) [60].

2.4.3 German Pavilion Expo 67

Frei Otto and Rolf Gutbrod endeavored, alongside these competition winning undertaking, to craft the man made landscape as shown in Figure 2.5. The cavernous inside encompassed modular steel periods coordinated at disparate levels. The whole span was obscured via the solitary membrane for abnormal design and fluctuating heights. Its contours were ambitious via the elevated points for the standard and the soft points whereas the membrane has drawn, repression such as down into a ground. Eye loops loaded alongside clearly plastic physical accentuated this points and a packsaddle surfaces they created. A prestressed membrane encompassed for a translucent skin hung from a steel wire net, that, via eye, solid, and frontier ropes, has related alongside the mast heads and anchor blocks.

Construction specifics: complex high and low point pure with 8 backing points, 3 restraining points on collection with 3 continued ridges, 31 perimeter anchor points maximum length: 130 m, maximum width: 105 m, covered area: 8000 m2, mast heights: 14 to 38 m [61].

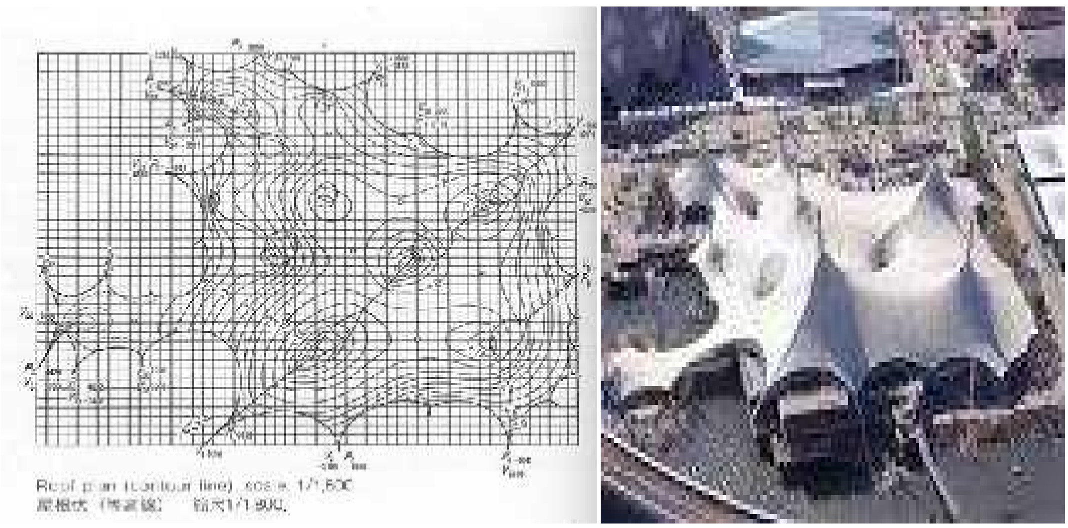

Figure 2.5 German pavilions Expo 67

2.4.4 United States pavilion 1970 Globe exposition

Sunk partly to the earth, the elliptical U.S. pavilion at Expo ’70 as in Figure 2.6. was roofed via the biggest clear-span air-supported cable rooftop ever built. Made of a translucent, vinyl-coated, fiberglass fabric, the rooftop endowed filtered usual light by date, and radiated at night. The fabric weighed 1 Ib/ft2 and was retained inflated by an inner pressure of considering three hollowed out of the earth; the inside construction housed seven main exhibits below the finished heading “Image of America”. It increased two levels alongside a joined floor span of 100000 ft^2. The undertaking was exceptional collaboration amid the architects and display designers, Charmayeff &Geismar. The constructing form and its inside spaces were conceived by both offices.

Figure 2.6 United States pavilion 1970 World exposition

Earlier main structural change (like the Galerie des Machines, the Eiffel Tower, Brooklyn Bridge, hyperbolic parabolic and slender shell) has arose on the exceedingly visible and oftentimes startling change in physical form. This change was an exception. Like the urbane high-speed computer, its probable was not exposed by infrequent physical form. It was the structural metamorphosis hardly visible to the expert and nearly completely invisible to the layman. Its encounter might nevertheless be incredibly visible, for this assembly makes such schemes as totally encircled metropolis spans believable and feasible. Its architects, Davis, Brody & Associates, alongside designers Chermayeff, Geismar, de Harak &

Associates, of New York, envision whole spans, states and even the lunar external encompassed inside low-profile air constructions [62].

The air inflated constructions by David Geiger: Inspired by the accomplishment of the EXPO' 70 American pavilion, David Geiger industrialized countless undertakings retaining cable underpinned, insufflated membranes, for sport stadiums in the United States and Canada, from 1974 to 1984. The biggest of these stadiums are the Pontiac (1983) and the Minneapolis Metrodome (1982), all of them obscuring extra than 40000.0 m2, alongside capacities above 60000 persons. These rooftops drastically cut the worth each chair, contrasted alongside average stadium, and have worked satisfactorily, except for a slight operational setbacks, managing do deflations, in the Minnesota Metrodome, due to excessive accumulation of snow. It can be appointed as a paradox, that the main factor steering to encounter of closed settings (harsh winter) is additionally the foulest enemy of the large pneumatic domes. Later domes such as the Tokyo "Big-Egg" Dome (1988) and the Akita SKY Metrodome, projected and crafted by Kajima Firm (1990) evaded setbacks alongside snow employing larger inner pressures, tinier distance amid cables and higher profiles [62].

2.4.5 Munich Olympic Stadium

The rooftop of the main stadium and indoor arenas for the 1972 Munich Olympic Games as in Figure 2.7. Projected by Gunter Behnisch alongside Frei Otto as rooftop design consultant, comprehended an completely new scale for thistype of strycture, and grasped to the pioneering of completely mathematical computer established procedures for ascertaining their form and behavior.

The varied tent and umbrella rooftop erected at Munich were the culmination of Otto's countless years' experience. Preceding examples had indicated the probable of such provisional but frugal large-span structures.

But at Munich the scale was incredible, encompassing the erection and associating of varied amoeba-shaped tents: the main spans obscured encompassed the main stadium, on one side merely, connected to the arena and the swimming span, both wholly covered.

Figure 2.7 Munich Olympic stadium

The rooftop obscuring the main stadium encompassed of a PVC coated polyester fabric suspended on hangers self-governing of the cable net. The upholding masts grasped the main cables in tension, consequently bestowing the vital prop for hanging rooftop areas.

Tent-link rooftops encompassing of the rooftop of the main stadium (34550.0 m^2), the gymnastic arena (21750.0 m^2), an inside pool (11900.0 m^2), the large (5800.0 m^2) and the puny (800.0 m^2) intermediate roof. Whole rooftops have translucent Plexiglas obscuring and are upheld via the web for twin strands alongside the mish width at 75 cm. A rooftop of a stadium is upheld by a arced cable encompassing of 10 parallel strand cables alongside the inner edge. A rooftop of the gymnastic arena is upheld by four cable-trusses that are anchored for the cable-stayed towers up to 70 m high. The rooftop of the inside pool is upheld by a solitary 80 m elevated tower [63-65].

2.4.6 Sport centre at the King Abdul Aziz University

Though it stands on high is 27.0 m and covers an area exceeding 9.500 m^2, the sports gallery in Jeddah's king Abdul Aziz University as in Figure 2.8 is unmistakably Arabian in architectural concept.

Figure 2.8 Sport centre at the King Abdul Aziz University

Designed by Professor Frei Otto and the Stuttgart architectural practice of Buro Gutbrod, with engineering design by Buro Happold, a structure is a vast and beautiful tensile membrane structure which despite its scale, is strongly reminiscent of the traditional Bedouin tent shape [66].

2.4.7 Ice skating rink (Olympic park Munich)

The enable the open ice surface of the Olympic park such in Figure 2.9 to be used whole round the year, independently of a weather, light roofing, naturally without supports, was required. Architects and engineers solved these problem jointly on an inspired style through way of the steel trussed arch of three chords. That the span of 100 m and the height is roughly 19 m at its apex, the arch is capable of transmitting any thrusts to two large concrete abutments. Two sets for cables hang in opposite bends from the arch, stabilizing it by their anchorage and growing a net. These symmetrical nets of cable have a grid of 75 X 75 cm and support a wooden lattice, on that is attached translucent plastic sheeting. The roof’s borders the cable nets are adjoined via garland formed cables that bypass above adjustable angled supports of steel being anchored fast. The assembly and shape of the hanging from the arch correspond in the main to that of the rooftop frontier, therefore permitting the alike constituents to be utilized and additionally producing a sequence of elliptically threaded starts below the latticed arch. These are loaded by “ glass eyes” outfitted alongside ventilators. The constant, amid concerning 3 and 5 m lanky “facades” amid the frontier of the rooftop and the earth in the span of the angled supports incline from the eaves to the inside at an slant corresponding to that of these supports.

Figure 2.9 Ice skating rink (Olympic park Munich)

The constructing therefore has the early ever in itself mobile, horizontally barred glass “facade” that is able to give in the proper adjustments allowed by the anchoring cables.

These comprehensive, and in itself symmetrical area-covering construction makes do alongside a minimum of materials. The logic of its construction, its beauty, elegance and exceptional boldness give the impression that genuine functionality, invented by technical intelligence, led to the real aesthetic effect [67].

2.4.8 King Fahd Global Stadium

King Fahd Global Stadium is a multi-purpose stadium in Riyadh, Saudi Arabia as in Figure 2.10. That presently uses mostly for football matches and it is also was athletics facilities. The stadium was built since 1987. It also one of the biggest stadium roofs around the world.

Figure 2.10 King Fahd International Stadiums

It was a venue for matches of the FIFA World Youth Championship in 1989 including the final match. The stadium's roof shades over 75000 seats and obscuring an area of 47000 m^2. The 24 columns are coordinated on a circlewith a 247 m diameter. The structure is made of 24 equal units. The entire roof has only two roof panel shapes which generate the rich sculpture of the roof umbrella. The huge umbrella keeps the sun off the seats and concourse slabs, providing shade and comfort in the hot desert climate [68].

2.4.9 Canada Harbor locale

The sail- like tensile membrane structure units of the Canada Harbor as in Figure 2.11. place convention center exhibit hall are skewed at 45^o in their plan orientation to imitate the road grid of the city of Vancouver.

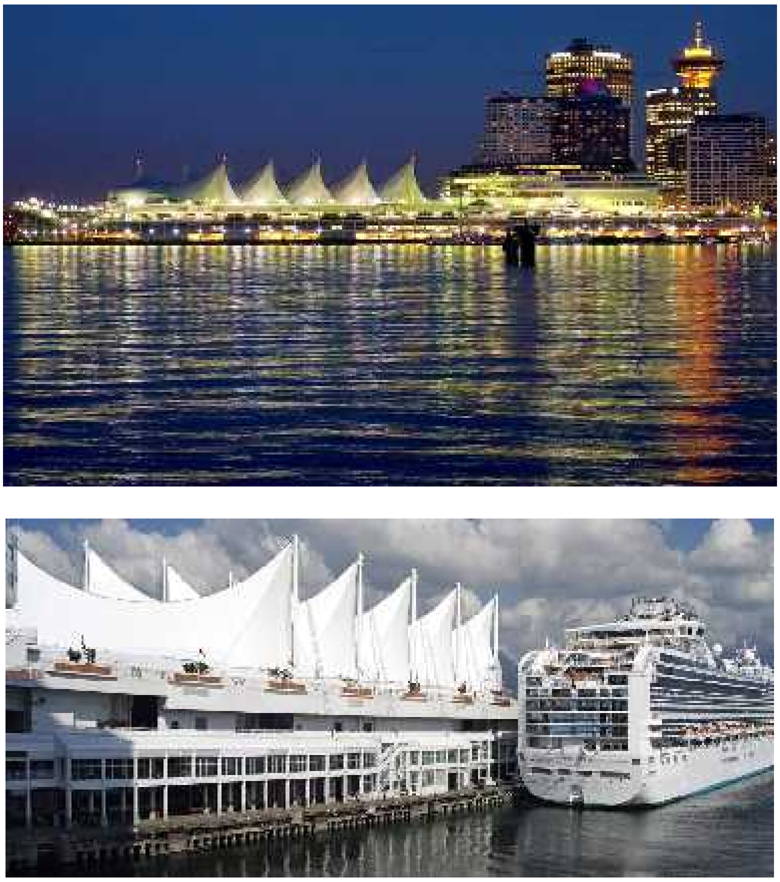

Figure 2.11 Canada Harbor place

This feature jointly with the peaks of the end-supported structural system gives the constructing its drama. It has become a symbol of the city. The structure has a clear span of 55 m and a length of 100 m. An inner liner fabric provides insulation and sound control [69].

2.4.10 Georgia dome

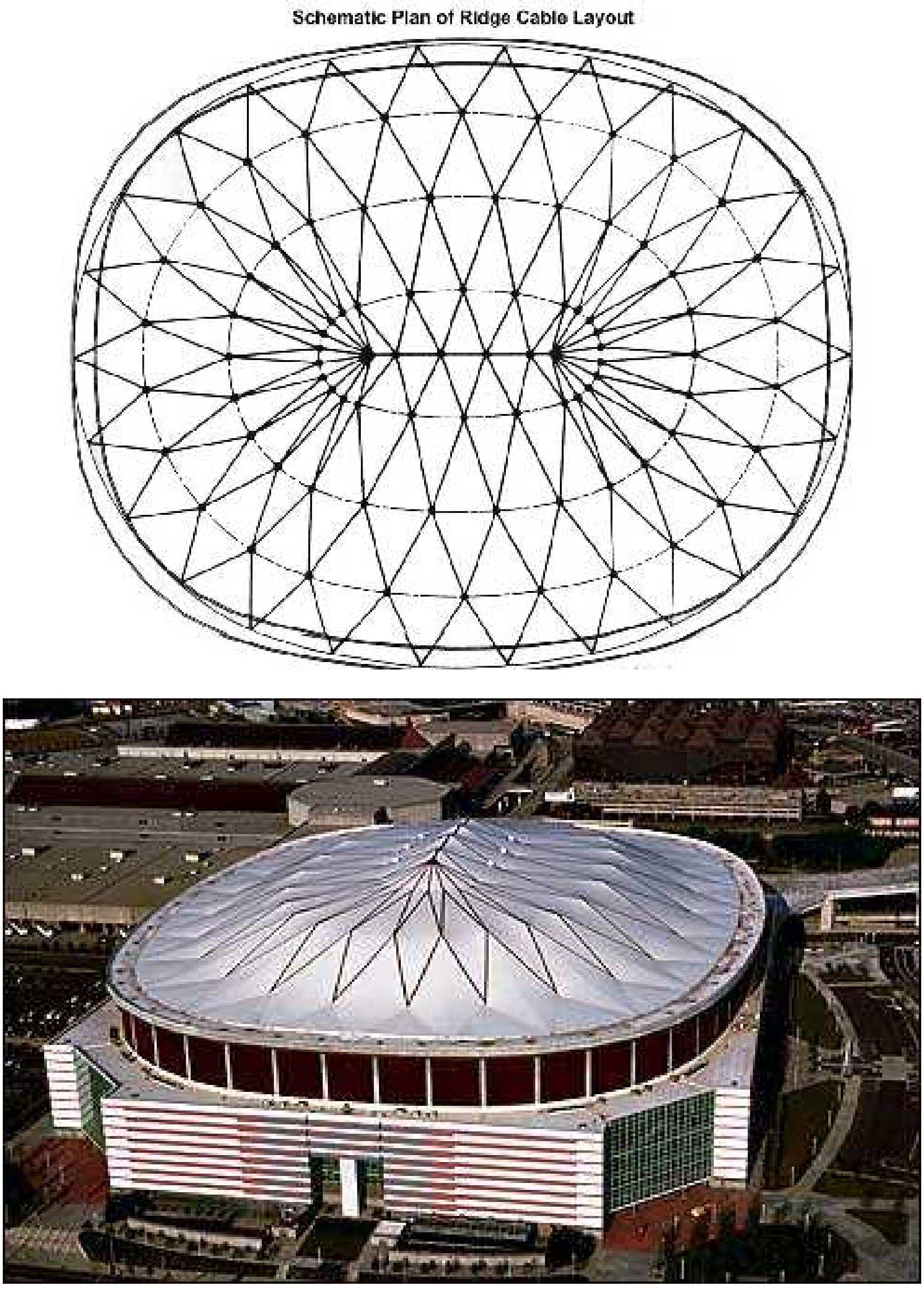

Figure 2.12 Georgia dome

The Georgia dome is shown in Figure 2.12, became the largest cable-supported fabric roof of the world. Stretching more than 395000.0 ft^2 , a Teflon-coated Fiberglas fabric roof is quite an engineering marvel. The roof weighs only 68 Ib, but it is strong enough to support a fully loaded pickup truck. How? The answer lies alongside a frank engineering breakthrough, one that architect- builder Buckminster Fuller dubbed “tensegrity” . Locale plainly, tensegrity is a convoluted sequence of triangles. Short, vertical posts hold the heaviness of the Georgia dome roof. The posts are grasped in locale by prestretched cables, attached to the top and bottom of every single post alongside steel pins and welded connections. The cables pull on the posts alongside equal power in all orders to form forceful, taut triangles. The cable rooftop is safeguarded to a underpinned concrete ring alongside the perimeter of the dome. The 2750.0 ft concrete ring rests on slid-bearing Teflon pads that permit the rooftop to flex somewhat across elevated winds. It is the precise dance of pulling and shoving that allows tensegrity roofs like the Georgia dome to soar for above the stands and the playing field below Here’s how this dome stacks up against some of the biggest domes in the world [70].

2.4.11 Stadium roofing for the Turkish soccer club Fenerbahce Istanbul

The supporting structure of stadium roofing is normally standing outside the stadium itself. Due into a tight traffic situation concerning a Fenerbahce stadium as shown in the Figure 2.13. That was impossible. Then the decision was possessed till do without some of the preceding 32000 seats and make use at an internal supporting structure and build four large concrete towers on the corners, that tower good above the seating area. These corner pillars, each with a surface of some 100 m^2 are the supports of the primary supporting structure for the roofing: the dimensions for the steel framework are 156 m on the longer sides by 123 m on the shorter sides, a four-belt carrier with a height of some 12 m.

These membrane which is at the normally curved structure consists of coated polyester fabric. It stretches amid round steel cantilever girders alongside the diameter of 400 mm that can be unhitched upwards and downwards alongside steel cables employing rising forces. The membrane will firstly be welded jointly from individual flawlessly fitting widths and afterward grasped as a finished earth and assembled by crane.

Figure 2.13 Stadium roofing for the Turkish soccer club Fenerbahce Istanbul

Consequent to their material and construction, membranes are less liable to vibration and therefore perfect of earthquake areas. Because achieve optimum earthquake protection, whole bearings within the construction are made you elastomeric bearings and are completely reversible after changes in strain, in other words they take on their original form. On top of these, special earthquake bearings are installed at the important points, so-called lead deformation bearings who can take deformation due to the relatively soft material such as opposed to rigid bearings [71].

2.4.12 Grandstand roofing for the Formula One race course in Istanbul (Turkey)

A grandstand area of more than 30000 spectators for an area approximately 17000.0 m2 was completed right at time of the first Formula One race in Istanbul such as shown in Figure 2.14. The roofing depend of 54 filler wall elements spanned via membranes, each for a size of 9.16 x33.5 m2. Due to the low design weight of the textile membrane, the roof structure could be given the light and filigree design despite its free overhang of approximately 30 m. Two large high-point canopies were constructed for the roof terrace areas at the two 25 m tre-high VIP towers. The membranes that are made of plastic coated polyester fabric both have a diameter is approximately 30 m, thus each covering an area of approx. 800 m^2. The Istanbul facility has a pair of VIP towers, each having 37 m. height, 7 storey, settled on 1.056 m^2 each area and total settlement area of 7392.0 m^2 each and two storey paddock buildings, having 11888.0 m^2 of seating area and 32616.0 m^2 of usage area.

Figure 2.14 Roofing of stands, Formula 1 ring

Designed by Orion Istanbul and Teschner, Kosel Germany architecture offices, the structure is a vast and beautiful and is the first main remarkable and the biggest tensile membrane structures in Turkey [72, 73].

2.4.13 Members of the Medina Haram Piazza project

Al-Masjid al-Nabawi is one of the biggest mosque on the world Located in a Al Madinah al-Munawwarah of Saudi Arabia, a Islam’s is the second holiest mosque built by the Prophet Mohammed. Over the centuries, because of increasing swell of Hajj pilgrims Al-Masjid al-Nabawī was enlarged. Bad climate in the summer which temperature exceeding 120 oF the radiation of solar and rain in the winter season affects swell of Hajj pilgrims. To such an exceptional situation, there had to be an exceptional solution and German designers, SL-Rasch, in collaboration for SEFAR Architecture came up with an ingenious way that improved the mosque’s natural micro climate.

Figure 2.15 Members of the Medina Haram Piazza project

without destroying its architectural character. At the November 2010, the largest umbrellas built up to that time, each almost being 20 meters tall. Umbrellas named the members of the Medina Haram Piazza project as shown in the Figure 2.15, Saudi Binladin Group (SBG) are the general contractor, Saudi Arabian Ministry of Finance is the customer, SL-Rasch is the architect, German umbrella manufacturer Liebherr and Japanese manufacturer Taiyo Kogyo. These umbrellas work together to constitute the convertible roof shading with a total of 143,000 m2, that to provide pilgrims with optimal shade and environment, the high tech sunscreens are made of a special material named PTFE fabric, used to give resistance for the aggressive solar radiation, and the material has an extremely high tensile strength owing to wind load, colorfastness, fire resistance, maximum flexibility, as well as efficient shading and suitable the light transmission. The affects of umbrellas was decreased at least 8°C. Characteristics of umbrellas in details as below:

- Type: suppression umbrella.
- Dimensions: Umbrella when height closed 21.7 m, while opened 14.4 m or 15.3 m,
- Weight: 20 tons.
- Materials: Peak yield steel structure, 700 g open weave PTFE membrane.
- Cladding: glass fiber settled complex panels, glass mosaic surface.
- Drive by: Electrical drum spinning wheel drive.
- Time taking for opening: 180 seconds.
- Completion of maniufacturing: 2011.

CHAPTER 3

THEORETICAL ANALYSIS OF TENSILE STRUCTURE

3.1 Introduction

Instituted constructing design involves the meaning of initial parameters such as member sizing and spacing, the analysis of these members below applied loads, and then the adjustment of the initial parameters below strength or displacement limitations. This procedure normally needs a insufficient easy iterations and can be finished with classical (and frequently linear) analysis methods. Furthermore, as the majority of buildings in the last century have been projected in this method, the behavior of standard constructing systems is well understood and documented. A design and analysis for tensile membrane structures, at the other hand, differs greatly from this traditional procedure, possessing a new set of design loads and considerations. Because initial geometry parameters can change so drastically, their analysis frequently needs several iterations with newer computational methods. In fact, the overall from of a tensile membrane structures changes so much that this process is commonly referred to as “shape” or “form” finding [74].

This chapter begins with general considerations of a design for tensile membrane structures and then explains the basics of how tensile membrane structures work. The rest of the chapter presents and discusses the design procedure and assorted numerical methods obtainable for their analysis.

3.2 Design of Considerations

As remarked above, the design of tensile membrane structures comes with many considerations that demand not be made for conventional structures. These contain certain load and meteorological conditions, availability of material and labor, acoustic performance, fire protection, energy use and lights, as well as material maintenance, durability, and inspection [74].

3.3 Mathematical work of tensile membrane structures

Standard structures depend on gravity and inner rigidity for load transfer and for stability. Beams and columns in these constructions can resist axial, shear, and bending stresses. Fabric structures, on the other hand, are so lightweight that gravity does not have any weighty effect. Furthermore, fabric elements transfer all loads axially, as they have negligible bending and shear stiffness. They consequently gain stability from their curved form and inner axial prestressing alone.

As remarked beforehand, the basic structural element of a fabric membrane is set of cables running in perpendicular directions. Discussing the behavior of a single cable can consequently aid to illuminate certain behavioral properties of a fabric membrane. To better understand this behavior, first consider the uniformly loaded beam and it's bending moment diagram in Figure 3.1.

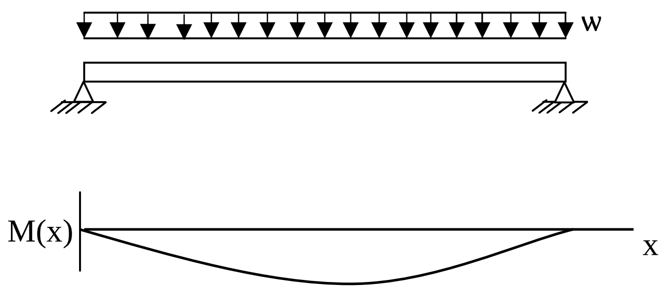

Figure 3.1 Uniformly loaded beam and moment diagram

The form that a cable takes below this alike load is believed optimal because it follows the bending moment diagram. After considering a cable’s self weight only, the shape it takes called catenary (although this term is often used when describing the natural form resulting from each requested load). Because a cable cannot resist shear and bending, it will consequently deflect in such a method as to hold requested loads in axial tension only, all the as acting so with much less material than a straight beam below the alike loads. Nowadays consider the uniformly loaded cable and deflected shape in Figure 3.2 *w* is the load per unit length, *L* or *S*(span) is the finished length of cable, *h* or *d* is the maximum vertical deflection at midspan, and *H* and *V* are horizontal and vertical reaction forces, respectively [74].

The parabola curve occurs between two supports at a uniformly loaded cable the curve intermediate give largest distance, that can be made approximate circular *arc* (of radias *R*).

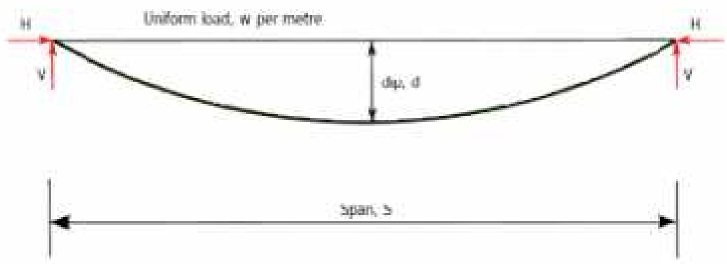

Figure 3.2 Uniformly loaded cable

The vertical and horizontal reactions:

$$V = \frac{WL}{2} \tag{3.1}$$

$$H = \frac{WL^2}{8h} \tag{3.2}$$

Length of the cable:

$$L = 2R \arcsin \frac{S}{2R} \tag{3.3}$$

Tension in the cable:

$$T = F = \sqrt{H^2 + V^2} \tag{3.4}$$

Also tension is equal:

$$T = WR \tag{3.5}$$

Sum of the moments about any point will be equal to zero, and bending resistance cannot be occurs in the cable:

$$\sum M_{midpoint} = 0 \tag{3.6}$$

$$H(h) + W \cdot \left(\frac{L}{2}\right) \cdot \left(\frac{L}{4}\right) - V\left(\frac{L}{2}\right) = 0 \tag{3.7}$$

The Hooke's Law, a axial stiffness, *k*, and the extension for the cable on the being loaded is equal to:

$$k = \frac{EA}{L} \tag{3.8}$$

$$e = \frac{TL}{EA} \tag{3.9}$$

Where the E is a Young's modulus of elastisity in the cable, and A is the cross-sectional area of cable.

The extension after added an initial pretension, T_o, to the cable becomes,:

$$e = L - L_o = \frac{L_o(T - T_o)}{EA} \tag{3.10}$$

The equations above after combining gives:

$$\frac{L_o(T - T_o)}{EA} + L_o = \frac{2T \arcsin\left(\frac{wS}{2T}\right)}{w} \tag{3.11}$$

By drawing a left hand side and the right hand side of this equation against *T*, in a actual equilibrium tension of the cable in the intersection will give from a given loading *w* and the given pretension T_o. As shown in Figure 3.3. Central point load in the cable:

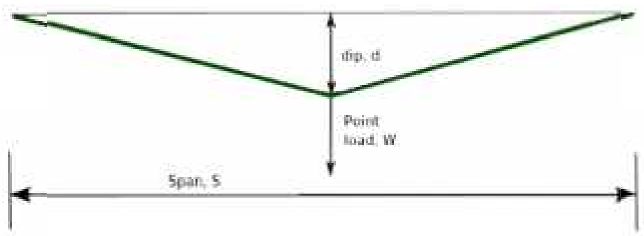

Figure 3.3 Load diagram of Uniformly loaded cable

The similar solution of the above can be given as:

$$W = \frac{4Td}{L} \tag{3.12}$$

$$d = \frac{WL}{4T} \tag{3.13}$$

From geometry:

$$L = \sqrt{S^2 + 4d^2} = \sqrt{S^2 + 4 \cdot \left(\frac{WL}{4T}\right)^2} \tag{3.14}$$

The following relationship is given:

$$L_o + \frac{L_o(T - T_o)}{EA} = \sqrt{S^2 + 4 \cdot \left(\frac{W\left(L_o + \frac{L_o(T - T_o)}{EA}\right)}{4T}\right)^2} \tag{3.15}$$

As plotting above the left and right hand side for a equation against the tension, *T*, will be present a equilibrium tensile of the given pretension, T_o and load, *W*.

A natural frequency fundamental of tensioned cables, f_1, is given as:

$$f_1 = \sqrt{\frac{\left(\frac{T}{m}\right)}{2L}} \tag{3.16}$$

Where: *m* = mass in kilograms, *T* = tension in newtons and *L* = span length in meter.

One can seen from cable expressions that the sag or vertical deflection of a cable varies with the horizontal reaction force. This is the idea behind pretensioning in fabric membranes. Adjusting the horizontal tension force is the primary limiting membrane deflection. Vertical "pins" is the also applied load (typically rigid supports such as mast or metal frames).

Depends on inner pre-stressing and boundary conditions, fabrics can either negative Gaussian curvature with form in to the anticlastic form or positive Gaussian curvature with the synclastic shape. These term anticlastic leads to a opposingdirections of perpendicular fiber element. Form A saddle as shape joint together, this elements exert equal forces for every single supplementary and internally brace opposing themselves. Synclastic forms contain for elements which are arced on a same direction such as a balloon. At the design for tensile membrane structures, upwardly curved elements are normally named “ridge” cables as downwardly curved ones are “valley” cables.

The anchor points in the minimum number of requirement of each section of a fabric is four. Three points are insufficient because the generated surface is the simple, flat triangle; as remarked on the previous discussion concerning cables fabric elements gain stability with curvature. A four point structure is consequently the most basic element of a tensile membrane structure. It can be created with and endless number of boundary conditions and joined together to make the collection for interesting forms and patterns.

3.4 Procedure of Design Tensile Membranes

Figure 3.4. Shown the description to a tensile membranes design procedure, which started from an initial preliminary sketches and finished in the realization of the structure. Many tasks required at the be completed to achieve the final structure [76].

Architects and engineers are implicated on the study of tensile membranes structures [77,79]. Mainly articulating, architects tent to focus in the geometric form and external emergence for a membrane, as engineers are extra distressed with the inner stress distribution at a membrane and the viability of it manufacture. Both procedure are directly related each other, as the geometric shape for a membrane depends in a given initial prestress at a membrane.

Figure 3.4, shown schematically design procedure of the tensile membrane method in that architects and engineers work's together.

- A first steps of the design procedure are a task usually shared by the client and their architect together. The architect establishes the client’s needs, for example the region to cover, height clearance and data concerning the location of the upcoming structure. It is vital that the architect sketches the three dimensional shape of the structure pondering all the necessities and some aesthetic criteria. For example the geological and geotechnical data associating to the locale for the structure have to be believed to locale anchorage points and masts. The shape described should provide all topological data on the structure, such as the locale of cables, masts, anchorage points and regions covered by the membrane. Alot of objects and volumes are placed on a selfsame space and different resolutions are proposed untill these desired layout and form are achieved. Furthermore the material kind ought to additionally be selected at this phase. In the case of the materials selection many factors should be considered for example: the needed number of lighting and heat insulation determines the heating requirements.

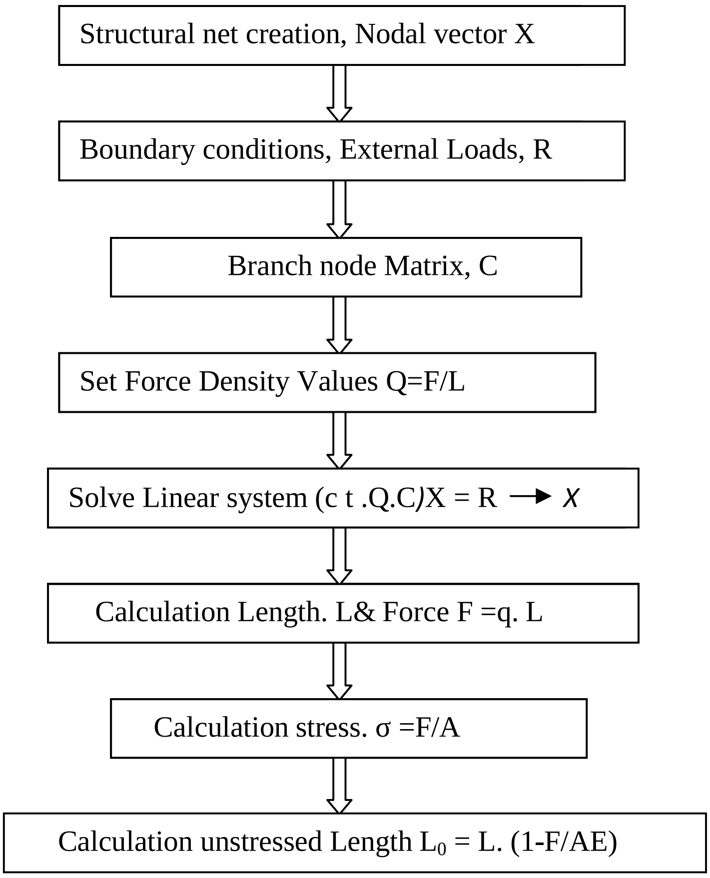

Figure 3.4 Force-density methods

- The conceptual design period is truly the maximum vital on a entire procedure because an initial conditions are described and will be a fundamental from the rest for a project. After a project was started, each change on this initial specifications affects the all project.

- The next step is Form-finding is contain of estimating the equilibrium form of a tensile structure. Many techniques exist to determine a form for the particular membrane [19, 80-82]. Force-density methods are based on linearization techniques [83-86]. Other form-finding procedures include the dynamic relaxation method [32, 87].

  These are different computer instruments based over this methods that support a designer into attain and reach the desired shape, even though most existing computer applications require advanced structural skills, and too a lot of tasks required to be finished before achieving to a final shape. Thus, a design instrument, in which the complete scene is shown (and redrawn) when the user in dragging a membrane vertex via means of a mouse, might be a extremely functional instrument for designers. Currently, there is a lack of design instruments covering this design period, and present form-finding instruments provide only a partial solution to the problem.

- Once a stage for conception has been finished, a static analysis for the structure is carried out. Properties of material are assigned to a membrane, and the stress distribution is estimated under different loads and boundary conditions to the initial shape of the membrane.

- Finally, structure detailing is carried out. These details concerning foundation, masts, clamps, connections, structure supports, selection, cable diameter, plotting and many others are defined at this stage. After detailing is finished, carried out membrane cutting. When the strips are joined, the completed membrane is prepared for the construction of the structure and elevation of the membrane.

3.4.1 Process of Form-finding

The geometrically non-linear problem is occurs from shape analysis of tensile structures, and contain of discovering an equilibrium shape compatible with given prestress conditions. The procedure of calculating these initial equilibrium shape is recognized as form-finding.

Design and analysis for the tensile structures uses for Non-linear methods. A lot of linear methods of form finding have been requested on the past in order to study the behavior of the tensile membranes. The Force Density Method and Dynamic Relaxation Method are the most public methods utilized in the form-finding process. In the present study force density method is used.

Force Density Method: for the linearize of form-finding equations of a tension net used an analytic method. The material properties of the membrane separate from linearization method. The ratio of force-density shown in Eq. (3.17) that relation between cable force and cable length required to be specified of every element, and different proportion give different equilibrium shapes.

$$q = \frac{F}{L} \qquad (3.17)$$

Where, F cable element force, L cable element length and q force-density ratio

Figure.3.4. shown A good description for a force-density method is given on a diagram for a tensile membrane is classified to the discrete number for elements, that are connected together at nodes. The place for the nodes is given via the Nodal Vector (X). Boundary conditions are described, so a some nodes (vertex nodes or edge nodes) could be restrained as others are free to translate. Loads are described by the vector (R).

A branch-node matrix C describes the topological relationship the nodes and the bar elements of the structure net. To linearization of the problem, the force-density ratio shown in the Eq. (3.17) is provided in any net element to associate the tension and corresponding length of respective elements. The constant value is given of the inner elements force density ratios, and different values are given for the boundary elements ratios.

$$\left(C^{T} Q \cdot C\right) \cdot X = R \tag{3.18}$$

Where, *Q* force-density matrix and *X* nodal displacement

These linear system is then solved as shown in Eq. (3.19) and the position for the net nodes (X) is gained. With the nodal coordinates on the net, the force, lengths, stress and the unstressed length into element can be acquired using the following equations:

$$F = q \cdot L \tag{3.19}$$

$$\pm = \frac{F}{A} \tag{3.20}$$

$$L_{o} = L \cdot \left(1 - \frac{F}{AE}\right) \tag{3.21}$$

These way is numerically robust, autonomous for a early locations for a nodes and enables a equilibrium form into be discovered easily. With these linear way it is not probable into has manipulation above an inner prestress for a net [76].

3.4.2 Analysis

Let a linear relation between applied forces and displacement in the analysis models for conventional structures. These linearization can be exactly characterize a structure’s form, but are manipulated into the scope for tiny displacements. But are manipulated into the scope of tiny displacements. Conversely, a design and scutiny of tensile membrane constructions needs a methodically non-linear way, modeling colossal deformation deeds across the use of iterative numerical methods [74].

Analysis of nonlinear structures is a classical approach of the Newton-Raphson method, which does not apply well to behavior of fabric because convergence is slow and sometimes does not happen at all. However, when an initial estimate of shape or geometry is specified the Newton-Raphson works would be better. That direct application of analyzing cable-net and tensile membrane structures are newer analysis methods have been developed. That contain the grid method and the force density method, that are both used to estimate initial system geometries before applying Newton-Raphson method. Dynamic relaxation method is the another nonlinear analysis which may be applied to a tensile membrane structures. The theory behind each of these methods is described in detail in the following sections [88].

Design Loads:

Through several building code stipulate design load requirements, the standards are usually intended for stiff and straight, conventional structures. ASCE is currently adapting their standards for application to tensioned fabric roofs. The following is an explanation of how load considerations will differ for tensile membrane structures [74].

Being much lighter than conventional structural members, tensile membrane roof structures and accompanying cables or ties incur only a small fraction of typical dead loading (generally less than 50 N/m2). For this same reason, seismic loads, which vary with mass of a building, usually do not constitute a serious concern in the design of tensile membrane structures.

Roof live load code requirements were determined based on the assumption of heavy rooftop machinery and other usages that do not apply to a fabric roof. Indeed, with their curved forms and high deformability, fabric roofs are usually inaccessible to people except for maintenance and repair. However, current code provisions do not exempt fabric roofs and they are therefore designed with normal live loads [89].

Wind loads usually control over other types of loading in the design of tensile membrane structures. Though wind load specifications are available in local building codes, the behavior of fabric roofs under wind is unpredictable enough as to warrant the use of wind tunnel testing in many situations. Depending on the direction of wind and geometric properties of the fabric, wind can either act as inward pressure or outward suction, in which case the suction will tend to counteract downward gravity loads.

In some regions, snow and rain will govern over wind loading. The curvature and natural flexibility of fabric membranes can load to a lot of uneven snow distribution.

It is important to note that concentrated loads like high snow drift will often be more critical than large uniformly distributed pressures. Melted snow or rain also tends to pond in the downwardly curved sections of membrane. For this reason, drains and snow melting techniques are often incorporated in to their design [90].

In general, temperature loads do not affect tensile membrane structures.

Tangent Stiffness Method:

Structural fabric exhibits large deformation and geometrically non-linear behavior. Because of this, it requires different methods of analysis, which tend to be numerical and iterative. The following describes the theory behind the tangent stiffness method (sometimes known as the transient stiffness method), which derives from the linear stiffness method discussed in the previous section.

The main reason that linear methods do not apply for large deformation is because the stiffness matrix depends on initial member geometries. When the members in a system deform by a significant amount, the stiffness matrix for the system will also change. The tangent stiffness method attempts to account for this discrepancy in the following way.

Begin by defining initial geometry vector, {X} I on which initial stiffness is based.
The displacement resulting from this initial stiffness will be:

$$\{\text{¢}\}_{i+1} = \{K\}_i^{-1}\{P\} \tag{3.22}$$

And the new system geometry is:

$$\{X\}_{i+1} = \{X\}_i + \{\text{¢}\}_{i+1} \tag{3.23}$$

From this updated geometry, one can find a new stiffness matrix; $\{K\}_{i+1}$. This stiffness combined with displacement will yield a set of internal forces, $\{P_{in}\}$ which differ from the set of external forces.

$$\{P_{in}\}_{i+1} = \{K\}_{i+1}^{-1}\{\text{¢}\}_{i+1} \tag{3.24}$$

For large displacements, $\{P_{in}\} \neq \{P\}$. Define an error term or residual, $\{R\}$ and then an incremental displacement vector, $\{\Delta\delta\}$:

$$\{R\}_{i+1} = \{P\} - \{P_{in}\}_{i+1} \tag{3.25}$$

$$\{\Delta \text{¢}\}_{i+1} = \{K\}_{i+1}^{-1} - \{R\}_{i+1} \tag{3.26}$$

At this point, the geometry vector is updated by the incremental displacement vector and more iteration can be performed until the residual vector converges on zero [74].

3.4.3 Detailing

Before the structure can be built several details should also be considered and designed for example:

The type of connections between different parts of the structure, gutters, water control systems and supporting structure as well as methods of fixing and anchoring cables. The above list is not exhaustive and it may vary from structure to structure. For example the connections may require special attention from the design engineer. Most of modern cable-membrane structures are complex and visualization and virtual reality models can be very helpful in the design process. Well designed connections ensure the smooth flow of the loads from one component to another of the structure. Therefore particular care is required during the component design of fabric-fabric, fabric-rigid edge, fabric-cable and cable-cable connector as well as cable-mast or rigid edges [13].

CHAPTER 4

EXAMPLES OF DESIGN

Two example problems which used in this chapter. These example problems are studied using commercial software FORTEN 2000. To demonstrate the different aspect of the computer-aided design of tensile membrane structures, such as: from-finding, and analysis. Both examples is Sunshade Lodge used once in shopping park second in car Park, as shown in the Figure 4.1.

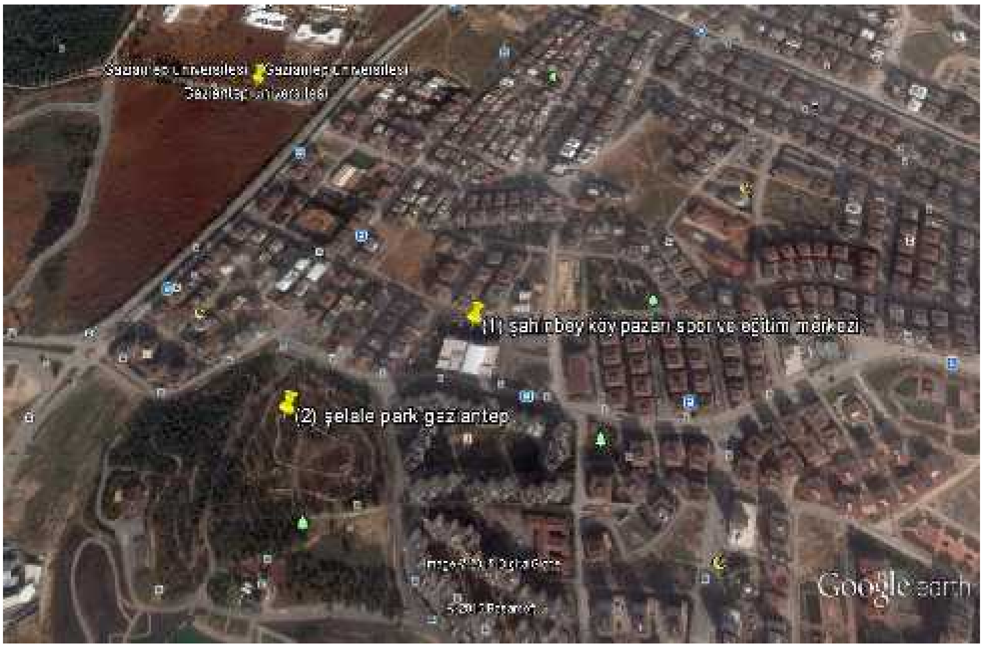

Figure 4.1 Location of two examples in Gaziantep

4.1 Sunshade Lodge in shopping park

Figure 4.2 - 4.3, shown the first case study deals with the sunshade lodge in shopping park in şahinbey municipality village market sports and training center. The estimate

area to be covered is approximately 100 m^2. It should be well designed structural forms and reflect the shopping park image.

Figure 4.2 Shopping park layout plan

Figure 4.3 Village market sports and training center

This structure should also become very attractive architectural landmarks and must offered wonderful design and structural efficiency. The sunshade must be departed from traditional constructions in order to emphasize the leading image of park. Because of their uniqueness and originally, tensile membrane structure which can attract extra attention to people is selected. The sunshade lodge must protect the people from sun and rain.

4.1.1 Conical shape with middle mast

In this case we will make a conical shape with a middle mast that can be analyzed in the nonlinear module. In this times require lighter, most energy-economy, more dynamic and more adjustable, on short natural buildings, without disregarding the instance of safety and security. How to make good more with minimal, while is, minimum material and effort? Structural elements in designs have the modern constructing type capable of uncommonly big spans from traditional structures. Tension structures envisioned for extreme lightness as well as extreme strength, that were into make optimum use for new materials like thin cables of high-strength steel or thin membranes for synthetic fabric.

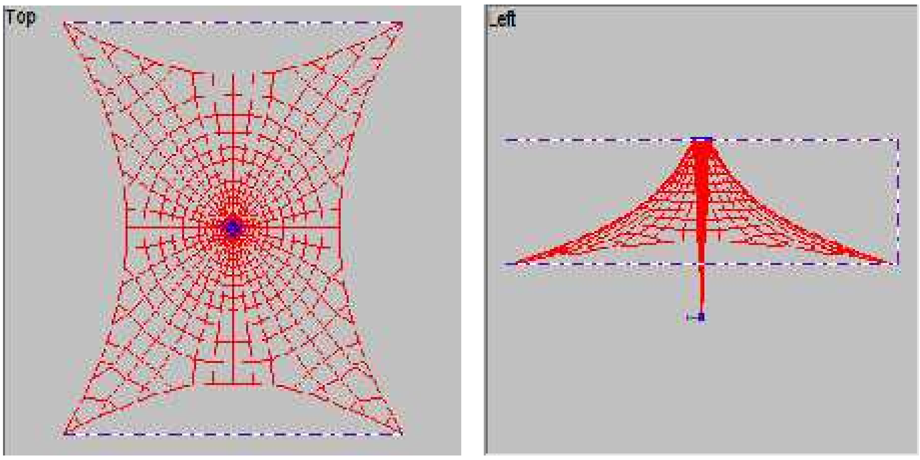

Figure 4.4 Conical shape with middle mast

A novel tensioned membrane structure for as a conical shape with middle mast form structural system have been studied. Basic design concept, form finding procedures to create various structural forms are explained below.

In this present study, a conical shape with middle mast in figure 4.4. Is taken as a model for conceptual design. The conical shape structure is formed with a middle mast that are the inclined arches, the cables or struts, and the membrane. A key concept for a structure is into use inclined arches into shape of a membrane boundary.

4.1.2 Form-finding

The arches, cables and beams are made of steel and PVC is selected as membrane material. The material properties of steel and PVC are as follows:

- Characteristic of PVC (isotropic material): E_{warp} = 44000 kg/m, E_{weft} = 39000 and density ρ = 0.9 kg/m^3.
- Characteristic of Steel: modulus of elasticity E = 210 GPa, Possion ratio ν = 0.3 and density ρ = 7800 kg/m^3.

The cable has a 16 mm diameter and a 157 mm^2 cross-section area. The cross-sectional dimension of steel tube which is used in arches and beams is shown in Figure 4.5.

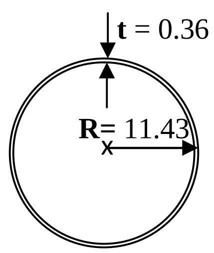

Figure 4.5 The cross sectional dimension of steel tube

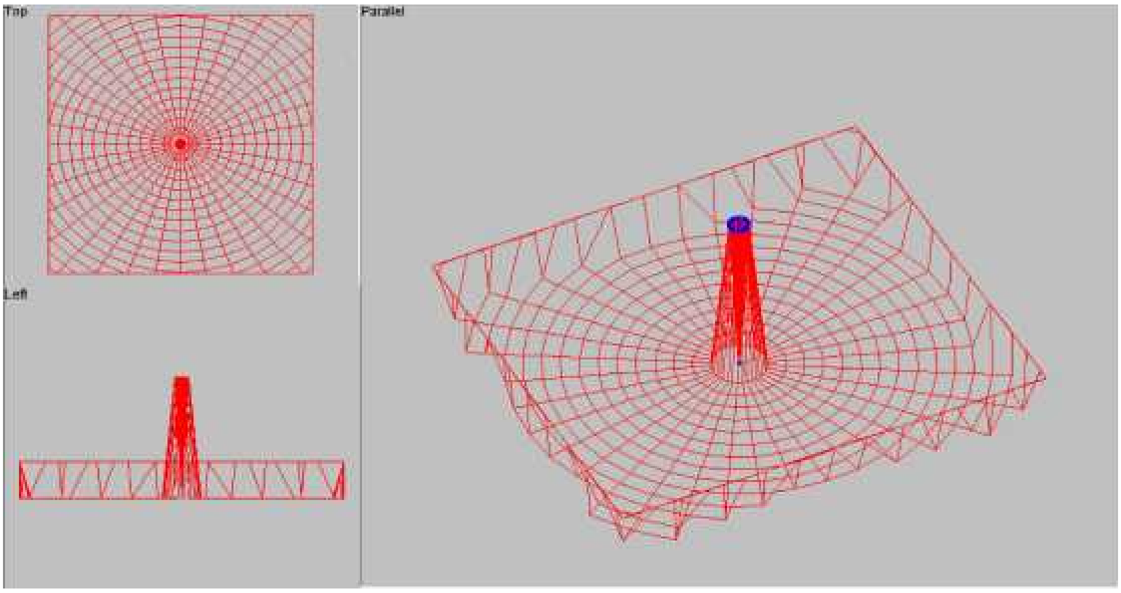

Figure 4.6 The boundaries and meshing for form finding

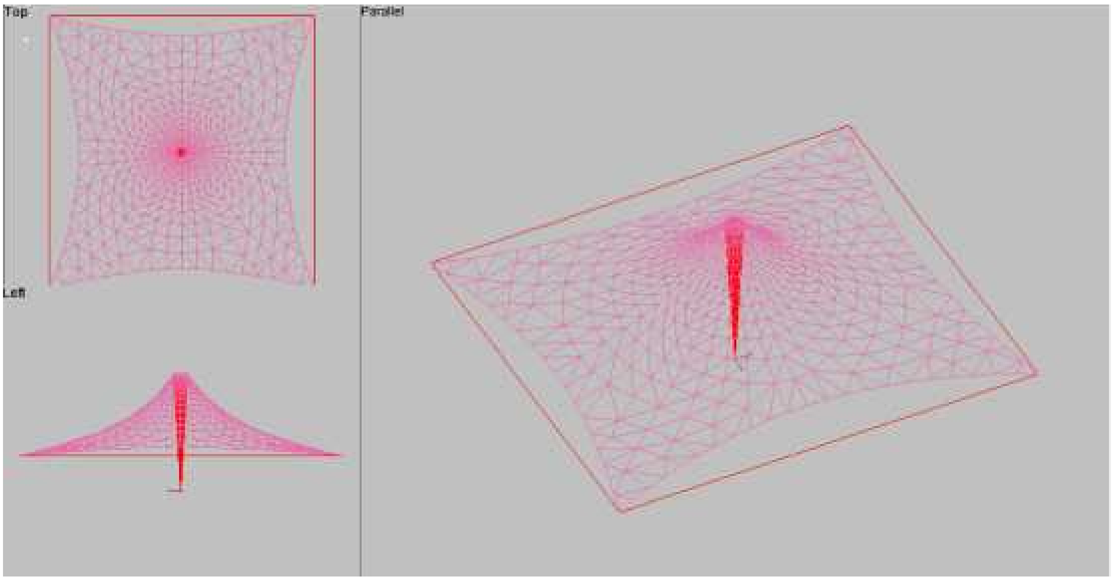

Figure 4.7 The general view of structure after form finding

The finite element meshing is made up for square membrane elements to model the fabric. Linear cable elements to model cables and linear beam elements to model beam and arches. The fine mesh is used in order to minimize the computation error. The hoops and fabric tips connected to the structure are considered rigid. For the boltropes, it is assumed that there is no slippage between the cable and the fabric. The meshing for form finding is presented in Figure 4.6.

The form finding is performed by defining various initial prestress values for fabric (in warp and weft direction) and cable. After so many trials, an initial prestress of 75 kg/m,in warp and weft direction , is used to the fabric. The prestress value applied to cables is equal to 20 kN/m. The force density method is used into define the form in initial equilibrium.

Figure 4.8, shows the major stress distribution (σ11) in the initial configuration. Under the action of the prestresses, a maximum value for stress that equal 21 N/mm on areas around the hoops. It is too noticed that a smooth appearance is obtained at the surface of the conical shape structure.

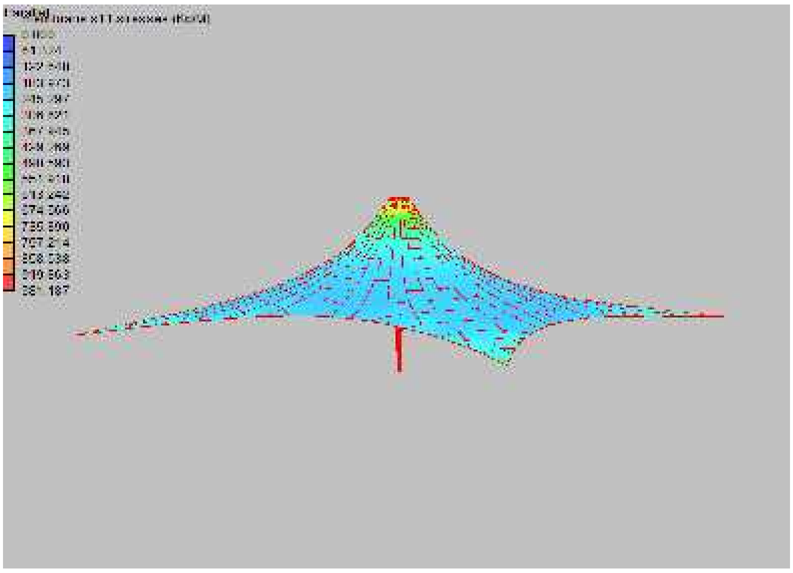

Figure 4.8 The membrane stress of form finding for Cable-nets and cable-beams

4.2 Sunshade Lodge in car Park

The second case study deals with the sunshade lodge in car park. The estimated area to be covered is approximately 100 m^2 .

The sunshade lodge in car park should be well designed structural forms and reflect the park image. The structures are designed so that the fabric can be removed if there is danger of a hurricane. This structure is selected to cover areas at very competitive costs per unit area. The sunshade lodge must protect the people and car from sun and rain.

4.2.1 A Simple Conical surface design

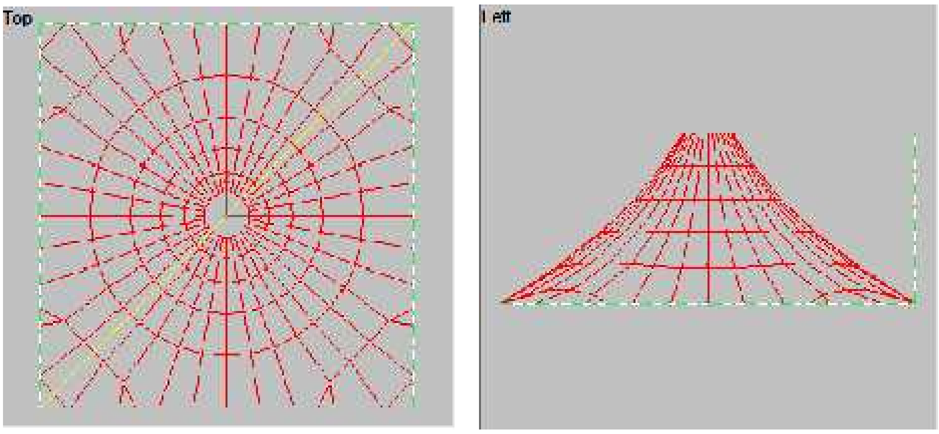

Figure 4.9 A simple conical surface design model

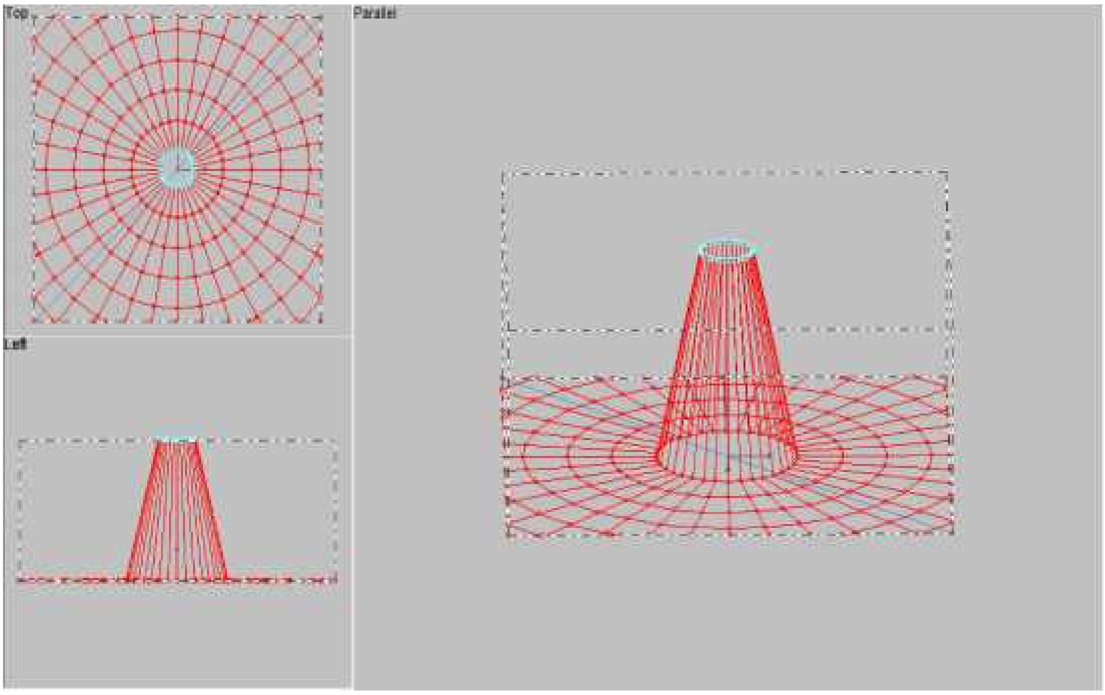

Figure 4.10 The Boundaries polar mesh before form finding

In this design, the sunshade will do a classical conical shape and try some new features for placing the middle ring of the cone where required. To keep things simple again we will not deal with the steel structure that keeps the ring in place.

4.2.2 Form-finding

The conical surface are made of steel and PVC is selected as membrane material. The material properties of steel and PVC are as follows:

- Characteristic of PVC (isotropic material): E_{warp} = 44000kg/m, E_{weft} = 39000 and density ρ =0.9 kg/m^3.
- Characteristic of Steel: modulus of elasticity E =210 GPa, Possion's Ratio v = 0.3 and density ρ =7800kg/m^3.

The finite element meshing is made up of square membrane elements to model the fabric and linear beam elements to this model. The fine mesh is used in order to minimize the computation error. The hoops and fabric tips connected to the structure are considered rigid. The meshing for form finding is presented in Figure 4.11.

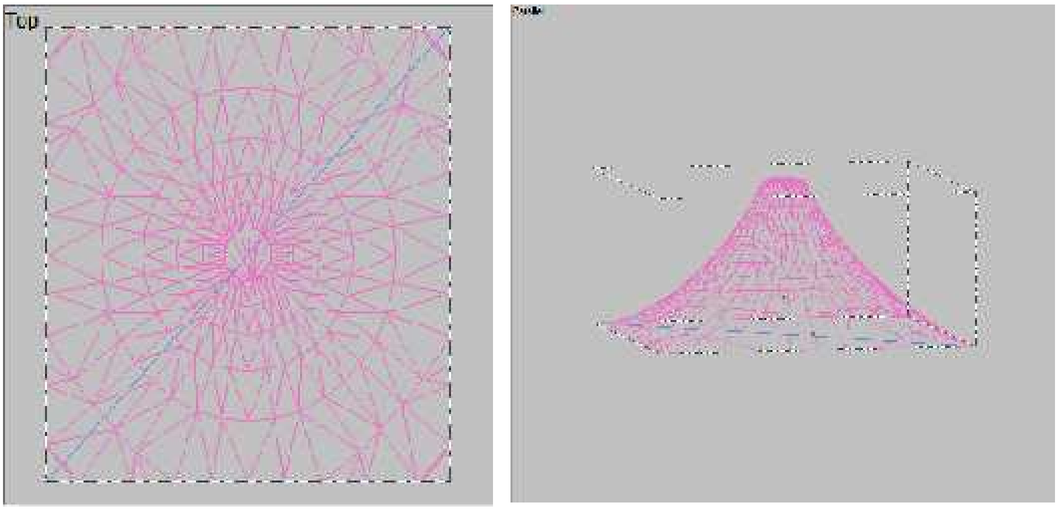

Figure 4.11 The boundaries and meshing for form finding

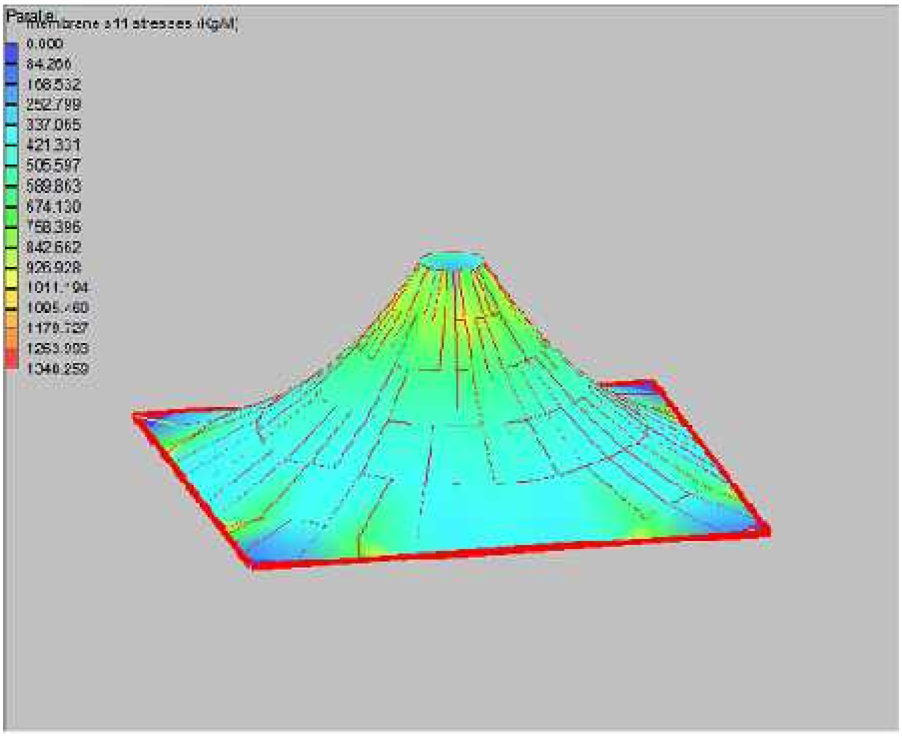

Figure 4.12 The membrane stress of form finding for boundary tensioned membranes

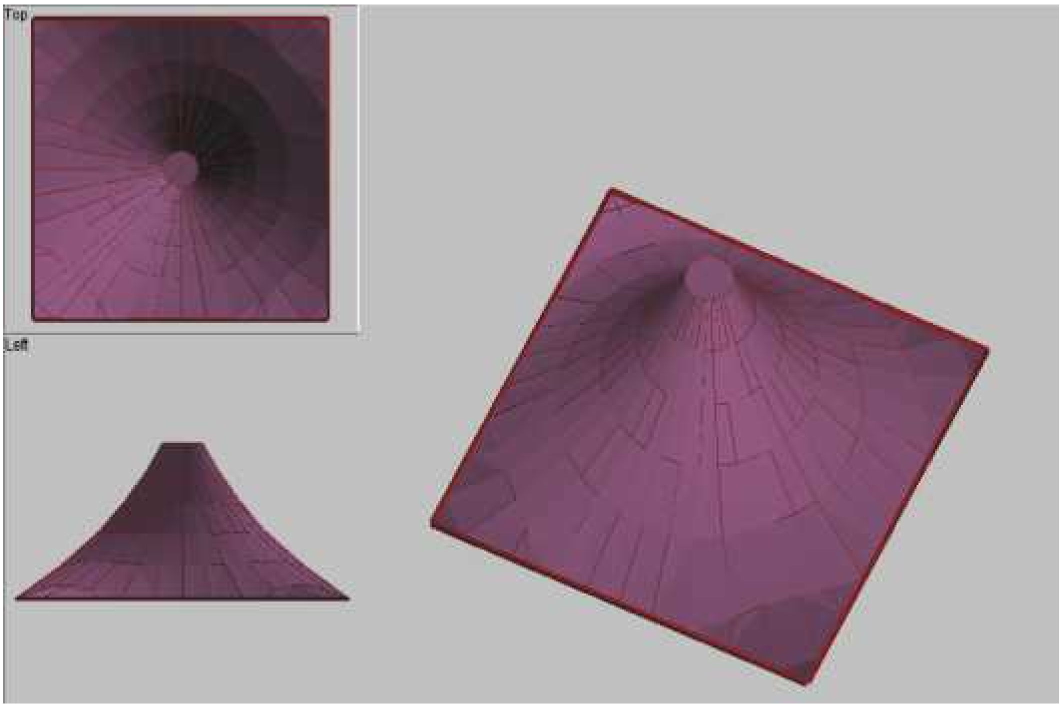

Figure 4.13 Boundaries and Shaded after form finding

The form finding is performed by defining various initial prestress values for fabric (in warp and weft direction). At this stage we will use a useful command to keep the geometry but change level of prestress. It is clear from the stress plot that we have a mean level of prestress of about 4.3 kg per centimeter. We want a lower level of prestress to 1.5 - 2 kg per centimeter but the geometry must be intact.

4.3 Pneumatic structures

A pneumatic construction is a membrane construction that is upheld by inner air pressure from fans, blowers, or compressors. It is a arrangement of interrelated constituents growing a fused finished to finish the goal of bestowing shelter. Pneumatic constructions are normally hemisphere or half-cylinder shapes. The two main kinds of pneumatic constructions are air-supported and air-inflated. Air-supported constructions have air somewhat higher than meterological pressure upholding the envelope from underneath. Airlocks or revolving doors aid uphold the inner pressure. Air-inflated constructions have air below elevated pressure filling merely the upholding construction or panels.

There are a number of gains to pneumatic constructions encompassing a expansive collection of uses, light heaviness, lack of inner supports for colossal spans, transparency to light and wireless waves, and low-cost. The disadvantages contain the demand for constant maintenance of inner pressure, meteorological conditions susceptibility, and shorter lifespan than standard buildings.

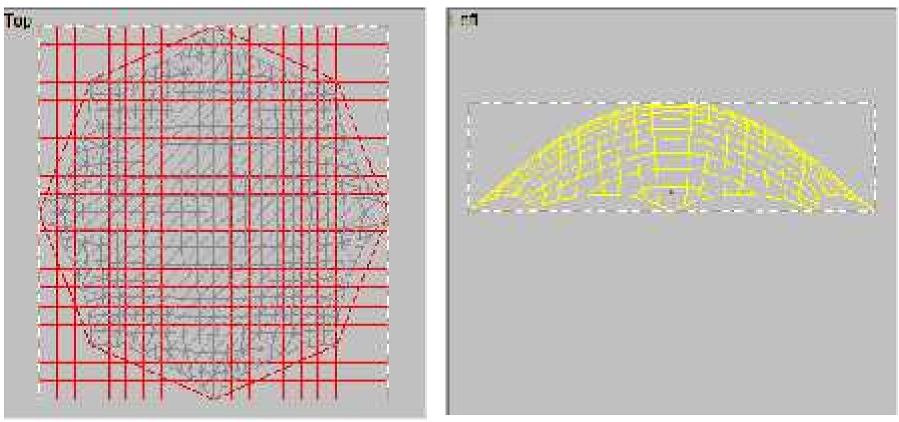

Figure 4.14 Pneumatic structure design model

Pneumatic constructions are exceedingly reliant on the HVAC arrangement for crafting the inner air pressure. In this case we seize a easy pneumatic construction display in Figure 4.14.

- **Form-finding**

Our design is made of steel and PVC is selected as membrane material. The material properties of steel and PVC are as follows:

- Characteristic of PVC (isotropic material): E_{warp} =44000kg/m, E_{weft} =39000 and density ρ =0.9 kg/m^3.

- Characteristic of Steel: modulus of elasticity E =210 GPa, Possion's Ratio ν = 0.3 and density ρ =7800kg/m^3.

The finite element meshing is made up of square membrane elements to model the fabric and linear beam elements to this model. The fine mesh is used in order to minimize the computation error. The hoops and fabric tips connected to the structure are considered solid. The meshing for form finding is presented in Figure 4.15.

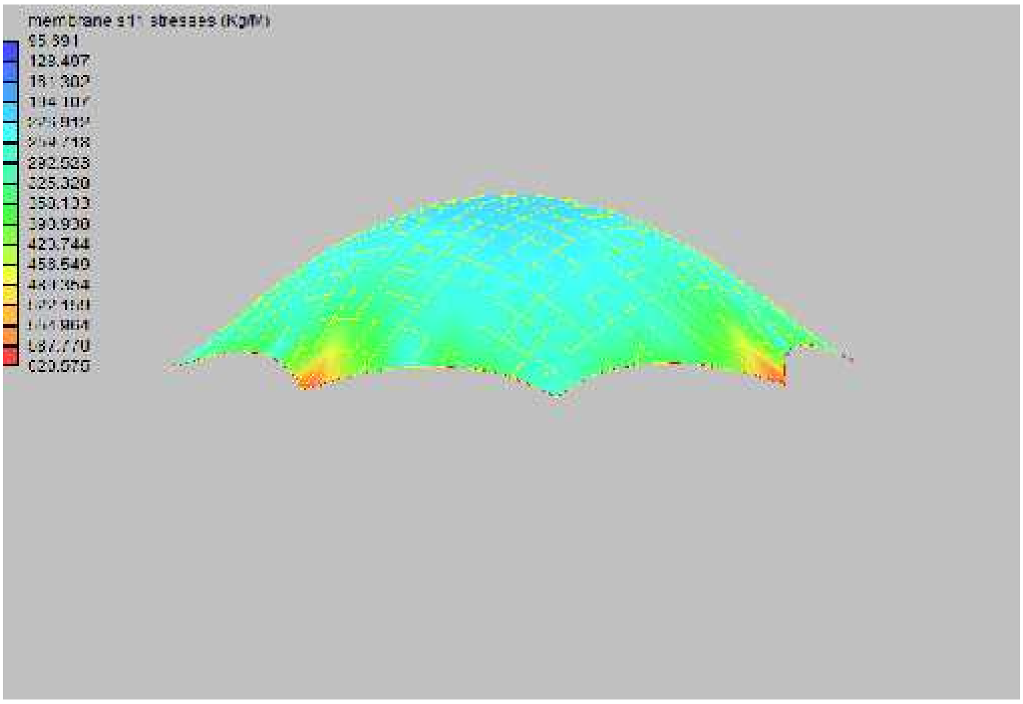

Figure 4.15 Membrane σ11 stresses in the pneumatic dome

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The development of the software for a engineering analysis of tensile membrane structures are the key points and in the design process should not take place any limitations, would integrate computer aided geometry design, should have a clear physical analogy, structural analysis and optimization methods, and most importantly, should be fully understood by the engineering.

- The model presented in this study, which can be established and install at any place on the world, which take place as useful, good quality and economical roofing system. A FORTEN 2000 program is used to to solve and reach to the tension load and bending moment in the structure of thes roofing system. Tensile membrane structures added a new chapter on a historical for building structures. Afford very little weight able of spanning large distances with the structure support, growths into the design for tensile membrane structure may be dramatically change the method we conceptualize permanent building construction.

- Tensile membrane structure is the analysis of computational method and building methods coming the long road since into a first modern fabric structure has built fifty years ago, there are still some challenges should be overcome before tensile membrane structure can be considered a viable option of a majority for new building projects and the modren design.

- An advent for computer technology changed tensile architecture for ever. The possibilities of accuratly calculating form and values for ever more complicated project proposals opened the door to an architectural language which we are still embracing end expanding to this day. Since then there has been a steady procession of projects which have pushed the boundary of this technology.

- The design and analysis process is perhaps the most limiting factor in the implementation of tensile membrane structure. Exhibiting highly nonlinear behavior, the behavior of fabric under applied loads is often difficult to understand and to model. Beginning with simple fabric models in the days of Frei Otto at the Institute of Lightweight Structures, analysis theories and methods have adapted into complex computational capable of quickly and accurately determining the form and behavior of a fabric membrane.

- In this study of this thesis, tow tensile membrane structures are designed using new commerical software. The program used in this study is quit simple into generate and modify forms at the exact time, assign material, loads or modify the boundary conditions for a design. That designer can get accustomed to the application in very small time. However, program has certain limitation and does not have any optimization module.

- Fabric materials and their associated properties tolerate to change to new and interesting problems. Nevertheless they display drawbacks such as low durability due to UV degradation and fire confrontation, they tolerate to enhance in tensile and ripping strength capacities. Furthermore, increased light transmission and translucency permit for higher power savings, a thought that is pending ever extra vital to the green constructing industry.

- Small adjustments to the dimensions or specifications of a fabric construction normally consequence in main or finished redesign. Tensile membrane constructions need countless considerations, after projected each adjustments to tension form need main and expensive redesign. Unlike standard constructions, fabric constructions do not permit adjustments at each point in the x, y, of z association lacking finished redesign.

- Although strengths is minimum in the membrane materials compared to with the steel, these structures have flexibility in use, lightness coverings, minimum costs and faster construction time. Therefore special commercial software is used to investigate behaviour of tensile structures.

5.2. Recommendations

- It is necessary to develop an engineering analysis and design software for further study and roofing on tensile membrane structures.

- Measured solar radiation, ambient temperature, wind energy, amount of rainfall during 24 hours through one year if possible, which can be given approximately climate condition for place when tensile membrane structure will be using.

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