THESIS

-Research and development is a process based on knowledge, individual interests and inspiration, that cannot be objectified.

-Acquiring knowledge of a research subject is based on acquiring knowledge of its development in the past and present, to be extended in the future.

-Science and technology is a language common to scholars, which should not be restricted inside boundaries.

-The development of our knowledge results from the knowledge of those who died and left behind their inventions, new solutions and brilliant ideas.

-Freedom is a choice, achieving freedom is a struggle, having freedom is a need, bestowing freedom is a logical step towards development.

-The new solutions and ideas have never arisen by chance, they are the result of intensive and persistent mental work, which requires devotion and research.

-Man in harmony with nature: when a simple hut, a tent or tent-like structure contributes to this, then our great aim in architecture will have been achieved.

-If, apart from the struggle for success, life is a quest for comfort and shelter, then architects must respond to this great challenge.

A. Hai Yousufi
FABRIC STRUCTURES

TRENDS OF FABRIC STRUCTURES IN ARCHITECTURE

Abdul Hai Yousufi
FABRIC STRUCTURES

TRENDS OF FABRIC STRUCTURES IN ARCHITECTURE

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bouwkundig ingenieur
geboren te Kabul-Afghanistan
Dit proefschrift is goedgekeurd door de promotor Prof. ir. J. Brouwer, TU-Delft

Promotiecommissie:

dr.ir. P. Huybers, TU-Delft, Faculty of Civil Engineering
Prof.ir. A. Krijgsman, TU-Delft, Faculty of Architecture
Prof.ir. L.C. Röling, TU-Delft, Faculty of Architecture
Prof.ir. J. Brouwer, TU-Delft, Faculty of Architecture
Prof.dr.ir. P. van der Veer, TU-Delft, Faculty of Civil Engineering
Prof.dr. G.G. Schierle, USC, School of Architecture

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To my parents

from whom I learned to love Architecture
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In carrying out this study I wish to thank Prof. ir. L. van Wilder who initiated the original idea to write a book on "Fabric Structures, Trends of Fabric Structures in Architecture". Also Prof. ir. J. Brouwer for his special assistance and encouraging advice (after the death of the former promotor of this dissertation Prof. ir. L. van Wilder) towards the completion of this study.

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A. Hai Yousufi
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Abstract

This book "Fabric structures, Trends of Fabric Structures in Architecture" is the result of a research project conducted at the University of Technology in Delft, the Netherlands, Faculty of Architecture from 1986-1991 by A. Hai Yousufi. The aim of the research project was to describe the state of the art of Fabric Structure, as a development from traditional nomad dwellings, via emergency tent shelters for housing up to current large-span structural applications in modern architecture.

The first part of this book is focused on the form and structure of traditional tents, and the techniques associated with traditional building materials. Each section describes the physical and structural properties of materials, its construction and the geographical styles associated with its use. It is also explained how the building process is related to the choice of materials, and its evolution through history. The evolution of these simple shelters is an attempt to evaluate and understand the different cultural and structural concepts behind the different traditional tents and its impulses for the current state of the art.

The second part of this book is focused on the current development of fabric structure in architecture. It discusses contemporary themes which influence the design and construction of membrane structures today. Also in current membrane designs there is a responsive and sensitive balance between the skills and ingenuity of the designer and builder, and the available materials, structural systems, products and inventions. The lesson to be learned is that there is a sensitive and necessary balance between what can be done without sophisticated machinery and what must be done with technological development.
Aims and outline of study

The aim of the study was to provide a general overview of structural methods using woven fabrics and plastic coatings. The book covers tent structures in a number of aspects, as durable, practical and portable lightweight structures. The main objective was the identification of various types of tent structures, their classification in conjunction with the material properties, from traditional building techniques, to development of innovative tent structures and of modern structures. The research has also been carried out to clarify the following aspects:

- To analyse traditional tent techniques as an inspiration for current membrane structures.
- To give a methodological overview of fabric material and its application in emergency tents for a number of social and economical demands.
- To examine current membrane structures in architecture and the influence of architectural form using fabric structures.
- To explain the mechanisms of architectural fabric structures and suggest their potential for architectural design.
- To identify fabric structural systems and components in current use.
- To evaluate the performance of fabric structures together in regard to materials, structural systems and environmental control.
- To develop new recommendations for such structural systems in current use.

Apart from the above mentioned aspects, there is a detailed and comprehensive presentation of traditional tents and contemporary membrane structures that can also form a basis for future development.

Introduction

Throughout the history of mankind, along with conventional building materials in rigid structures, such as stone, brick, timber and steel, there have always been flexible materials for tents and membrane structures. Apart from the cave, the tent is the oldest dwelling of mankind, used by nomadic societies. Membrane structures are built on similar principles and are present in our modern world, employed for temporary and permanent use. Also emergency shelters are known, used for human relief in natural and manmade disasters. So, tents have been used for thousands of years in a variety of ways and means, in many different forms.
Frei Otto said:

"Tent communities are needed, whenever necessary they could be established in a few days at almost any point in the world, which requires devotion, study patience, and research."
Nomads live in tents, because they are easy to put up, take down and transport. They are usually made of animal skins. However, there are many different kinds of nomadic tents. Some American Indians live in cone-shaped tents, others in dome-shaped and ridge tents; while in Northern Eurasia a variety of barrel-vaulted, polygonal, cylindro-conical, and lattice tents are used by nomads. In fact, tents of nomads all over the world form a remarkable addition to the world's architecture, although they have been little known or understood. This book attempts to list these tent designs as a practical building technology, even outside nomadic use.

Membrane structures today are considered as an alternative building technology to conventional structures, and have gained popularity through their versatility, portability, lightness, and flexibility in structural behaviour and design. Today membrane structures are even considered as non-temporary when woven fabrics such as nylon, polyester, or glass fiber are coated with durable plastics such as PVC, neoprene, hypalon, or PTFE. These membrane materials have stimulated many new building applications.

Fabric structures like both traditional nomadic tents and today's standard tents are lightweight structures, covering smaller or larger areas for human activities. Fabric structures offer possibilities for the creation of habitable space, the shape of which can be various.

In general, there are four basic factors which dominate the structural characteristics of fabric structures:
- Form
- Structural system
- Materials
- Details or connections

In order to explain and evaluate the development of fabric structures, the book is divided into three main stages. The presentation of the traditional tents in the first stage is followed by standard tent structures in the second stage. As a matter of fact, these tent applications indicate the demand for tent structures in modern life.

The different tent applications have been explained in Table-A, showing the predominant applications in relation to their function, user, location, structural type and supplier. The table reflects the demand for such structures that links traditional tents to contemporary tents.

The third stage is described in the second part of this book: modern large-span structures. A structure that defines and encloses space, reflects the particular society of its time. The meaning of a structure is created by the materials in which it is built, by the function it is designed for, and by the structural shape.

Structures made with fabric materials have a flexible surface, and are different from the structural rigidity of timber, steel, or concrete structures. The
## Tent Environment and Process

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<td>Sport halls</td>
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<td>green houses</td>
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<td>Schools</td>
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<td>Office buildings</td>
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<td>Mobile hospital</td>
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<td>Warehouses</td>
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</tbody>
</table>

Table-A. The various applications of fabric structures.
necessary characteristic membrane structural form is different from the solid geometry of straight walls and floors. Membrane structures enable the covering of spaces, sometimes without really enclosed space, in the case of roofs without walls.

"The roof had a charm of its own. It was a strict minimum surface, like a soap-bubble. It was discovered, not designed. It was white and transparant like a spider web in the morning dew. We had helped it to come into being, we had not designed it."
Frei. Otto, 1957, (about the Tanzbrunnen tent for the Cologne Garden Exhibition.)
A. Hai Yousufi
Tent village in Afghanistan. Source: Abdullah Yousufi

PART I

TRADITIONAL TENTS

1-Traditional tent environment and process
1.01-Traditional tent environments

The tent and shelter is a primitive creation, its evolution reaches far back into the very beginning of mankind. Man has always protected his living space by roots. Building a shelter was a basic activity of life and survival just like the search for food and self-defence. A study of traditional tents sheds light on the efficient use of traditional materials, structure and technique, and also provides a stimulus for the development of current and future membrane structures.

Traditional tents usually have a minimum deadweight when maximisation has taken place of all static, structural and material dependent properties, while maximising the loadbearing capacity.

This part of the book will evaluate traditional tent structures made of vegetal poles and other wooden rods and the tent shape; the covering material. They are illustrated throughout this book by a pictorial presentation of basic pole constructional systems and their loadbearing behaviour.

Not all aspects of traditional tents are treated. Rather a limited number of relatively detailed studies are given, each of which deals with the tent of a specific geographical area, tribe or other community. The reader will find a table at the beginning of each section, describing the main properties of the tent in relation to its location, materials and users etc. Accordingly, tents are characterized by their shape such as domical, conical and barrel-vaulted, or by the user/location as well as material and supporting systems.

One of the largest group of nomads who dwell in tents are the pastoral nomads, found from South-East Asia up to North and Central Africa. They usually follow traditional routes within the tribal territory. Movement is geared to the pace of the flocks, herds, and of the camels and donkeys, which carry the tents and other life necessities. In nomad societies it is unusual for any member or individual family not to go with the rest of the group; every family member lives in the tent which is his only home. Families who are on the move or camping for more than half of the year, have little contact with the people who stayed in the permanent village to attend to farming.

Nowadays, the pace and character of migration of nomads has become different. The old concerted, time-consuming move no longer takes place in the same frequency, which is largely the result of political and social changes that have limited free movements of nomads in many parts of the world. They do not camp in large groups and good grazing ground is scarce. It is likely that more tribesmen have built permanent mud houses, but some tribes still have no dwellings other than their tents. For many other tribesmen, tent villages are the only home and mud houses are used as society headquarters. One or more sons of large families may still move with the
flocks and tents, and only spend part of the winter or summer at the permanent village. An increasing number of former nomads derive their income from other sources. Current nomadic life and settlement around Kabul as an example of this change of lifestyle, will be explained in the section 1.04 of this chapter.

Directly or indirectly the nomads of today have already been changed by contemporary economic and political systems of the sedentary world. The change-over from nomadic to sedentary society depends on the economic needs of all its members and on the socio-political aspirations of individuals and groups. Important are the specific opportunities and limitations which nomads have to contend with. The sedentary society does not usually act as a passive background for nomads; they want to keep pushing this interaction. The development of new tent materials and other necessary items enables nomads to make better and durable tents. Obviously, the tents of those tribes that do not have direct contact with a sedentary society remain in their original form.

1.02-Traditional tent dwellers

Tents have been tested during long periods of life in different points of the world by nomadic herdsmen and hunters. Tents have been built and pitched by nomads in a variety of forms and styles to protect nomads from the most severe extremes in their particular environment.

Although most of the nomad way of life has disappeared, after settlement the tent is usually still pitched next to the house. Nomads have always had their own laws and have never accepted other rules and regulations. Nomads have lived freely and simply in their mobility to travel and their search for food for themselves and their animals.

The combination of seasonal and geographic variability in the location of pasture and water makes the movements of nomads necessary. Movement of a seasonal nature is the key characteristic of a pastoral society. Pasture and water are distributed in accordance with a particular seasonal and predictable pattern of climate. The territory and pattern of a tribe’s movement varies according to the size, wealth, mobility, power and prestige of the tribe within a certain territory. Some tribes have very large areas, others very small areas and sometimes within the territories of larger tribes.

In general, tents provide flexibility for nomads in their search for pasture, water and food with respect to local conditions. Animals played an important role in the world of nomads, they provided the ability to move farther, to confer capital, prestige, and power.
In many nomadic camps animals such as goats, sheeps, camels, yaks and reindeers are essential for survival, as they provide milk and meat and most of the hair used for tents.

Although animals are used for milk, meat, transportation, clothing and tents, they also form an exchange mechanism, in trading on local markets in urban communities along the nomadic route. In general, all nomads use their contact with sedentary communities to exchange other necessary materials.

Nomads share certain common characteristics that distinguish them from the sedentary communities. They live in temporary dwellings such as goat hair tents, skin tents, felt yurts, and brush or mat tents. Nomads can be classified as two major groups¹:
-Sedentary nomads
-Pure Nomads

The lives of sedentary nomads are dependent on agriculture and have no need for movement, but the tent remains the dwelling.

Pure nomads herd camels and other animals, migrate over longer rather than shorter distances, and obtain their agricultural supplies by trade.

Therefore, nomads are classified according to the length of the seasonal displacement which is the key to distinguish various sub-types of nomads. They are classified more specifically as follows:
-For Semi-sedentary nomads agriculture is more important than herding; their movements are limited locally.

-Full nomads live in steppe areas and change locations yearly.

-Semi-nomads dwell on the border of cultivated zones and raise some crops themselves, have distinct summer and winter camp sites.

Tribes may pass from one category to another in response to natural environmental fluctuations: they may have a restrained migration pattern one year and move over greater distances in other years.

1.03-The Arabian black tent

There are two basic types of black tents in Arabian territories:
-The eastern or Persian type.

- The western or Arabian type.

The Persian type is found in the eastern part of the black tent territory, running from Iran (Persia) to Tibet.
The Persian tent is used mainly by Irano-Afghan groups, as well as Tibetans. In these tents, the poles are generally placed under the seams in order to take the stress at that point. The main tension of ropes must be in the same direction of the seams, otherwise it would pull them apart.

<table>
<thead>
<tr>
<th>used by or location</th>
<th>Shape</th>
<th>Material</th>
<th>Supported</th>
<th>Covered</th>
<th>Basic form and feature</th>
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<tr>
<td>Ghilzai Durrani Baluch Tajani Hazaraaj Band-i-amir Sistant Baluchistan Brahui Badakhshan Achakhzai Kabul Qawwal</td>
<td>barrel-vaulted Rectangular Saddle surface Aerodynamic-mica shape</td>
<td>Rock Cloth Goat’s hair Wood Willow Reed mat Rope Clay Bamboo Mud Stone Straw</td>
<td>Straight pole Reed bundle Willow pole Fork stakes Bent Arch Anchoring Mud wall Stone wall</td>
<td>Cloth Goat’s hair Reed mata Clay Wool Cotton</td>
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<tr>
<td>Iran Zagros mountains Kurdistan Luristan Qashqai Bakhtiari basseri</td>
<td>Aerodynamic/mica shape Horse shoe Saddle surface Rectangular</td>
<td>Mats Rope Mud Stone Wood Clay Straw Rock Cloth</td>
<td>Wooden stick Willow pole Anchoring Long wooden pole</td>
<td>Goates hair Reed mat Wattle Mud Clay Straw Cloth</td>
<td></td>
</tr>
</tbody>
</table>

Table-b. Main characteristics of Arabian, Afghan and Iranian tents.
The western or Arab type of the black tent is used by the bedouin tribes of Arabia, usually in Iraq and Syria. Other tribes in the western territory have adopted the black tent directly from them. The Arab tent is made of the same basic cloth as the Persian tent, and an additional tension band is sewn over the cloth seam. The ropes are attached to the tension bands in order to get the main tension of the ropes at the seams. Pulling the ropes will result in tension, concentrated in the tension bands, and stabilizing the poles underneath.

The homeland of the black tents of the bedouins is the desert. Bedouins have a culture that fits the desert, they are the nomads of nomads, who travel faster and farther than any other black tent nomad. The pastoral nomadic way of life makes it necessary to travel with shelter and the bedouin tent is a direct expression of it. Its covering of woven black goat hair provides shade, and makes it possible to camp in the desert.

The nomadic way of living requires the tent to be light, flexible and easy to carry and erect. The bedouin tent of the Middle East desert is designed like this. Herds of goats, camels and black tents are the basic necessities of the bedouin way of life.

According to Philip Drew new skills in camel riding helped the bedouin to keep large herds, and caused their dispersal from northern Arabia to the southern regions. This allowed them to communicate and trade frequently with the settled population. This in turn improved the economic conditions of the bedouins, as well as promoting cultural exchange between the settled and nomadic Arabs.

The tent awnings are woven from goat hair by bedouin women, and in some cases camel hair, but cotton or wool is also used. The tents are usually erected by bedouin women in the late afternoon hours. Children join the women in erecting poles and stretching ropes to the stakes. The woven goat hair tent covering of the Arabian tent is supported on three longitudinal rows of double wooden poles. The central row is kept higher than the left and the right rows.

According to C.G. Feilberg, the north Arabian tent differs from those of southern Arabia, because its frame is made of only two rows of poles placed in the front and center. The rear awning is stretched and supported by the anchor ropes attached to the stakes. The roof of the Arabian tent is gabled, following the poles. Anchor stakes secure the tent against the strong desert wind. Sometimes thick woollen cloth may be used as an additional covering.

These tents are generally divided into two units, one for men and one for women, by a curtain made of the same material as the walls, suspended either from the tent poles or reinforcing straps and the front tent rope. The right hand for the women and the left hand for the men. A small hole is provided in the curtain to enable the women to observe the men on the other side. Guests

Fig-1. A typical scheme of a two rows of double poles tent.

Fig-2. A typical tent, showing the long ropes characteristic of the Arabian tent.

Fig-3. Section of the North Arabian tent with the carved wooden saddle on top of the pole to prevent the roof cloth from tearing.
Fig-4. A typical three rows of double poles tent scheme of Arabian bedouins.

Fig-5. A typical three rows of double poles tent with side curtains pinned to the tent roof.
are received in the men’s room which contains a fire place in the form of ditch. The women’s room is also used as a store room for tools and luggage, and the kitchen is located in the front of the women’s room. The location of the dividing curtains depends on the position of the poles in the central row.

The black tent uses very little wood in its frame. Only a few other tents in the world have similar bearings, such as north American Inuit ridge tents. The minimal use of wood is possible because the black tent is a largely tensile structure. In the black tent the weight of the tent cloth and the great tensions are created by stretching the cloth. They are concentrated on a few vertical poles. Cover and the frame are strongly interdependent, because of the tension neither can stand without the other.

Long tent ropes are typical for the Arabian black tent. These ropes are attached to each side by means of short decorated straps sewn onto the topside of the roof cloth. The rope is usually connected to the short straps with a type of hinged fastening, which is a small piece of wooden stick sewn into the ends of the straps. The type of fastening employed varies considerably according to location and tribe.²

The tent of the Swahire bedouin is supported on three rows of three poles, of which the middle one is tallest, the tent is therefore higher at its center. The tent of the Anazia can be found from North Arabia to Syria and Mesopotamia. It is necessary therefore to specify to which Anazia tribe a tent belongs to. The two high central poles along the middle row are specific for Sbaa and Ruwalla tents. The tents of northern Syria is comparatively longer, they have from four to six poles in the central row, and sometimes the back side of the awning is kept down. The side walls are covered by means of wattles made of ruches or papyrus, they form translucent low walls.

1.04-The black tent of Afghanistan

Afghanistan is at the crossroads of East and the West, and influences are felt from Turkey, Arabia, Iran, India, and Central Asia. As the result of free movements, tribal territories have changed over the centuries. The main black tents of Afghanistan are used by the Pushtunes, in two tribal divisions:
- Ghilzai; moving to the north and east.
- Durran; moving to the south and west.

Afghanistan is the home of different nomad cultures, and they use many different types of tents. Also black tents are found all the way to the Soviet

² The names and type of fastenings are related to the specific tribes and territories. This study makes no serious attempt to enter into such matters, but a recognized number of fastenings are illustrated in table-g.
Fig-6. A typical Ghilzai tent, made of three poles erected in three rows, showing the scheme and form.

Fig-7. A summer tent system of Durrani nomads, with a T-centre pole.

Fig-8. A winter tent system of Durrani nomads, with either a single bent branches held by central pole or a double arch held by one T-central pole.
border with a great variety of semi-permanent dwellings, such as the yurt. The line between the tent and the hut cannot be simply drawn in Afghanistan, as the tent is usually in the process of becoming a house, when the nomads become settled.

Rock walls are built outside the tent to keep the weather out. If the nomad does not move, he adds the walls; with time rock walls have replaced the cloth walls and the tent cloth is only the roof. Finally the cloth is taken down, a permanent roof is built, and the nomad moves no more; the tent has become a house.

In general there are four types of black tents in Afghanistan:
- The Ghilzai straight pole type.
- The Durrani barrel vaulted type.
- The Baluch barrel vaulted type.
- The Taimani semi-permanent type.

The tent cloth for all of these types is usually woven of pure goat hair.

- The Ghilzai tribes are spread throughout the eastern part of Afghanistan, mostly in the Nangrahar province, and as far south as the Kandahar province, some of the camps can be found even in the Pushto speaking part of Pakistan. The Ghilzai tent is pitched with three parallel rows of straight poles under the roof. The center row of poles is high giving the roof a moderate pitch and the outer edges of the roof cloth are pulled almost to the ground. A small wooden saddle or bunch of rags is set on top of the poles to prevent them from pushing through the cloth; the front and rear sides are left open in the summer and closed in the winter with curtains pinned to the tent roof. (see Fig-6). The black tent of Ghilzai and its variations can also be found in central Hazarajat.

- The Durrani tribes are pastoral nomads and sheep breeders. During the winter they live in the warm (southern and western) parts of Afghanistan. They migrate in the spring while grazing their animals along the way. (see Fig-7,8). The covering of the Durrani tent is made of goat hair cloth, but the type of frame used varies depending on the season of the year and how nomadic the tent dwellers are. The semi-sedentary nomad uses a tent frame of five hoops, made of reed bundles. The frame is always left in place and the cover moved; a second type is used by semi nomads using a double arch of bent branches held up by a (T) center pole. The Durrani nomads use two types of black tents, a winter tent frame with a (T) pole serving as the middle element of an arch and a summer tent frame that uses the (T) center poles alone.

- The Baluch tent has at least three different forms adapted for winter, summer and for travelling; in addition to this a sub-type of the summer tent, lighter for spring. (see Fig-9,10). The winter tent is relatively heavier for better insulation and normally has three transverse wooden hoops. Their number varies between two and four compared with the summer tent which has two or three. Each hoop of winter tents consists of two or three large irregular curved wooden rods, lashed together in one piece in order to provide an arch.
A. Hai Yousufi

The Baluch tent has transverse arch-supports bounded on the short sides by forked sticks. They are usually placed under the stay fastening ropes and the fastenings at each corner, but sometimes intermediate sticks are provided at each seam in the roof cloth. The awning of the summer tent is stretched between two or three forked sticks at each short side, the tent awnings are woven from dark goat hair. The winter tent is larger, has more hoops, fitted with larger roof cloths that often have sides and has more end stakes.

The tent awning is stressed along its length by woollen rope-stays, and anchored to wooden pegs in the ground at the short sides. The four forked stakes are presented at each short side. They correspond to a roof cloth with a main panel of three widths.

The short sides may be closed by a single width of material, and fastened to the edge of the roof cloth with small individual wooden sticks. The tent is surrounded by four or five oval plaited mats, lined with a mixture of clay and straw. These mats which stand a little over one meter high are secured to hoops, the end stakes and the smaller upright sticks are driven into the ground, and an additional protection is made by means of a low clay wall at the foot of the mats along the short sides and rear.

-The taimani tent is similar to the mat tent of the Middle East. It is not a true black tent. (see Fig-11). The frame of the Taimani tent is made of willow poles driven into the ground at two foot intervals to form a rectangle about ten feet by twenty feet with walls six feet high, a row of high center poles run down to the center of the rectangle, rafters are added to this framework running from the wall poles to the ridge. The goat hair tent cloth is thrown over this frame to form a gable roof of moderate pitch with vertical walls, and the reed mats are often placed over the cloth walls.

Kabul and other major cities in Afghanistan have attracted sub-types of the above nomads to migrate to the edge of the city, living on odd jobs such as repairing and making articles etc. Many of these migrants would prefer to live in Kabul city, but there is no plot for them to build a house. Their tents are too light to protect them from the severe Kabul winter, therefore they gradually transform gradually the form of their tent into a more permanent shelter. In fact the tent is pitched up in the original way. When they stay more than a few days, a low wall is built around the edge of the tents. Slowly the wall grows higher until the tent becomes a roof, eventually the tent roof is taken off and replaced with a simple wooden pole and mud roof. In this way, the tent becomes a hut and slowly the hut become a room of a simple house, surrounded by a small court for privacy and cooking. (see Fig-12)

However, most of these nomads leave their tent because of the climate. Those who settle down build more complete houses in other parts of the city. This activity is the beginning of a squatter settlement. They settle nowadays in a row of white tents, often with low walls around their tents and sometimes almost huts which depend on the duration of their stay. Both vertical and horizontal poles are made of bamboo, and the white tent cloth is made of canvas, imported from Pakistan. The tent is often pitched up against a low
Fig-9. A typical Baluch tent system and form, used in summer and travelling.

Fig-10. A typical Baluch tent skeleton and system, used in winter with three bent arches. The roof is stretched between sticks at each short side.

Fig-11. Showing a typical Taimani tent system and feature, which is made of willow poles driven into the ground. The cloth roof is thrown over this frame to form a gable roof of moderate pitch with vertical walls.
a- A typical pup tent system and feature used by sub-type of nomads in Afghanistan

b- The pup tent has low walls, in order to keep the water out of the tent in rainy season.

c- The pup tent becomes the roof of a mud hut.

Fig-12. The gradual change of a simple tent to a permanent dwelling in Afghanistan.
existing wall, in order to keep the water out of the tent. In a rainy season the side walls become higher and the tent is used as a roof of a mud house.

Since 1978, the social and political conditions of the country have changed, the state and private sectors have ignored such interactions of nomads and their settlements. Therefore they have moved towards the south, and a large part of the population apart from nomads have also moved, in order to seek refuge in neighbouring countries. Some of those nomads are still moving inside Afghanistan, but in new and safe patterns. According to the statistics of the UN the estimated number of Afghan refugees living in neighbouring countries are above five million and tents are their only shelter. These refugees, who had no experience of living in tents as nomads, are still living in donated shelters, mostly provided by international rescue teams, or governmental organisations.

As the population integrated in the above mentioned regions, their tents slowly became mud houses. The tent is used as the guest room beside the house. The integration of tent into a permanent shelter and local materials reflects a process that a community needs to fulfil in order to meet certain functional and social demands.

1.05-The black tent of Iran

The largest and strongest tribes of nomads and semi-nomads are found in the Zagros mountains, which extend from Turkey to the Persian golf, and the black tent is found among the Kurds, Lurs, Bakhtiari, Basseri, Qashqai, and Baluch nomads in these regions.

The Iranian tent is different from the Arabian black tent: the roof and walls are usually made in one piece. The roof cloth is divided along the longitudinal axis, and the awnings are made in two sections, each section has a narrow band with loops sewn along the edge at each end to which the ropes are tied. Another difference between Arabian and Iranian tents is the stress on the longitudinal direction, so that the rows of poles and ridge bars are parallel to the length of the tent.

The black tent of Iran, including the ropes, is made of pure black goat hair. They are similar to each other in construction, but they appear quite different, as the internal framework differs and the tents are pitched in a variety of ways. The Kurds use straight center poles and others use (T) shaped center poles.

Fig-13. The Kurd’s black tent system and form. Similar to Taimani tent of Afghanistan based on a rectangular form, erected on three longitudinal rows of poles.

Fig-14. The black tent of Luristan pitched by two or three central T-poles, made in two parts.
Trends of Fabric Structures in Architecture

(see Fig-13)

-The Kurdic black tent is made in a rectangular form with three longitudinal rows of poles and stakes on two sides, which can be taken apart into several pieces. The awnings are made in two sections, joined down with loops and wooden sticks. The side poles are set under the rope-stays at the edge of the roof, and walls of reed matting surround the tent and are also used for the dividing curtain between the two sides of the tent.

-The Lur’s tent is usually made of black goat’s hair, and the awning is supported by two or three (T) shaped poles, divided into two sections and joined by means of loops and wooden sticks, placed on the longitudinal direction of the tent. (see Fig-14) The center poles are made in two parts and are easy to transport. Shorter poles are set along the sides and corners in order to elevate a side of the tent when it is warm. The middle poles support a short bar to form the (T) shape. The walls are made of reed mats, but in the winter the mat walls are plastered with mud, and often low stone walls are built around the tent.

-The Qashqai tents are distinguished by their horse-shoe shape, the stay fasteners and the slotted poles. The Qashqai tent is pitched up with (T) shaped center poles, giving it a high ridge to drain off the rain. When they are moving the tent is pitched without center poles, the roof becomes flat and the tent looks like a black box.4

-The Bakhtairi and Basseri tents are similar to the Qashqai tents. They use four walls of curtains in the winter and only a roof cloth in the summer.

1.06-The black tent of the Middle East

Hunting people have a variety of building materials. They dwell with simple sticks or pole frames, which are covered with skins, bark or mats; they use these covering materials both for clothing and shelter. They dwell where suitable reeds, rushes or long thin leaves grow, which can be plaited or woven into mats, suitable for both floor and tent coverings. Their materials are very flexible; they can be rolled up and removed, and when the covering is removed the frame is often left behind. When there is an ample supply of frame material, it is always easier to cut new frame poles than to carry the old ones along. When the tent is used in territory where wood is scarce, the frame has to be moved too. The frame is lightened as much as possible, and traditional systems have evolved to make assemblage easier.

4 The Qashqai and other related tribes dwell in similar tents as illustrated in Fig-13. In its appearance the Kurd’s tent also resembles the Bakhtairi and Basseri tents.
### Tent Characteristics

<table>
<thead>
<tr>
<th>Used by or location</th>
<th>Shape</th>
<th>Material</th>
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<th>Basic form and feature</th>
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</tbody>
</table>

Table c. Main characteristics of North Africa and the Middle East tents.

These black tents are made of prestressed cloth of an almost aerodynamic shape over minimal wood supports, and are able to withstand strong winds. The black tent, unlike the conical tent and the yurt, is a nonskeleton tent with a prestressed cloth.

The transformation of the black tent from a skeleton dwelling to a nonskeleton structure was made possible by the replacement of mats and leather awnings, strong enough in tension to be prestressed. In this way, the differences between the tent and hut tend to disappear in primitive dwellings.⁵

In fact, there are various sub-types of black tents, which are defined as regional types. Apart from the Arabian and Persian black tent, there is the Tibetan black tent, which is specific to the region.⁶

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⁵ *The distribution of the black tent is best understood in terms of its attachment to a particular way of life adapted to a select range of environments, which in turn limit its spread.*

⁶ *The division of the black tents into groups is based on similarities of shape. The fact that the three basic black tent types are spread throughout Asia could indicate that the early evolution of the black tent took place there.*
Fig-15. Various frame systems of skin-mat tent of the Middle East, which are different from the black tent of Arabia, because skin and mats have little tensile strength and cannot be greatly stretched.

Fig-16. The curved poles are lashed together and form arches, driven into the ground with additional poles on both sides ready for covering.

Fig-17. The mat tent system and feature, which is covered with palm mats, and secured by rope.
Fig-18. Showing various type of skin tent frames, which are peculiar to the Middle East nomads.

Fig-19. Showing various type of arched-frame skin tent systems.
The main climatic function of the black tent is to give protection from the sun, and act as a very effective wind break. The loosely woven goat hair cloth is a responsive material in hot dry weather. The fabric is relatively open, permitting air to flow through, but when it rains the fabric shrinks and the weave is denser, thus offering greater resistance to rain penetration. The black colour of the cloth gives an advantage over lighter colours because it shades better.

The stability of the black tent in strong winds is achieved by an efficient aerodynamic profile, long anchor ropes, and the variable geometry of the tent form. The orientation of the tent is determined by the wind direction. The stability of the tent is threatened by sudden and unexpected changes in wind direction which might dislodge the pegs or penetrate to the open front of the tent. If the wind changes, the front poles must be moved to the rear, and the back wall taken down and refixed across the tent front. The geometry of the tent can be varied as required to give it a more efficient aerodynamic shape. In extreme conditions, the tent can be lowered to reduce the effect of wind. Also the number of ropes can be increased and the pegs can be driven deeper into the ground.

The portability of the black tent is especially significant in warfare or as an emergency shelter, because it can be dismantled or erected again in a short time compared with the yurt and the conical tents. The black tent also uses the least amount of wood or other supporting materials for its size and the space enclosed.

Tuareg tents were originally stationary structures; Tuareg converted the mat and skin huts into portable tents for the sake of mobility. Often the frames are left in place and only the mats are removed. The skin tents have a very simple frame, some of them have used elements borrowed from the old hut. Others have abandoned the hut frame and borrowed the (T) center pole frame of the black tent.

The mat tent cover is made of palm leaves, plaited by hand into narrow strips, sewn together with large needles, and used for the roof cover. The wall mats are different: they are made of straw or grass with leather weft strips woven in decorative patterns. The difference between a mat tent and a skin tent is the covering. The mat covering is fastened to the tent structure, and the skin tent sheet is anchored to poles, pegs or other objects outside the supporting structure.

Although many of these tents have disappeared or have been replaced by other more elaborate tents, those which have remained, had the most fundamental elements of the black tents.

Today woven fabrics, mostly canvas, have replaced the skins and hides, but the decorative mats are used in a large scale even outside nomadic societies.

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Fig-20. Typical skin tents system and feature, showing a box-frame and an arched-frame tent.

Fig-21. Showing a typical T-pole frame of skin tent stabilized by rope, because the skin has little tensile strength.
Fig-22. Typical T-pole frame of skin tents, showing the system of structures which are peculiar to the Middle Eastern nomads.

Fig-23. A typical mat tent system and feature, made by driving three parallel rows of forked poles into the ground and the middle row of poles is set slightly higher to bend the roof rafters, and palm mats are rolled over the frame and tied down.
1.07-The North African black tent

North Africa was the home of Berbers and influenced by the Arabic culture, some of them kept their own cultures and most of the tribes such as Moors have a mixture of Berber and Arabian cultures. In general, the nomads of North Africa dwell in two different environments, and can be described as:7a
- Mountain nomads.
- Desert nomads.
- The mountain nomads move up into the mountains in the summer and down to the valleys in the winter. They usually follow short and regular paths, and travel on donkeys.
- The desert nomads travel farther and move often on camel, their seasonal pattern of movement is the opposite of the mountain nomad.

However, the following two tribes of North Africa have different tents than the others:
- Ouled Ali tribe
- Kababish tribe
- The Ouled Ali tribe, dwelling in Libya, uses a tent which has more pitch on the roof giving it a prominent peak, unlike those of the Arabian tents. (see Fig-24). They use two cloth loops sewn at each end of the tent, as extra tension bands which are running through the whole length of the tent. This tent is transitional between the Arabian bedouin and the other North African black tent types.
- The Kababish tribe who dwells in Sudan uses the tent with two tension bands which is related to the Ouled Ali tent. The frame system is different: it consists of four forked center poles, (see Fig-26) two in the middle supporting a long ridge stake, and two on the ends which support a short curved ridge piece.8

Some nomadic tribes from the south come into Tekna territory, are traders and in some circumstances graze their animals. The Tekna is a confederation of tribes dominating the south west of Morocco. All tribes may live all the year in their tents or they may return to a house for a season according to the number and needs of their flocks. The peaked lines of the tent can be recognized from some distance. The roof is the whole form and it tilts in each sweep of the surface. The single peak rakes backwards away from the low shaded mouth, where the entrance side is lifted by two short stakes, and lift the cloth up in a gentle curve to fall away in a much steeper slope behind. A large or small tent is always provided with fastenings of four guy ropes on each short sides, which are made of bent branches to form a broad (V) with notches or shoulders near the tips of the horns. They are lashed by these

a-Cross-pole with ridge piece

b-Structural system of a typical North African tent

Fig-24. A typical tent of Northern Africa.

Fig-25. The tent of Ouled Ali which is transitional between the Arabian bedouin and other North African black tents, showing the structural system that is based on straight poles and tension bands, peculiar to African nomads.
Fig-26. A typical tent system of Kababish, showing the four ridge pole stabilized by tension bands in both directions.

Fig-27. Showing a typical tent frame characteristic of a Moroccan tent.

Fig-28. Two different types of tent frames used by Algerian nomads based on similar characteristics and systems as the Moroccan tent; left the Djebel Amour tent, and right, the Ouled Nail tent.
shoulders to the edge of the cloth, one at each corner at the ends of the lip cloths, and two at intermediate points near the center of each side. The size of these (V) becketts varies, not only with the size of the tent but according to their position along its edge. In general, the smallest are those at the corner of the cloth, and particularly those at the rear corners. The exact position of the central pair of becketts depends on the placing of the peak under the seam. The becketts are usually fastened to the two cloths on each side of the seam. They may be placed on the corner of the cloth, close to the next seam along to the front or the rear. The effect of the central pairs of becketts is to stretch the cloth downwards and outwards on each side of the peak. Once the tent has been erected, the junction of the poles cannot slip under the cloth. They are placed just far enough apart, allowing the cloth to stretch a little at that point.

The whole weight of the cloth can be supported on the two main poles, which meet at the peak, though they are set far enough to form an equilateral triangle. The tent is provided with a ridge piece in which the tips of the poles lodge, holding them fastened and protecting the cloth from the pressure.

There are different types of tents found among Algerian tribes. The main difference between the central Algerian tent of Auled Nail and the west Algerian tent lies in the great depth of the latter. The awning of the west Algerian tent is fabricated on different patterns. The central panel that constitutes the actual roof of the central Algerian tent, is much narrower than the west Algerian tent, and the front and back panels are considerably wider. In the west of Algeria the front and back panels are integrated with the center panel in the awning and stabilized by means of poles. Each tribe has its own particular pattern of stripes, that can be identified by the color of its tent. The Ouled Nail tribe colors the center warp brownblack with a reddish brown stripe on each side.9

Large tents are made in three sections and fastened together with toggles and loops. Unlike the Moroccan tent the side tension bands are sewn back from the edge, so that a low wall hangs from the tension band when the tent is pitched. The tent is divided into men’s and women’s sides by means of a curtain suspended from the center poles, another curtain extends across the front of the women’s side in order to provide more privacy. The opening is left where the cloths join together and held open by stakes to provide a smoke hole.

The Algerian black tent differs from Moroccan tents in several aspects. The wider stripes of material is common in the Moroccan tent. The triangular opening is a smoke vent, the main poles and ridge piece of an Algerian tent are smaller than the Moroccan tents.

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9 The North African tents are different than Arabian and Middle East, mainly in terms of internal structures, method of covering and tension bands which are peculiar to African nomads. They can be identified by a specific tribe or their locations in connection of material, colour and special pattern of stripes. T. Faegre. Tents. Architecture of the nomads. 1979, USA. pp. 32-38
Fig-29. A typical tent system and feature belongs to Ouled Nail and is peculiar to the nomads of Northern Africa.
## Tent Characteristics

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| Northern America    |       |          |           |         |                        |
| Eskimos             | Domeal| Whale-rb | Whale-rb | Seal skins |                        |
| Northern-canada     | Conical| Jawbone | Jawbone | Caribou hides |                    |
| Alaska              | Hemispherical| Stone | Stone | Brush |                        |
| Greenland           | Ridge | Drift wood | Drift wood | Bark |                        |
| Indians of great plains | Semi-conical | Seal skins | Seal skins | Birch bark |                      |
| South Ampton Island |       | Caribou hide | Caribou hide | Snow |                      |
|                     |       | Willow | Willow |       |                        |
|                     |       | Timber | Dog rib |       |                        |
|                     |       | Brush |       |       |                        |
|                     |       | Bark |       |       |                        |
|                     |       | Dog rib |       |       |                        |
|                     |       | Bush |       |       |                        |

Table d. Main characteristics of Northern Eurasia and the Northern American tents.

### 1.08-The North Eurasian tent

The area of North Asia from the Ural mountains to the Pacific Ocean, north of Sayan mountains including the Amur river and Siberia, is the home of the nomads, furnished with a variety of tent types. In general, their tents are classified in term of their shapes and structures as:

- Domeal
- Conical and composite conical
- Cylindro-conical and polygonal

In fact, the circumpolar area from North Pole through Eurasia and North America should be seen as a whole. The access to tent materials such as plant, animal and the human cultures are related to each other. They are dependent on the reindeer or caribou, those who dwell across the coast or live by inland water depend on hunting and fishing.

35
-The form of domical tent was the best choice of dwelling across the whole circumpolar region. They are found in association with hunting and fishing economies along the river and on the pacific coast. The tent frame is constructed by means of branches and covered with reindeer skins and birch bark. (see Fig-30)

-The conical tent which is covered with skins or birch bark, is the predominant tent of Northern Asia. The conical tent is found among hunter and herder tribes who lives in forest areas for at least part of the year. The conical tent originated in Siberia and spread all over the west, such as Lapland and east to North America. (see Fig-31)

The tent frame is constructed on numerous round wood poles which are easily obtained from forest areas. The tent consists of a conical frame of inclined poles, arranged in a circle and secured at the peak. The form of the conical tent is not uniform throughout Siberia. It can be distinguished by its foundation frame, which is always placed in an established order. The foundation poles are lashed to each other in order to create a stable frame on which to build the conical tent.

Another important feature of the conical tent is the multiplicity of methods used to secure the end of the poles at the peak. They are usually tied by a plaited willow ring through the holes in the poles. The conical tents are also covered by other materials, such as felt, sod, earth, and snow, which provides insulation in the winter.

-The cylindro-conical tents of South West and Northern Siberia are much less well known. These tents are somewhat related to the Mongolian yurts. In fact, they are not only primitive but also isolated from other tent types which indicate that they were an independent, and natural development from the conical tent, regarded as a more advanced tent in terms of its structure and architectural appearance. (see Fig-32)

The cylindrical compound tent belongs to the Chukchee and Koryaks people, who form a single ethnic group with a common origin in North Eastern Siberia. In general, the Chukchee tribes possess the following two types of tents:
-Cylindro-conical tent
-Polygonal compound tent

-Cylindro-conical tents belong to settled people. The upper end of the roof poles are supported by a central stake. Their lower ends rest on a cylindrical wall frame, consisting of a perimeter ring of poles. (see Fig-33)

-The polygonal compound tents support the roof apex by means of a foundation frame of three or more poles arranged in a pyramidal form. The polygonal Koryak tent has a tripod foundation frame and a perimeter wall frame, in the same way as the Chukchee tents. The framing of the Chukchee tent is lighter and more open than the Koryak tent. (see Fig-34)

The Siberian compound tents are usually covered with reindeer skins and sometimes with birch bark, and heavy reindeer skins are used in the winter.
Fig-30. The domical tent system and form, the tent frame is constructed with bent arches and covered with reindeer skin, birch bark and mats.

Fig-31. A typical conical tent originated in Siberia, the frame is constructed on numerous wooden poles arranged in a circle and the foundation poles are secured at the peak by a plaited willow ring through the holes in the pole.
Fig-32. The cylindro-conical tent which is related to the Mongolian yurt.

Fig-33. A typical cylindro-conical tent belongs to the Chukchee and Koryaks people of Siberia, the conical roof poles are either supported by a central pole or a conical frame.

Fig-34. The polygonal compound tent roof is supported by three or more poles arranged in a pyramidal form, consisting of tripod foundation wall frames.
Fig-35. The turf tent of Lappland, showing the heavy frame which is usually covered with turf.

Fig-36. The forked tent system and form, the conical frame which consists of forked poles is covered with birch bark or canvas.

Fig-37. The curved pole tent is similar to the turf tent structure, consisting of two pairs of curved poles forming the arches and secured by ridge poles around the tent.
To the west of Siberia is Lapland, home of the Lapps. They originally migrated from Siberia and have a culture similar to North Siberian tribes. There are mainly three following types of tent:

- Turf kata
- Forked kata
- Curved kata

-The turf kata is a sedentary tent, which uses the same basic frame system as the curved pole kata. Its frame is much heavier and the whole frame is covered with turf. (see Fig-35)

-The forked pole kata has similar features to other semi-portable tents of the nomads. The frame which is a cone of forked poles is left behind when the Laps move. Originally the tent cover was reindeer skins in the winter and birch bark in the summer. Nowadays canvas is used in the summer and a double layer of woollen blankets in the winter tents. There is one disadvantage, the hole at the apex of the tent is quite large so in the winter snow fills the tent. (see Fig-36)

-Curved pole kata, peculiar to the fully nomadic Lapps, has a remarkable support structure. It consists of two pairs of curved poles forming the arches which are connected with ridge poles around the tent. (see Fig-37)

The material of the tent cloth is changed according to the season. Originally they used birch bark in summer and reindeer skins in winter. Nowadays those materials are replaced by canvas in summer and woollen rugs in the winter.

1.09-The North American tent

Three main types of tents have been used by North American nomads. They are semi-portable and fully portable tents, and can be simply classified as:

- Domeal; a semi-portable tent
- Conical; a semi-portable tent
- Hemispherical; portable tent

---

10 Kata is the Lapp name for their conical tents. The three types of tents belong to three different groups. Obviously the heavy and complex curved structures belong to the sedentary and semi-sedentary groups, and the forked poles are related to pure nomads. As the structure becomes more complex, the nomads tend to become stationary, rather than mobile. This indicates the process from a mobile tent to a permanent dwelling.

- The domical and conical tent were once used by all the North American tribes, and as usual, when they moved the frame was left in place and only the cover was moved. In fact, the domical tent was found throughout the forest regions. A typical example of this tent is the Ojibway, which is covered with rush, mats, bark and skins. The rush mats were commonly used for the walls and birch bark for the roof. The frame was made of willow wood. The poles were stuck in the ground in an oval shape. The opposing poles were bent towards each other, overlapped and lashed together. Other horizontal poles were lashed around, in order to strengthen the frame. Birch bark was placed over the dome with a smoke hole in the middle of the roof. (see Fig-38)

- The birch bark conical tent was used by a number of North Eastern tribes. The frame was made of long cedar poles. A foundation was made of two pairs of poles tied at the top with cedar bark. Other poles were laid in between and a hoop of bent willow was lashed inside, to strengthen the frame. (see Fig-39)

- The Hemispherical tent belongs to Kutchin nomads, which was the only completely portable tent found among the North American tribes. From the outside it looks similar to the dome tent used by the North American Eskimos. The hemispherical Kutchine tent employs a unique systems of arched poles to create a large oval shape. The frame was made of curved poles supported by two arches and additional short poles are lashed at the front and rear. (see Fig-40)

There are many different types of tents used by Eskimos. Although their tents provided adequate protection in severe cold, they are used almost as a temporary shelter. In winter they cover their tents with shrubs and secondary skins. Their rock igloos are constructed like the snow block igloos. The sides are banked with sod, and the roof is covered with grass, and earth. The sod wall dwellings are built on a frame of drift wood, and sometimes with large whale bones, acting as structural members. In spring, they move back into their seal and caribou skin tents for hunting and fishing until the next winter. The framework of summer tents consist of numerous poles, usually lashed together and shaped in such a way as to resist the seasonal wind. The covering is held down on the outside of the tent by a ring of heavy stones, ropes or raw hide strips wrapped around the tents and attached to the rocks. In general, there are three main types of Eskimo tents that are classified as:

- Domical tent
- Conical tent
- Ridge tent

- The domical shape dwelling is used only in winter and is said to be the original Eskimo tent. Some Eskimos use this tent to create a domical snow house. The willow frame is covered with snow and heated rocks are brought inside the tent to melt the walls, then the rocks are removed and the walls freeze, finally the frame is removed, leaving a domical snow dwelling. The frame of the dome is made of willow poles, driven into the ground and
Fig-38. A typical domical tent used throughout the forest regions of Northern America. The frame is made of willow wood and stuck in the ground in an oval shape. The opposing overlapped poles are lashed together strengthening the frame.

Fig-39. A typical conical tent frame, made of long cedar poles with a foundation made of two pairs of poles.
Fig-40. The hemispherical tent frame is made of curved poles supported by two arches with additional short poles at the front and rear.

Fig-41. A domical tent schemes of Skimo, made of willow frame.
Fig-42. The conical tent without smoke hole is peculiar to Northern Alaska, covered with seal or caribou skins.

Fig-43. A typical conical tent frame made of two pairs of poles forming the foundation and tied by means of a ring at the middle, additional short poles are also added.
forming a rough circle. Other opposing poles are bent towards each other and lashed by ropes. The frame is usually covered by sewn caribou-skins. (see Fig-41)

-The conical tent is confined to the Northern and Central region of Alaska. (see Fig-42) There is a peculiar sub-type which has no smoke hole, and can be distinguished from other conical tents. The conical tent is identified by its long poles tied together at the top by means of raw hide and seal skin. Other short poles are held together by a wooden hoop to provide a stable frame. The cover for the conical tent is usually caribou skins and some coastal nomads use seal skins. (see Fig-43)

-There is a variety of ridge tents in Greenland. Mainly they use very long ridge poles, arranged in a rough semi-circle at one end and supported by two crossed poles. (see Fig-44) The diversity of ridge tent frames arose from the arrangement of poles. They are used to support the two high points at each end of the ridge tent. The tent is covered by seal skins sewn together and secured by stones around the tent.\(^{11}\)

However, one of the advanced and significant conical tents belongs to the native Indian tipi. In general, it has all the essential features of the Eurasian conical tent, such as the central fire, a smoke hole at the apex of the tent, and an entrance, but in specifics they are different. (see Fig-45) They use three or four pole foundations, one-piece covering, an oval-shape door, and above all two ears beside the smoke hole.\(^{12}\)

The tipi conical tent was developed in a cold windy climate, the tent structure serves as a chimney, wind break and dwelling. In fact, it is not a true cone, the foundation is based in a declined circle which increases the usable interior space and permits the hearth to be moved forward to the center, allowing head clearance in the rear of the tent. The smoke flaps are attached to the poles that can be adjusted according to the wind direction. In case of rain or snow they can be folded over each other. The tent is covered with skins or canvas sewn together in one piece.

\(^{11}\) As a matter of fact the Eskimo's way of live has been entirely changed by integration into sedentary world. Therefore, today they use modern shelters and well equipped technology, but the sign of their craftsmanship and ideas have still remained remarkable.


\(^{12}\) The constructional method and structural elements are explained in section 2.1.1. The tipi tent is one of the structures that is used even today outside nomadic environment. Doris cole. From tipi to skyscraper. A history of women in Architecture. 1973, New York. pp. 4-10
Fig-44. Showing various types of ridge tent systems used in Greenland and covered with seal skins, secured by stones around the tent.
Fig-45. A typical conical tent, belongs to the Indian tipi, covered with skins or canvas sewn together in one piece.
1.10-The skeleton tent of Central Asia

The skeleton tent of Central Asia called yurt. It is an appropriate form of housing for the nomad's needs; a very portable home. The traditional yurt is significant, because it can be erected and dismantled in half an hour. The whole yurt could be carried by camel or other animals, which consists of wood pieces, crown, felt and canvas. The yurt of nomads is a proper shelter structure which is easy to heat and has a great capacity for thermal retention in the winter. Above all the yurt resists winds, so that high winds cannot threaten to blow-up the structure. Other tents in the form of rectangle or square would not resist strong winds. The winds slip around the curved walls, and the warm air cannot get lost in a circular form.

The yurt of nomads is adaptable enough, to easily conform to the changes in the natural environment. For example, in summer the outer layers of felt can be removed, leaving the latticework walls exposed. (see Fig-47.a)

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<thead>
<tr>
<th>Used by or location</th>
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<th>Supported</th>
<th>Covered</th>
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Table-e. Main characteristics of Central Asian tents.
Fig-46. Showing various types of skeleton tent (Yurt) of Central Asia.
The yurt was made from a series of components that were assembled on a particular site, and the variation of form and components is found in different regions of Central Asia. Several pieces of lattice walls composed of sticks could comprise the wall of the yurt. (see Fig-48) Each section of the wall is opened and lashed in an upright position to other wall sections when the yurt is being assembled. When the dwelling is being packed and transported, the pieces of each section are pushed together for ease of mobility. The number of sticks in each section can vary according to the size of the yurt. The size of the yurt also depends on the number of wall sections. A yurt usually consists of a minimum of four to six wall sections, lashed together in a circle. In addition, a door panel is lashed to the each side of the lattice wall and tied at the top with roof rafters by means of rope. (see Fig-49) The roof pieces are single strips of wood, either straight or slightly curved downwards. They are slotted to the crown at the top and lashed over the wall pieces. The slots of the crown can hold the sticks and prevent the lateral twist. The number of roof poles correspond to the number of sticks in the wall section. (see Fig-50)

There are mainly two types of yurt used by Central Asian nomads, distinguished according to their roofs as follows:

- Conical roof
- Domical roof

-The Mongol, Tatar, and Kalmuck tribes use straight roof poles, which makes the roof into a cone. The structure and roof crown are usually simpler than a domical yurt, and belong to poor tribes. (see Fig-46.a)

-The Turkish-speaking peoples such as Kirgiz, Kazaks, Uzbeks, and Turkman use curved roof poles which make the roof into a dome. (see Fig-6) The complexity of wall sections and roof rafters including their crowns indicate the wealth of the tribes. However, one advantage of the yurt lies in the frame which does not use poles of any great diameter. The wall sections of the yurt are made of willow rods an inch or less in diameter. The willow rods are arranged in diagonal directions to increase the strength and stability of the walls. Each tribe has its own particular configuration of these rods. Some poor semi-nomads use straight poles, driven into the ground in a circle, forming the walls of the yurt. (see Fig-46.d) The roof poles are lashed to the perimeter poles, and at the top they are laid over each other in a tipi style.13

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Fig-47. Various types of skeleton tent (Yurt) and their development outside nomadic societies.
Fig-48. Various types of folded lattice wall, either with knots through bored hole or simple lashing. The modern screw also used to make the wall section more foldable.

Fig-49. Showing various types of jointing by means of lashing. It also shows the jointing between lattice wall, door, and roof rafters.
The nomads cover their dwellings with felt which is their invention. (see Fig-47.b) Some nomads use reed and mats for wall coverings which lets air circulate in the summer time. (see Fig-47.c)

There was a famous skeleton tent called Alachigh, which was developed for Shah Savan, that was similar to the nomad's yurt. The Alachigh was much simpler to construct than the yurt, it used crown and curved roof poles but not lattice walls. (see Fig-46.c)

In the early 1960s the yurt has been experienced by teachers and students in the United States. They were fascinated with the space potential of the yurt structure, and developed yurts as an alternative structure for human dwellings. In 1962, Bill Coperthwaite, who was a teacher at the meeting school in Ringe New Hampshire, carried out a research with students in this field. They brought the yurt of nomads in the form of modern life with natural materials. They removed the central crown by placing the roof pieces close together to create a self supporting tension ring and sloped the wall sections slightly outwards in order to increase the rigidity of the structure. (see Fig-47.c)

The yurt of nomads is a flexible structure, it can be built in a variety of forms and structures. In 1973, Len Charney designed his own yurt in which he lived as a student. He used rectangular pieces of wood, nailed together in a (V) shape, then, placed these pieces in a circle and nailed them at the top to each other in order to produce a lattice wall. (see Fig-47.f) A cable is fixed at the top of the nails between the two pieces of wall to increase the stability of the wall, and placed the (V) shape rafter on the cable in the same way as the nomads placed the roof poles on the wall sections. The rafters are inserted close to one another at the top of the roof, reinforced by nails, and create a strong roof ring.

Fig-50. The two different types of roof ring (Crown) used by nomads of Central Asia, either lashed or joined by means of interlocking.

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2-Traditional tent analysis

2.1-Traditional tent system

The timber poles and vegetal rods have been used in tent structures in order to transmit outside forces and other horizontal loads into the ground. These poles may be fixed into the ground in a variety of ways. Such as, sunk into the ground, stabilized by means of anchoring and other articulated manners. These poles or rigid elements on which the structure is stabilized will form the system of a specific structure. Any change in the load-bearing elements of a structure such as poles and tension bands will directly affect the form and system of a structure. In this way, a structure can easily be modified or transformed from one category to another.

The arrangement and techniques involved in tent structures indicate the nature or the system of structure, each of which has been designed to meet the need of its users, and reflects the society of its time, skill and local custom. On the basis of the above knowledge which was acquired from traditional tent structures, they can be classified as the three following main systems: (see Table-F)

-Self-supported structure; a structure can be stabilized by itself, the forces can be transmitted through its surface by means of fabric and anchors. The best examples are the Arabian black tents and other related prestressed tents. The structure is usually pitched by single or multipoles. The poles are located under the load symmetrical conditions and will move in relation to the whole
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<th>structural systems</th>
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<td>self-supported structure</td>
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Table-F. The three main systems of traditional tent structures.
structure.

-Tension-band stayed structure; a structure can be stabilized by ropes or tension bands. The forces can be transmitted through a line by means of anchoring. In fact, when the surface or covering of a structure is not strong enough in tension, an additional tension band is used in order, to stabilize the main poles of the structure. In this way the fabric is used as covering. In most cases both systems have been used in order to obtain a strong aerodynamical form and structure.

-Skeleton structure; a structure can be stabilized by its rigid elements. The elements are placed in a way to be stabilized by themselves. The fabrics are used only as cladding or covering. The system is stable when it is designed on a round or polygonal plan. The best examples are the yurt of Central Asia and conical tent of North America.

2.1.1-Structural element

Many tent structures still exist in the world, some of them have disappeared, but a surprising number are still available and used. They are as comfortable and attractive as modern development tents. Those tents that have remained deserve our immediate attention. Mainly in terms of their function, structural systems and elements, and minimum use of material into a certain context.

The main elements by which a tent can be characterized are the rigid elements. Such as straight poles, barrel-vaulted arches, the variety of anchors, ropes and covering systems. These elements may be arranged and designed according to the need of its users, availability of relevant materials and skill, and the climatical condition of the context.

The most popular tent in terms of minimum use of material are the black tents. A few straight poles arranged on three longitudinal rows support the Arabian black tent. The central row is usually taller than the right and left poles, in order to provide enough interior space. Some black tents use only two rows of poles, a right row and a central row, so that the anchor ropes perform the same function as the left pole row. In this way, the tent cloth can rest on goat straps; the number of straps is determined by the length of the roof and the number of poles in the central row.

The long anchor ropes are the main feature of the Arabian tents. Three ropes are attached to each short side by means of short straps. They are sewn on the top side of the roof. In addition, small rounded pieces of wood are inserted between the pole tips and the reinforcing bands in order to prevent them from pushing through the cloth. In general, one can say that, the shape of the black tent results from the placement of tall poles in the middle row and
corresponding poles in the right or left with long anchor ropes.

When the long poles are joined at the top and placed on a circle, they will form a conical shape. It is subjected to compression and bending loads. The conical shape supports the sloping roof poles which are joined in a way to be able to turn when a load is applied. The best example is the tipi conical tent, four or three long poles are laid together on the ground and tied firmly with a thong. Then the poles are raised and their free ends are spread apart and thrust firmly into the ground. These poles form the true framework or foundation of the tent. Other poles are also arranged in a circle according to the size of the tent. There is a definite order in setting up the poles so that they will lock one another. When they are all in place, they will constitute an elastic but firm frame which can resist a fairly heavy wind.

The fresh timber poles and rods (unlike dried poles and rods) can also curved. The curvature usually increases from the thick to the thin side. In this way the poles and rods create the possibility of obtaining a domical or barrel-vaulted tent. In order to have a suitable structure the arches are placed against each other. Additional timber members are also added to stabilize the whole structure. The timber rods are usually very long, the shapes are dependent on how the timber rods are fixed to the support or foundation.

The skeleton structure of the Middle East is formed by timber poles which are sunk into the ground forming the walls. The long rods serve as rafters and roofing simultaneously. The openings in the walls were achieved easily in order to serve as doors, windows and chimneys, and provide ventilation. The floor consists of compacted earth, plaited palm leaves and mats. These huts may be very simple in terms of structure, but they provide an optimum protection against sun, wind, and rain. In looking at the shelters of nomads, it is difficult to draw a line between a hut and a tent, because they are periodically transitional from one to another. In addition, they have certain elements in common such as tent poles, rods, cloths, etc. The skeleton structures are dwellings having only a single room or an additional kitchen area. These dwellings provide protection against the weather, ground moisture and animals.

The abovementioned traditional tents of nomads have revealed all the typical elements of tent design. The skeleton structure of Central Asia is the most popular of all structures in the field of poles, rod, and timber construction. The tensile forces which occur in the whole framework can be transmitted easily by means of lashing. The structural safety is provided by the timber strips, forming a lattice wall, are wrapped by clothes and ropes. The frame is connected by articulated joints which can move in relation to one another. It is also able to transfer forces to other members, but it is not able to transfer bending or flexing forces.
2.2-Form and structure

The person who designed the first traditional tent mentioned above is unknown. In fact, it is impossible to name any single individual as an architect in this field. The design of the various traditional tents in their present form developed over an unknown length of time. They have been adapted to changing conditions in the tribal community. The design and fabrication of these tents was always communal. Many peoples were working on each structure and leaving the mark of their craftsmanship and ideas.

The development of the tent as an architectural form was also dependent on the availability of material and the purpose which the tent had been designed to perform. On such a basis, when the skin of animals became more scarce and contact with the traders became more frequent, they adapted their architectural form to the material that was available such as canvas. Almost all traditional tents could be made from canvas as well as from skin of animals, birch bark, mat, etc.

When we are talking about structure and form in this field, it is obvious to say that the structure is the form and the form is the structure. There is a unique relationship between form and structure in this field. The simple poles that pitch the tent are the main structure and determine the form and scale of the tent. The anchoring and securing techniques are also supplementary components of the structure. Any change in a bearing element will directly affect the form of the tents. Its elimination will cause the failure of the whole structure. On the other hand, by adding a new element or modifying one or more elements, a new form will be generated. The best examples are the Arabian black tent, the form is dependent on the number and size of the poles and the tension strength of the cloth.

The traditional tent environment explained in the first part of this study has displayed the requirements of a suitable tent structure. The requirements are based on the need of its user within a specific context, and the availability of building materials and the intended use of the structure. In general the form and structure of the traditional tents are entirely dependent on the following aspects:
- The need for mobility
- The access to building material
- The performance of the structure within the environmental context
- The ingenuity of users and skill of craftsmanship
- The wealth of nomads
2.3-Jointing technique

The traditional jointing techniques were characterized by the use of local materials, a definite style of design and a well-established method of construction. It was usually the work of a small society with its own set of rules. These rules were passed on from father to son. The simple use of one or two natural materials led to a few recognized methods of construction. Correspondingly a limited number of ways of making the few joints were needed. These methods were used, tried and tested over many generations, so that they became proven and reliable.

Some nomads used several pieces of poles jointed together and formed a long pole. They usually used overlap jointing. The two pieces of timber were formed by placing the end of one piece over the end of the other and fastening them by means of lashing. Sometimes the half joint has been used, it is made of two pieces of wood of the same thickness. It is formed by cutting away half the end of each timber and placing the cut surfaces together, then the joint is lashed by means of rope or raw hide.

However, the performance of a joint in a structure is the way it behaves under stress. Such behaviour depends on the material and form of the joint, its location, and the external forces to which it is subjected. The location of the joint in the structure determines the forces that will be transmitted, and accordingly it will be designed. The forces which operate at a given location determine the functions of the joint at that location and should determine its design.

The two components that are to be joined are connected by means of a jointing section or component such as dowel, nail, pin, and rope lashing. The best example is the lattice yurt, the lattice wall and roof of the yurt. It is the most efficient form of simple jointing technique. The holes are drilled in the roof's ring or crown and the sharp end of the roof poles are driven into the holes to give a tight fit. The frictional forces between the sharp end of poles and the sides of the holes in the components combined with the elasticity of the materials produce the fixing. The two components are fitted together and fixed without the intervention of a jointing component such as nail, pin, or rope. In general the jointing techniques and other forms of connections are largely dependent on the following principles:

- The function; a joint aimed to perform a specific function. Controlling a passage of water, snow, dust, and heat or resisting stress in one or more directions. It might be subjected to compression, tension, shear, torsion, etc. The specific function of a particular joint is to a large extent determined by its location in the structure.

- The location; the performance of a joint is dependent on its place in the structure. The joint between the same two components will have to perform in different ways if the location is changed. The location effects the behaviour of
Table-g. Various types of traditional tent fasteners and jointing techniques of black tents.
the joint, and also determines the function requirements of the joint.

-Material and form; the performance of a joint is also dependent on the material on which the size and the form of the joint can be determined. The techniques, treatment and size of a joint is not necessarily the same with all materials. They may be simple with one material and complex with others.

The industrial and social revolution with new materials and methods of manufacturing have changed the relationship between man and his environment. The ability to construct effective joints in the traditional way, have together with craftsmanship gradually been lost. The new materials and the new needs have resulted in new forms of construction, methods of assembly and jointing techniques.

2.3.1-Lashing method

The term lashing is used when two or more solid elements are jointed together by means of rope. Lashing is an extremely useful way of tying the structural components. It offers enough rigidity to stabilize the structure in certain circumstances. The amount of rope material used in a particular joint is dependent on the sizes of the elements being lashed. Also on the intended use of the joint in relation to the function it has to perform. The type of lashing is largely dependent on the type of loads applied on certain joints and the usage of the structure.

The lashing methods are the simplest form of jointing in the field of tent structures. They are believed to be the fullest kind of self-help way of construction. These methods which are described below are also used together with other components such as nail, and bolt, to ensure the stability of the structure. In general they are classified as follows:

-The square lashing; this is the simplest and best method of fastening. The two poles are situated at right angles from one another. Then the ropes are turned squarely around both poles, with maximum tension at every turn. The number of turns is dependent on the relative sizes of the poles and the ropes. On average it can be said around four times. When sufficient turns have been put around the two poles, the frapping turns will be put on. These turns have the effect of pulling the whole lashing together and making it impossible for the rope or poles to slip. The square lashing will be finished with a clove hitch on the opposite pole, in the same way it was started. (see Fig-51.a)

\[\text{15} \quad \text{These simple lashing techniques have promoted the use of rope and steel wire in jointing large components even outside nomadic environments. Apart from the unique advantages, lashing also provides an obvious recycling opportunity in the construction of similar structures.}\]
Trends of Fabric Structures in Architecture

(a) square lashing

(b) diagonal lashing

(c) sheer lashing; tripot lashing

(d) sheer lashing; round lashing

Fig-51. The treatment of rope with round timber poles (lashing), can be recognized as the simplest way of jointing two rigid elements.
- The diagonal lashing; when two poles are crossing each other and forming a (V) shape, then a diagonal lashing is applicable. First two poles are attached in the right place, where the lashing must take place. Then a knot, and rope turns in both directions as square lashing. Finally the rope is turned between them in order to tighten the main turns by squeezing them between their wraps. It is usually finished with a clove hitch as in square lashing. (see Fig-51.b)

- The sheer lashing; sheer lashing is used when two or more poles are lashed to form a structure. There are two forms of sheer lashing used to stabilize a structure. The round lashing which are tighteneded together and no movement is possible. The tripod lashing or loose lashing, which offers the flexibility in the direction where it must spread.

- The round lashing; this is a very simple form of lashing, where no frapping turns are employed. The lashing is used for overlapping poles, in order to obtain greater length. The rope is turned parallel to each other, and for each overlap at least two lashings are used. The lashing will be finished with a clove hitch around both poles in the same way as it was started. It is usually tightened by driving wedges into the end of the lashing at the gaps between the poles. (see Fig-51.d)

- The tripod lashing; this method of lashing is used in order to form a conical frame, such as a tipi conical tent. The poles are laid parallel to each other and the ropes turned parallel to each other. The poles are opened before completion, then the rope turned between them. The opening of poles will tighten the main turns. The last turns between them will provide further tightening to the main turns. The length of lashing depends on experience, it can be said that the long sheer lashing will prevent the opening of the poles. (see Fig-51.c)

2.3.2-Covering and cutting pattern

The method and principle of a cutting pattern lies in the strengthening properties of the material and the load applied to the surface. The form and the geometry of the surface are entirely dependent on the loadbearing capacity of the material. Thus, the determination of the roof cloth is based on the behaviour of the material and the geometry of the surface, which is usually determined on the principle of load applied to a surface.

The aerodynamical form of black tents such as the Arabian black tent and its related form through Africa and Asia arose from the covering materials such as black goat hair, cotton, and wool. These materials have the capacity to be stretched and fabricated in a way according to the size and system of structure. It is the particular tensile quality of goat hair that gives the black tent
its distinctive form. They are made of pure goat hair, but often sheep and camel wool or a plant fiber are added. The sheep wool stretches much more under tension than camel hair which is short and weak.

The black tent dwellers are weavers, they use looms to weave different types of cloth, such as a roof, walls, tension bands, and floor carpet. The life of these materials are usually from five to seven years, and are gradually replaced by adding new strips. The lower part of the cloth is kept higher from the ground in order to avoid rotting, by using the long rope anchors. The roof cloth of the tent is determined by the number of strips of fabric sewn together. The size of the strips is determined according to the size of the tent and the load applied to the surface, such as poles and anchors. In most cases, additional tension bands are sewn on each seam of the cloth, in order to resist the high tension forces.

In general, the black tent is covered with a rectangular cloth which is made of a series of cloth strips sewn side by side with loops at the edges for the rope stays. The poles are mainly placed under the seams in order to take the stress, and the cloth is stretched in the same direction as the seams by means of rope. The second type of black tent used by Arabian tribes has a different cloth than the Persian type mentioned above. The difference lies in the additional tension bands which are sewn across the cloth seams. In this case the tension bands are acting as beams for transmitting tension forces. The stability of the structure is based on the number and situation of these tension bands. In fact, the main characteristic of the black tent is based on the geometry of the surface and the strips. Each tribe has its own particular pattern of stripes, which can be identified by the color, wider stripes and jointing techniques. They are usually sewn together or fastened with toggles and loops.

However, when the nomads had no access to such materials, they used other forms of structure in order to suit the covering material, which are not usually strong in tension, such as felt, skins, birch-bark, and mat. Therefore, the skeleton or framed structure has been derived, the covering material can be laid on the frame or wrapped around the structure, such as the conical tent of Siberia and many domical and conical tents of North America. The pattern of the covering depends on the size and the nature of the materials that are sewn together, such as reindeer or caribou skins which have a different appearance than birch-bark, although both materials are used for the same structure in winter and summer coverings. These materials have almost similar capabilities for being sewn together and are provided in one or more pieces. Some conical tents used one-piece covering in the form of a half circle such as the tipi, and most tents used several round strips, others used rectangular pieces overlapped and tied around the structure.
2.4-Material and craft

The professional craft, which grew from domestic craft, must have started with the very earliest nomads and has developed under nomadic conditions continuously from that time. The variety of crafts practiced within the nomadic groups and the development of professional craft as a separate area of production were a response to the demands of the nomadic society. They were very often unable to meet their material needs by means of exchange with neighbouring settled peoples. The development of professional craft was intensified in those places, where there was regular contact with settled people or ethnically related nomadic groups who had gone over to a settled existence. The availability of goods produced by these, based on a social division of labour, meant that the professional craft practices of the true nomads were comparatively less developed.

The different ways in which the nomadic societies developed through history gave rise to unequal development of professional craft traditions. In general, a nomadic society could not function without its professional crafts, and their products have always come from the following two main sources:
- The nomadic economy itself
- The exchange with the settled people

The relative importance of these two sources of acquisition has changed in different historical conditions, but they have always had their place. The best examples in this respect are the skeleton structure of Central Asia, and the conical tent of North America.

Materials on the nomadic society suggests that all of them had their professional crafts to a greater or lesser extent. The bulk of the raw materials used for constructing dwellings, making clothes, and tools were produced and processed by the efforts of each nomadic household individually or with the help of other members of the community to which it belonged. It was in the domestic setting that the methods of leather, wool and wood working which have become tradition were developed. Some of the achievements of the nomads of that time were so well adapted to nomadic conditions that they hardly changed over the centuries and were retained by other nomads until recent times.

Wood has long been used as building and craft material by nomads, as it is very easy to work with, but is also very light and this is important in the nomadic context. All nomads migrated around forests or open steppe so that they could easily reach timber, whenever needed. One of the best examples of the wooden work is the yurt, they were usually made in the home. Most households had a basic set of wood-working implements, although it was possible to have certain articles made in wood by a professional, who took orders from his neighbours, these included parts of the yurt frame and a few other items. Many wooden articles, especially the
wall section and their decorative ornaments were made by craftsmen. Carpentry was sometimes combined with metal-work, although it was most often practiced as a separate speciality.

There was also a division into specific areas of carpentry, whereby some craftsmen dealt mainly with the construction of tent frames, some with decorative ornaments, and others with saddle-frames and bed-frames. Carpenters usually worked on order, and often received orders from people, who paid for the goods with sheep, and goats etc. The skeleton tent dwellers used various kinds of wood for their craft. The favourite was larch, which was even used for crossbows and arrows. The more valuable items like chests and various carved items were manufactured in cedar. Birch wood, including the root, was widely used as an alternative after larch. The wall section of the yurt were made primarily of poplar and willow, both were constructed according to strictly defined traditional patterns. The smoke-hole or crown was made of undried timber, they were bent into shape and pegged down on the ground for drying. The holes in the lattice members were made using a bow-drill, and the members were lashed together with softened leather straps.

Another favourite material especially with the reindeer herders was birch bark. The bark was peeled from young trees and turned inside, ready for boiling, boiling usually continued for few days, then each piece of bark was unrolled separately and kept until roofing commenced.

A communal type of domestic craft among ancient pastoralists was felt-making. The processing of wool into felt was too much work for one family, since the work requires many people. The felt was usually made by all the households, working together. Two types of felt were produced by nomads:
- The thicker or double-layered type of felt, used for making roof covering, rugs, and bed mattresses.
- The thinner or fine type of felt, used for clothes and outside wear.

Felt-making requires large quantities of wool, for covering a yurt the fleeces of at least two hundred sheep were needed.

The rope was made out of horse’s mane and tail-hair. However, several methods have been used to make different types of ropes for various purposes. They are strong in tension, therefore they can anchor the tent and stabilize the structure. A thin form of thread is used mainly for stitching clothes, leather, and bag weaving.

All nomads were in a way leather craftsmen since ancient times. They used every type of animal skin, including their domestic animals. The leather work was usually decorated with very expressive patterns. The use of leather in making containers for carrying and storing liquids, rope, and cloth was one of the oldest invention of pastoral nomads. They were used by nomads and became widespread throughout the world.
Temporary tent community. Source: Oxfam

3-Contemporary tent environment
3.1-General principle of standard tent

The contemporary standard tents in architecture are developed and based on the creation of a human environment, that will not destroy the natural environment. Traditional structures and building materials cannot achieve the mobility and variability that the fabric structures offer, for almost any application involving small and large spaces, enveloped or covered with an infinite variety of forms.\textsuperscript{16}

The standard tents presented in the following pages are the concept of the fabric structures as a new way of thinking and a new approach towards designing and constructing. It also recognizes the overall impact of these concepts to some extent where architecture is facing today.

It is important to mention that the result of this concept could not replace the conventional structures and materials, but rather sensibly supplement them. They are true alternative solutions for a large number of housing and building tasks. They are recognized as alternatives to conventional building systems, because they indicate a trend towards building evolution. This trend will develop a new structural grammar of a completely new field of architecture, which has been developed and experienced throughout the history of mankind, and form the basis for a new architecture.

The vast number of new designs and developments has resulted from the old reliable supply and demand principle. The demand for new and better structural materials absolutely exists and manufacturers are competing to make their products lighter, stronger, weather-proof and easier to build.

In general, the tents are being developed in terms of their feasible use of interior space, as well as their shape for coping with specific environments. The tent with a rectangular floor uses space more efficiently than those with square and circular floor plans. The tent with vertical sides offers more usable space than those with sloping sides. On the other hand, low profile tents with sloping sides shed water and wind better than the frame tents with vertical sides, although they are roomier and recommended for large families and permanent dwellers.

However, these tents must be able to withstand heavy winds and snow loads, and have often been chosen for their efficiency in meeting the intended use. There are designs, features and materials to fit virtually every need. On such a basis, when these tents are used by a larger groups of people, then a form of camp or community will be developed which is fundamentally as follows:

-Temporary communities; they are durable but always erected at new places without altering their form of organization. They include the tent village of the nomads of all continents and also the very large and complex military camps.
-Semi-permanent communities; they are used for short periods and regular

\textsuperscript{16} The development of traditional tent structures to contemporary tent environment is also based on the vast demands and new applications, that required new forms and materials.
intervals which serve the purpose better than permanent buildings, such as religious festivals, markets and the modern camping sites.

-Stationary communities; they are used for the periods intended as permanent dwellings, such as refugee camps and other disaster areas. They are slowly integrated with local materials and form a traditional building system.

There are different ways and means allowing one to build dwellings more quickly and cheaply. It is necessary however, to know about several initiatives and procedures used at present, in order to appreciate the many efforts that have been undertaken in producing building materials. The procedures and initiatives are promoted by manufacturers that are producing prefabrications. The flexible fabric produced in a factory is a form of prefabricated material to be transported on site. The prefabrication of tent structures can generally be divided into the following two groups:

-Total prefabrication; the whole structure can be made in the workshop, ready to be transported to site and used immediately.

-Partial prefabrication; the structure is partly made on site, only certain essential elements have been made in the factory to be integrated in the whole structure.

In this connection, there are other ways capable of improving dwelling productivity such as:

-Standardized elements; they are decreasing the cost and improving dwelling productivity and replacement.

-Normalization; establishing the characteristics and modules in relation to the shape, quality and dimension of the different constructional elements.

-Simplicity; towards minimum use of machinery and labour.

-Flexibility; establishing the structure for ease of assembly in practical application, which brings a decrease in price.

3.2-Standard tent

The thin woven walls and roofs, the unlimited adaptabilities to function, the easy, quick and safe way of erecting and dismantling, even of converting according to need and other related factors make the standard tent the most efficient form of a one storey dwelling.

The traditional standard tent materials and systems are replaced by sheets of canvas and woven fabric, stretched over tubular steel or aluminium frames. The manufacturers of tents today try to produce as cheaply as possible in order to compete. This results in a reduction of quality, and has become a characteristic of the majority of standard tents. On the other hand they are improved technically and aesthetically, for instance by eliminating the guy ropes, they are offering a better form and interior space for further combination, and by making them flame-resistant.
The standard tents for living accommodation are arranged individually and often special service tents are integrated into the camps or communities in the form of mobile homes, offering as much comfort as permanent houses. In order to form a community and living spaces, the family skeleton tent should be considered, which functions without guy ropes with climatic improvements. In addition, with large tent structures higher densities are possible, but they require more technical skills to erect. However, it can be said that the standard family tents forming a community offers higher densities of accommodation than any other form of single storey building systems. They have thin walls with adaptabilities to serve as sleeping, living and circulation areas.

3.3-Emergency shelter

In order to understand the problems that are associated with emergency shelters and disaster housings, we must realize that disasters, man-made or natural are a human problem. The impact of our effort on housing must be viewed in the context of the particular society that builds and occupies the housing units. Housing is not a simple design or structure, it is a complex product of a very complicated process within a culture and a society. It has been described many times in detail and is far beyond the scope of this study. This study is rather an attempt to introduce the capability of tent structures as a possible shelter accommodation and textile as a proper building material.

The emergency housing program today excludes the victims from participation in decision making and ignores the local building community. When a disaster occurs an area is requested or assigned by the government. They estimate how many victims need housing, and the availability of funds. They divide the amount of funds by the number of structures needed in order to determine the investment per structure unit. The implementation agency runs its program in such a way as to provide shelter for the families. The agency designs a few standard structures to be adopted, local personnel are hired and trained and mass construction begins. In most cases the funds run out at the middle of the program and the agency measures their success by the number of structures that were built. There is no consideration within a certain time, if they are above or under budget, and the percentage of families that have been accommodated. The success is usually measured in terms of the donor and not of the user. The materials used may not be replaced, and the structures which have been built cannot be repaired or maintained.

However, the emergency shelter and disaster housing can not be achieved by the normal housing process in the preliminary stage. Disasters are a separate event, therefore an urgent immediate need for shelter is required. This need
can only be fulfilled by means of portable textile structures, so called tents. They can be integrated little by little with local materials in the subsequent program.

There are also some disruptions in the normal building process, both in long and short term disasters. Such as transportation of materials, the normal market for building materials and coping mechanisms to enable a community to begin the process of normal construction. Therefore, there is a need for rapid delivery of relief items, which requires an immediate response. The normal process of building development is too slow.

Apart from the above needs; disasters provide an opportunity to create changes in housing and adequate understanding, to create long-term changes within the community.

The tent and textile structures have the ability to effect changes in housing by means of technology transfer. Change in housing is a long-term process that is dependent on the availability of materials, the ability to teach and transfer the technology. In a way that is comprehensible to the users, and the ability to keep the costs of construction and maintenance within the reach of the users.

In general, the tent could not replace traditional or existing housing methods. It can offer an opportunity for the agency to acquire some knowledge and understanding of the situation which is different, country to country and village to village. It can strengthen the development program and process towards its implementation.

The tent structures can be developed even in the less developed countries. All members of families can participate to erect and modify the structure. It offers a high flexibility in terms of its function. It copes in every ground condition and can be replaced or formulated within a normal housing unit. The tent structure is the only shelter unit that can meet the need of victims, it is compact, transportable, and can be produced all over the world.

3.3.1-Tent as emergency shelter

The slums and disaster environments in the world are the greatest challenge to the architect, engineer, and today’s industry. Indeed, there is clearly a failure in terms of shelter to meet the needs of hundreds of millions of refugees who live in unhuman conditions, which are as disastrous as a disaster itself.

There are a few agencies and organizations established to relieve human suffering in this matter, which are based on fund raising capabilities. The united state agency, Agency for International Development has a specialized directorate for international disaster assistance (OFDA). They have the responsibility to coordinate programmes, expertise personnel, provide technical assistance and maintain foreign relations.
Fig-52. Showing a simple tent designed by Oxfam, it uses plastic sheeting, realized in many African countries.
The OFDA carries programmes with other agencies to furnish assistance to any foreign country or international organization for international disaster relief. This includes assistance related to disasters, manmade or natural, and appeared as humanitarian help.
The OFDA does not normally provide shelter or any research in the field of shelter provision for victims. It rather carries programmes of application of technologies which exist or are being developed by other related agencies. They are prepared to respond immediately on request of foreign governments in connection of shelter for homeless victims of natural and manmade disasters.

However, the oxfam agency based in UK have been using plastic sheeting in many instances with local materials such as bamboo and mud. It has a proven value as a waterproof membrane, ground sheets, damproof, and windproof. They respond to deliver emergency shelters and primary tents within a few hours, from their stockpiles or commercial tent suppliers. They can be moved quickly by commercial or military aircrafts, ships, and other vehicles to any place in the world. (see Fig-52)

As a matter of fact these programmes and activities have developed a new alternative and improvement towards tent structures that are being evaluated by victim occupants.

These universal emergency tents are developed to be delivered in a given condition such as, snowy, cold, dry, hot, and windy. It is made of cotton with external aluminium frames. The pegs are usually longer than family size commercial tents which can be used in sandy soil. In addition, there is a separate roof made of canvas installed as a fly above the tent to break rainfall and keep the sun off the tent roof.

As all scholars believe that whenever possible local materials and local labour should be used. If this were not practical other materials should be searched, that would be inexpensive to transport, both in terms of weight and space.

However, the first material investigated was polystyrene, with the advantage of low cost and high expansion qualities. The material has excellent thermal properties for insulation. It resists to fungi, bacteria, and rot, and has no food value for rats and insects. On the basis of being a thermoplastic, the material shrinks from the intense heat of fire, and self extinguishing grades are available which prevent fire spreading.\textsuperscript{17}

The polystyrene can also be moulded, it can be designed to produce a shape that can withstand high wind forces. The resulting structure is strong and rigid but of low weight, so that the dwelling can be relocated quickly in any event.

Fig-53. Plastic sheeting as a waterproof and windproof membrane, sandwiched between an inner and outer woven bamboo and round timber mat. By Oxfam and CONCERN, realized in Bangladesh.
The second alternative material is polyurethane with the same advantages as polystyrene but of lower cost in equipment. Although the spray-gun equipment and the use of liquid chemicals is quite complicated in terms of sophisticated technology, Oxfam proceeds with its development towards provision of emergency shelter overseas.

Oxfam and the Irish agency CONCERN have developed panels for housing in Bangladesh. Polythene sheeting were sandwiched between bamboo matting. The resulting panels were suitable for roofs or walls, and for housing of various shapes and sizes. The houses can be moved easily to new sites when required. The bamboo is available locally and the imported polythene sheeting has the advantage of being cheap and easy to transport. The panels are made on site and some houses have been built by the families themselves. (see Fig-53)

The panels can be made from a variety of materials, local and imported. They are very light, have good thermal properties, and provide rigidity and water proofing.

3.4-Structural system

The various structural systems which are particularly suited for standard fabric structures are presented in Table-h. They use straight and curved poles or are stabilized by means of reinforced woven fabrics.

The single straight or vertical pole can be arranged in a variety of ways such as fixed at the base, stabilized by means of rope or cable and woven fabric. (see Fig-54) Other structural measures that use a single rigid element or multipoles also offer a variety of forms and interior spaces. (see Fig-55)

By placing the horizontal pole on a vertical support, other forms of tent structures can be obtained which require reinforcing. The structural elements can also be arranged parallel or diagonal to each other. With various heights, forming box frame structures, suitable for single standard dwellings. The covering fabric will transmit forces to the ground and keep the structure under tension. If by any chance the woven fabric is not reliable, other additional rope anchors will be fixed to the critical point of the structure and secured to the ground.

The simple standard tent without central support can also be constructed, using poles jointed to one another at the top, forming A-frame tent. Each additional pole will provide additional stability. In this case if the poles are connected in pairs and arranged parallel to one another, a highly efficient system will be produced. (see Fig-56)

Arch and curved poles also allow new structures to be developed. They are determined by the elasto-mechanical behaviour of the elements used either in one or several pieces. On the basis of this principle, polygonal and round domical tents have been developed. The domical and arch tents are typical
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Table-h. The main structural system of standard tents, using straight and curved poles. Showing their evolution towards permanent dwellings.
frame tents. The bearing structure is formed by relatively rigid elements. The woven fabric is extended as covering, at the same time reinforcing the relatively light frame. (see Fig-57) In fact, the woven fabric is capable of sustaining tensile forces, transverse to the rigid tent elements. The strength of the woven fabric gives a double curved, highly stable, and biaxially prestressed form. A variety of characteristic arch forms can be produced, depending on the end fixings of the bearing elements. It is important to say that as a part of a structural system the arch must be prevented from tilting. This can be achieved easily by means of anchoring. Other forms can also be produced by means of additional arches. The single arch usually requires additional reinforcing measures. The arches arranged parallel to one another will form a tunnel tent structure. Arches inclined against one another will need a special connection. Finally arches tied together at the top will form a domical stable form.

From the above basic knowledge in this field one can realize the possibilities of changing conventional dwellings and living spaces. By replacing the covering material to woven fabric and by reduction of elements in a heavy skeleton structure such as the bearing system, a very efficient system of construction will be produced. This is in response to many social and economical demands that require rapid physical form. (see Fig-59)

3.5-standard tent classification

The various structural forms of woven fabric dwellings have been realized to meet the need of their occupants in different environmental contexts. In general they are classified in terms of their interior spaces, ground plan and as well as their structural form, that can be described as follows:18
- The square and rectangular tent
- The round and polygonal tent
- The large standard tent

-The square and rectangular tents are a very old form of tent, which can be manufactured from a few simple poles. The erection of such a tent is very simple and does not require great accuracy, it is stretched out on the ground and tied down with ropes. In the event of intense heat from the sun, the whole tent can be double skinned, in this way there will be a pleasant, cool and diffuse atmosphere. The square and rectangular tents are today produced on a larger scale and have resulted in permanent family dwelling. (see Fig-55)

18 The nature and characteristics of various standard tents have been investigated in Saudi Arabia by Bodo Rasch. The tent cities of the Hajj. Institute for light weight structures, University of Stuttgart, 1980, pp. 61-68, 91-92
Fig-54. The possible forms and structures using only single straight pole and rope anchoring. These tents are designed under the effect of the load symmetrical in regard to the central pole.
Fig-55. Showing various type of tents using multi-straight poles and rope anchors. The fabric material is not only used as covering but is also strengthening the stability of the structure.
Fig-56. Various types of tent using diagonal poles. The fabric material covers the structure and at the same time strengthens the tent frame.
Fig-57. A variety of possible tent types that use arched and curved poles. The system is stable when the fabric material is used to carry loads and strengthen the tent frame.
Fig-58. Showing different types of family tents, designed as semi-permanent dwelling.
Fig-59. Showing the possible skeleton tents designed as permanent dwellings. The walls are mixed structures, consist of timber and the cladding material is woven fabric with wind and rain proof properties. Sandwich panels are also applicable, providing high heat insulating properties.
A. Hai Yousufi.

-The round tent cannot be used repetitively, unlike the square and rectangular tents, it remains a single unit. (see Fig-54) Therefore, the polygonal tent has been produced in order to arrange the combination of various structural forms for a certain order and pattern of a specific community. The grouping of such tents are necessary to establish a high density community.

-The large standard tent has been derived from square and rectangular standard tents, by adding a few more poles and masts. The large standard tent in a community or camp serves a variety of functions, such as restaurants, shopping centers, meeting places, schools and many other social and religious activities. (see Fig-55) The roof is simply stretched over the rows of poles with sloping, in order to shed the water. The front is usually kept open with the tent flap, or a separated panel held up by poles forming a shading canopy.

The large standard tent, the skeleton tent cladd by woven fabric has been derived from this. It is as comfortable as conventional housing accommodation. (see Fig-59) In fact, such structures indicate the evolution of a simple tent to a permanent dwelling. The construction of these tents is dependent on the complexity of the structure, the size and the climatical condition of the environment. However, it is likely to use double layers of woven fabric or sandwich panels with insulation material which will improve its long-term performance.

3.5.1-The wall

The walls are initially associated with the roof, which are different according to the form and structure. In general, it is useful to make walls made of mud, woven fabric sandwiched between bamboo, earth mixed with straw and mud walls reinforced by tree branches.

The choice of wall construction depends on the requirements in respect to the strength of the wall material and its use. The requirements which walls and wall openings should fulfill are protection against animals, rain, wind and sun. Providing optimal ventilation, lighting and an optimal view.

The following types of wall construction are also believed to be suitable as roofing:
- The woven fabric walls; which are mixed structures because only the wall frame or structure consists of timber. The cladding materials are woven fabric and they are wind and rain proof. They have good heat insulation properties and a very low weight that can be used as roof covering.

- The sandwich panel; they are made of double layers of woven fabric, acting as a double glassed panel within a timber or aluminium frame. The cavity which in most cases will be filled with leaves and straw will provide high heat insulating properties.
3.5.2-The door and window

The openings for doors and windows can be provided on the places where less tension occurs. They are usually made by a cladded frame or by available local material in an integrated manner. When the openings in tent structures are the only source of leakage, the number and size of the openings must be minimized.

The simplest form of window and door is an curtain in the wall without frame, which can be rolled and pined or zipped. These openings are used for a very temporary form of structure and considered as screen openings without using any fittings. (see Fig-60)

The most common form of doors and windows are the framed openings with a shutter. They are used to meet the need of permanent tent dwellers. The frame is made of timber, aluminium or steel covered by transparent or translucent woven fabric and fixed to the main structure.
The jointing techniques of the opening frame to the bearing structures are dependent on the local skills and applicable devices.
For simple standard tent structures the hinged shutters are suitable, they do not require more developed technical methods of construction. They are made from the same transparent materials and are slightly larger than the wall opening. They are usually tilted outwards in order to shed the seasonal water and provide shade in sunny days.

3.5.3-The roof

The roof of tent structures is made of fabrics, and fabrics sandwiched between bamboos. They can be covered with straw, mud and other available local materials, in order to improve their performances in a particular environment.

Primarily the shape of the roof is dependent on the climatical condition of an environment. Therefore, the tent structures through their flexibility and adaptability offer the possibility of roof modifications in any desired shape.
The roof structure of the family dwellings (see Fig-59), is constructed from timber members. They are a primitive form of construction having the form of a pitched roof. Their bearing supports are anchored and sunk in the ground, stabilized by additional rafters to form a skeleton frame structure.
It is important to mention that the roof is also the place of leakage in a rainy season, therefore additional protective layers are needed to make the roof as waterproof as possible.
Fig-60. Showing various possible openings used in fabric structures.
3.5.4-The ceiling

The tent and tent-like dwellings are usually single storey accommodations. Therefore, there is no need for an upper horizontal load bearing structure. In most forms of such structures the wall is the roof and the roof is the wall. An additional curtain as a suspended ceiling can also be used to change the interior space in any desired form. In general the wall and the roof which appears to act as a ceiling must be considered together in the form described earlier.

3.5.5-The floor

Floors are constructed according to the ground condition. They are made of mud with straw covered by carpets, timber and mud combinations, brick masonry, and wooden constructions in various available techniques. The floor of traditional tents of nomads were rarely raised high off the ground. Rather they used perimeter walls to prevent the water penetration and covered the compacted floor by straw mats, felt and skin of their animals.

The floor and foundation is dependent on the intended ground and climatical condition. It is, however, possible to erect the structure on a plane compacted soil, or slightly high or low from soil surfaces. They are usually considered for temporary and instant structures. However, the most common floor surface is round timber laid parallel to each other on the ground and covered with wooden boards. (see Fig-61) The round timber poles are usually placed loosely and held by floor finishings. It keeps the floor slightly above the ground surface, suitable for the purpose of sleeping. When the ground is not suitable to be raised with earth, than the floor can be raised on structural poles. It is more practical and will create a useful storage space underneath. They are usually considered for permanent dwellings.

3.5.6-The foundation

Foundations are also dependent on the ground and climatical condition of the circumstances. If the structure and the entire building are very light, it is possible to avoid foundations. On the other hand, the foundations are also dependent on the system of the structure and the purpose of usage. For a very temporary and simple form of structure, the anchors by means of stakes, pegs and skewers are applicable. They are designed to meet the needs of various structural forms in any condition.
Fig-61. Showing different types of floors and foundations, which are dependent on the ground and climatical condition of the context.
In general, it can be said that the elements which are capable of transforming the forces to the ground are considered as foundations of the tent structure, either by tension anchors or rigid elements. Sometimes brick or stone masonry can be integrated together with the main post of the structure. The construction method of stone is simple, firstly the ground can be dug (its depth is dependent on the soil condition, structure and circumstances). (see Fig-59) Then the pieces of stone are placed on one another until they reach the required level of the ground floor. Normally the stones are used with mortar or mud. In this case the floor will be raised above the ground level to avoid the dampness.

As long as the structures do not possess any bearing walls, they do not require any massive foundation. The weight of the entire building can be transformed through the main pillars of the structure.

The main pillars of the structure can be achieved by timber or steel. The availability of wood and its treatment within our building technology tends to be the best structural material in this field. Therefore, the wooden pillars which can support the entire structure can be driven into or just rested on a piece of stone in order to be protected from rapid decaying rises due to dampness from the ground, fungi and insects. In addition, it is also protected from water and snow during wet seasons that normally affects the base or lower portions of the structure.

Timber can be protected against fungi and insects by chemical means and by proper ways of designing. The problems arise from the foundations of the structure where soil constitutes the major source of moisture. The protection of timber from termite attacks by chemical methods can be achieved through poisoning of the soil around the foundation and beneath the suspended floor. It is also possible to keep the timber dry in a structure through proper design, to avoid the weather hazards and to keep the rain water and direct sun off the wooden parts of the structure.

However, the foundation in a permanent structure must have a good bending and torsion strength to keep the dwelling safe from outside forces, such as high winds, rain, snow and frost action.

### 3.5.7-The anchoring

The detail, treatment, size and number of the anchors used in fabric structures are dependent entirely on the design, the system of the structure and the ground conditions. When the ground is poor such as sandy or muddy soil, the fork peg in the form of a tree-branch is applicable in order to keep the anchoring rope constantly in tension at all times, providing adequate holding power. (see Fig-62) A variety of tent pegs and stakes are available for various conditions, and they are usually made of timber, steel, aluminium and plastic.
Fig-62. Showing various types of anchoring, which are dependent on the nature and system of structure and ground condition.
Fig-63. Showing the various techniques used for securing the woven fabric to the structure. The sharp edges along the rigid elements are avoided in order to prevent tear and degradation of fabric material along the edges.
The stability of a structure is dependent on the rigidity of its elements and the anchoring of fabric at the soil level. It is preferable to sandwich the fabric between the sawn timber which will resist tearing. If sufficient sawn timber is available, the full length of the tent could be used and nailed at several point. Sharp edges and unsuitable materials for securing the fabric should be avoided.

The simplest method of anchoring the woven fabric to the ground is to dig a shallow trench and bury the length of the fabric. The following illustrations show the methods of improving the anchorage between the woven fabric and the ground. It also explains the basic techniques for securing the tent fabric to any part of the structure. (see Fig-63)

However, the fabric structures are inherently economical structures, since they utilize rope and cable in the most efficient way. In general, the most expensive part of a fabric structure is the support system and the tension anchors, or the system in which a structure is stabilized. The structure can be self supported, in which the tensile forces can be resisted by the boundary structure. Due to either its geometry, weight or both, and non-self supported, in which the forces can be transmitted to and resisted by anchors in the ground. The type and method of anchoring are chiefly dependent on the following aspects:

- The structural system; whether it is a skeleton, single or multipole structure, stabilized by its covering fabric and anchors.
- The climatical condition; which is dependent on the location and environmental context.
- The ground condition; which depends on the regional context.
- The availability of relevant materials.
- The skill and cost of available manufacturers and labour.

The anchor which is made of rope and cable has played an important role in the field of fabric structures. Apart from its force transmitting capability, it determines the shape or the main form of the structure. It is considered as important as rigid elements towards the form determination.

3.5.8-Service and infrastructure

As all conventional dwellings need a place for stove, cooking and sanitary, the fabric structure also offers the possibility of constructing a chimney and connecting water facilities. The sanitary and facilities are dependent on the circumstances. It is likely to build apart as a common or public sanitary center for a specific community.
Sun collectors and sun cells can also be used to warm water, and artificial light can be installed either inside the structure or outside in different spots around the area.
The provision of infrastructure is based on the same principle as a conventional or normal sanitary network. When the community is set up as a temporary camp the arrangements for supply and drainage are kept mobile. In order to avoid permanent alterations through water pipes, ducts and electricity mains. These can be arranged in a form which is independent from the main supply network. Toilets and washing facilities can be put into mobile units. Supplying fresh water to be sufficient for an intended period of time, waste water will be collected in a container which can be emptied regularly.

The washing and toilet facilities can also be installed in a permanent manner. They can be integrated with the existing infrastructure and connected to the public utility network. In general, one can say that the principal mode of use of all toilet and washing systems can conform to local customs.

3.6-Fabric properties

The fabric material fails when its tensile strength properties are no longer able to withstand the stresses to which it is subjected; under the influence of its own weight, tension forces and outside forces such as rain, snow, and wind. Therefore, the fabric material must be strong enough to stand up under the various conditions of field use. The tensile strength properties of the fabric are much more important than other properties such as water, fire and mildew resistance.

The fabrics which are used in tents and tent-like structures must also be weather-proof and waterproof. Canvas fabric has both advantages, but it is subject to mildew and rot if it is not dried. It will begin to leak during the rain storms as a result of tent poles and frames. However, in order to solve the problem of leaking, the roof of the tent must be made of nylon fabric. Also by adding a suspended waterproof fly a few centimeters above the roof of the tent to get the water out of the main tent surface.

However, today various type of fabrics have been developed which are much lighter than canvas and will not rot or mildew. The fabrics are flame retardant, made of strong and durable materials with excellent flexibility and will not stretch or shrink.

In fact, these qualities have contributed to the creation of modern and functional tent designs. Because fabric properties have always been a limitation to structural and architectural design.
3.6.1-Fabric behaviour

The plastic materials such as polythene, polyvinyl chloride (PVC) nylon, terylene, polypropylene, etc. are produced in the form of thin flexible sheeting. They can be reinforced with a square mesh of natural or synthetic fibers, or even, reinforced with steel wire, nets and cables to give greater strength and resistance to tearing. These reinforcements will also increase the cost and weight of the fabrics.

The polythene sheeting has many advantages when compared to other materials. It can be used as a waterproof material, its cost and weight per unit area are very low, and the main advantages over many other materials are as follows:
- It is waterproof and has a very low moisture vapour permeability.
- It is unaffected by salts, dung-urine and most agricultural chemicals.
- It is unaffected by moisture, and deteriorates slowly in the sunshine.
- It is flexible to temperatures below freezing point, and melts at 115 °C but starts to soften and loose strength at above 80 °C.
- It will not rot even if buried in fertile soil and it is not readily attacked by insects.

The unreinforced polythene is also tough enough to withstand wind stress adequately if correctly fixed to the structure. In addition, the thermal insulation properties of polythene are poor, but by using double layers of fabric and sandwich panels with an insulating material such as fiberglass, mineral wool and straw, a well insulated atmosphere will be created.

However, when the temperature within the structure is high in the sunshine, it can be reduced by means of pigmentation and even mud slurry. The condensation may form on the inner surface of the structure. It is the result of ground dampness and occupancy inside the structure. It can also be reduced by using ground sheets and carpets to prevent ground evaporation and by increasing the ventilation possibilities.

Although, these materials can be used with great effect for the purposes intended, they can also be a major form of trash in urban or rural areas. Some materials will deteriorate with age, exposure and disintegrate. Thus it is essential that every effort must be made to control the distribution of fabric and dispose of its waste in an appropriate manner.

3.6.2-Fabric degradation

Degradation of the fabrics is determined on the basis of the exposure time and
the solar radiation received. In fact, the degradation of a fabric is largely dependent on the meteorological conditions which prevailed at an exposure area and which are also a function of its geographical location. The factors which produce degradation are not necessarily the same in the various locations. These factors include solar radiation, temperature, moisture, rainfall, and dust or industrial gases in the area of exposure. The transparent fabrics are also slowly weakened by continuous exposure to sunshine. The durability of clear fabric used outside can be considerably increased by adding chemicals called ultra-violet light absorbers during manufacturing. It is available commercially and it lasts at least two years when continuously exposed to sunshine.

In some cases when the structure is exposed to sunshine for a long period at high temperatures, the rigid element of structure will absorb and hold heat such as metal and steel. The fabric in contact with this hot structure will weaken more quickly. It is necessary to protect the contact places by using anti-hot foam tape and other means of pigmentation.

3.6.3-Fire retardancy

The artificial textiles used today for tent structures are all combustible. The danger associated with fabrics in connection with fire is much less than timber, because they do not flame, but rather will melt slowly. However, it is possible and easy to flame-proof fabrics, such as military tents with an increase of about 15 to 25% in weight. Although fabric with natural fibers such as cotton burns slowly, it can also be treated with flame retardants and will become more expensive, darker in color and heavier than normal fabric.

3.6.4-Fabric colour

The choice of colour is usually dependent on the climatic and environmental condition of the context. The dark colour has been used and suggested in the areas which are cold and cloudy, it will absorb the heat and admit enough light. Light colours are used and advised in areas with constant sunlight and heat, in order to reflect the solar radiation and provide a relaxing atmosphere with natural light inside.

On the other hand, the choice of the colour is also related to the design, appearance of the structure as well as the surrounding landscape. Thus, it is advisable to build the fabric structure in two or more colours such as light roofs and dark walls or even with some decorative strips to conform with local customs.
4.1- The development of current large-span fabric structure

We have achieved so far the underlying factors that influence the development of such structures, which is the tendency towards the use of fabric structures and a large number of new applications. The tendency and demand for large span fabric structures arose from new functions, the structural properties of new concepts, which is far greater than any known structural schemes. It is difficult to measure the spanning potential of such structures, but it is obvious that they and their range of possibilities offers far greater spanning potential than any other known structural scheme.

The demand of fabric structures in architecture is based on the creation of a human environment that would not alter the natural environment. Conventional structures and building materials cannot achieve the mobility, variability and recycling that fabric structures offer, for almost any application involving small and large spaces, with an infinite variety of forms.

At the same time, one can state that the development of large-span membrane structures was largely dependent on the technological ability of computer aided design and development of new materials. New materials with a high performance quality have contributed to the creation of modern membrane structural designs, which until recently has always been seen as a limitation in many structural and architectural designs.

However, the recent advances in design techniques and increasing utilization of coated fabric and constructional materials have made it possible to construct large-span structures in a variety of geometrical forms. Thus, they offer many characteristic advantages over other conventional structures, such as lightness, economic, easy to transport and quick to erect and dismantle. Simultaneously they have also been proven to be the most efficient and successful of all recent forms of architectural experimentation, particularly in the field of large-span free interior spaces.

Since the development of large-span fabric structures in the early 1950s, the use of cable and anchors are emphasized as a convenient way of securing light weight structures. The main objectives for using fabric, and cables were large span capability and minimum use of material in free space applications. The types of anchorage were used according to the local circumstances and the development of anchorage related to the design principle. The anchorage and other supporting elements are the key in stabilizing fabric structures. The design and development of fabric structures are related to the choice and availability of cable and anchorage. The more complex the structure became, the more sophisticated anchorages were required.

In addition, it is important to mention that the development of any structure is largely based on its acceptability within a society, which is a result of its successful performances. As it was described before, the level of acceptability of fabric structures that the users offered towards new building technologies
depends to a certain extent on the adaptability of fabric structures to a higher society with recognized social standards. Thus, a higher society requires the identification of a new technology and prevention of needed technological developments to ensure a proper acceptability and make feasible the hi-tech large-span fabric structures that our social environment will accept.

4.2-A perspective on current large-span fabric structure

It has been verified throughout this study that flexible materials such as fabric and rope, together with few rigid elements, are able to provide habitable spaces, their potential for covering large-span spaces has been realized and improved with our building technology.

The new applications and demands in large-span fabric structures lead to the development of new materials and proper building techniques. The efficient use of these materials for large span applications have been improved by means of proper ways of designing and simultaneously reinforced by special building techniques.

The unique characteristics of these structures are based on the behaviour of fabric materials; as soon as the load is applied, the surface (fabric material) tends to get sufficient rigidity under a specific form. It is peculiar to tent and tent-like structures, such as monoclastic, anti-clastic, and syn-clastic. The rigidity of fabric material in some large-span structures are much more important in stabilizing the structure. Inappropriate loading will result in the failure of the whole structure.

The special forms in which fabric structures can be recognized, belong to flexible materials, that are usually produced by the incorporation of tension forces. There are mainly two types of fabric structures that have been characterized, due to the nature of the pretensioning forces:
- Air-structure or pneumatic; stabilized by the overpressure of air acting in compression perpendicular to the surface.
- Tension structure; stabilized by pretensioning of the surface, by forces in the plane of the membrane by means of anchors, masts, arches, braces, struts, etc.

The above two types of fabric structures gained their popularity since the Second World War. This was a result of the lack of building materials in the European countries.

The first pneumatic structure was built as a radome in the United States, developed by Walter Bird. In fact, he boosted the air-structure to a peak in its development by using proper mediums and related technologies to assure its function and stability. The tension structure was developed initially among professionals by Frei Otto. He developed the necessary tools and know-how, towards the vast potential that large-span structures require.
Pneumatic structures are usually associated with indoor and closed sided applications such as swimming pools, tennis halls, stadiums etc., but the tension structure with its sub-types are employed in outdoor activities and open sided applications.

Large-span fabric structures are composed of materials that can resist tensile forces such as woven fabrics, steel cables, and cable-nets. In tension structures, the compression elements such as columns, arches, braces and struts are used to shape up the intended form. Also having the ability to transmit compression forces. The fabric and cables used to build structures are extremely light and flexible. They have no rigidity or stiffness, therefore they carry loads only in tension and must be kept in tension to stabilize the structure.

However, tension fabric structures (prestressed) need guy ropes and anchors to lift up the surface and components which are under prestress, and to transfer these forces into the ground directly or indirectly. The tension structure which the forces are carried by the fabric itself and anchored to the ground, and cable-stayed structure which the structure is stabilized by external guy cables may cause some functional problems. Therefore, other forms of fabric structures have been developed to eliminate the need for external guy cables. The anchorages and guy ropes are an essential part of the structure, their elimination will change the form of the structure which has been expressed as a skeleton or a frame structure and a braced fabric structure. The fabric is planer or single curvature, and is used as cladding material. The variety of possible forms in fabric structures are infinite. Any manipulation within the structural system requires the knowledge of the interrelations between the form and structural tensions.

However, the problem in fabric structures are different from conventional structural systems. The main problem associated with a fabric structure is shape determination that is based on equal stress distribution all over the surface and the need for obtaining proper geometries as well as material properties of the initial surface. So that a complex curved surface is divided into some plain fabric strips, called cutting pattern, which are assembled to make the intended large anticlastically curved surface. This surface is not stable until the introduction of initial pre-stress or internal pressure. In general, it can be said that the final form of a structure in this field is largely dependent on the assembly of patterns which will be discussed in the second part of this study.
Conclusion

The first stage of this study has been devoted to simple forms of self-builder structures, and the current trends towards structural designs of membranes. It shows that architecture is an art and a science in one that goes parallel with science and technology. The technological developments today provide the opportunity to develop a system of structure which will fulfil the demand of our building environment and its impact as an alternative building system to conventional or traditional devices. Throughout this study one can find the capability and efficient use of such structures, which are adoptable and compatible for various applications.

The research is aimed at the study variables and to formulate the research structure based on knowledge and working hypothesis. Each section of research is at the same time concerned with the conceptual study and development of variables, and is concentrated on the design and development of fabric structures.

In fact, the dwelling is not a simple design and structure, it is a complex product of a very complicated process within a culture and society. Their characteristics differ from society to society based on political, social and economical aspects, where the relevant authorities are not at all able to cope with the urgent needs of large sectors of homeless populations. Therefore, the fabric structures in the field of low cost dwellings with a variety of options may offer a new successful alternative and solution towards the building process.

However, with the dynamic of low-income self-builders in Afghanistan and other similar countries, the research identified a tendency towards the use of fabric and plastic sheeting as a building material. The preliminary study of the social and economical aspects of the human sectors such as nomads of the world and disasters (man made or natural) have been understood and chosen as main targets.

The second stage of this study is focused on the technological development of fabric materials together with the potential improvement of the technological characteristics of tent structures for their use in low-cost dwellings. The feasibility of introducing such structures among people that have no other alternatives. The trends towards standard tents also indicates the possibility of being integrated with local materials and promises to be compatible with those made of conventional materials.

The result of this study besides the main conclusion can be outlined as follows:

- The first section of this study furnished a variety of tent structures and revealed a growing tendency towards the use of tent structures which has been neglected by relevant authorities.

- The traditional tent structures have been characterized by their vast potential
in the creation of architectural form and space. In addition, the tent systems and their mechanism have been evaluated in various environmental contexts.

- The use and advantages of these structures has been investigated and recommendations are made to improve their performances.

- The research evaluated the demand of tent structures even outside nomadic environments and their developments towards several new applications.

- The research identified the use of simple rigid poles, and anchors by means of ropes, and their impact in the tent dwelling spectrum through force transmission capabilities and form determination.

- The traditional tent environments have displayed the fact that there is a connection between traditional tent and contemporary tent environments. The connection lies on the inter-relationship between forms, forces and materials which were developed over time. In addition, one can see what can be done with natural materials and self-builders and what still could be done within our technological development.

- The research revealed the applicability of tent structures that large sectors of homeless populations are already using.

- The shelter developers in the world have created a dynamic self-supplied shelter based on the delivery system, in order to reinforce the long-term housing process. The housing process in most developing countries is not based on a static pattern but rather on an evolutionary one.

- The technological development in terms of materials and proper tools offers advantages regarding cost, time, and feasible alternatives.

- The fabric materials proved to be acceptable as proper building materials by implying proper techniques to insure its technical performances.

- Fabric structures offer in certain circumstances advantages over other structures such as portability and flexibility to be modified and above all they do not alter the landscape of environment as much as conventional structures.

- The fabric structures appeared to be the lightest structure of all, and are considered to be the most suitable structure in disaster-prone areas. The light-weight buildings and in particular the light-weight roofs are desirable in earth-quake areas; the heavier the building the greater the force is on it.

- Fabric structures (standard tents) are portable and light, they can be transported everywhere in the world within a few hours as an emergency shelter.
- The fabric materials are already distributed to homeless populations in the world by relief organizations and donating agencies working in the field of emergency shelters.

- The unique advantages of tent structures also lead to the development of new materials and have resulted in the blending of components such as sandwich panels and moulding techniques that have already found their practical applications.

- The research outlined the necessity of advanced fire protection techniques that should be developed in order to ensure the safe performances of fabric structures.

- The fabric materials are integrated with other conventional materials such as steel and concrete, producing high-tech building systems.

- The demands and new applications in fabric structures have promoted the development of tent structures for large-span applications. These demands are based on acceptability and reliability of the structure by its users.

- The research identified several new technical requirements and realized the additional analysis that would evaluate the feasibility of a high-technology application of large-span fabric structures.

- The analysis and technical requirements towards large-span structures will lead the research into its final stage in which the technological design will be achieved.

The study has also explained the existence of specific applications in the world towards the use of fabric structures and the requirements on economic, social and technological terms that are integrated in building technology.
PART II

CURRENT FABRIC STRUCTURES
Abstract

The technological developments, improvements in fabric materials, structural analysis by computer and environmental control made it possible to consider fabric structures as permanent buildings. The new technology in terms of reinforced fabric material offers a significant alternative to conventional structures with unique properties that make the roof fabric structures useful for large-span applications.

The development of fabric technology with a great number of fabric structural materials have contributed to a revolution in constructional techniques that we recognize today.

Experiences gained during the development of fabric structures in the first part of this study with particular reference to how they helped fabric development and understanding of the unique characteristics of this new technology and the special techniques for design, fabrication and construction. It also explains that the design, fabrication and construction of large-span fabric structures requires the close coordination of the architect, engineer, fabricator and installer throughout the process to assure the quality that the technology requires. The modern building technology in particular fabric structures allow design methods that develop into systems, which permit high quality.

The experiences gained in developing these structures gave us a thorough knowledge of the unique characteristics of large-span fabric structures, which is applicable not only to limited forms but to other types of fabric structures as well. It is very important to know about their structural characteristics which is much more critical than any other types of structures used in architectural applications.

Fabric structures have a significant greater span to weight ratio when compared with other structural systems. They are believed to be ideally suited for large-span and column free enclosures, because of their outstanding structural efficiency.

However, this study will promote ideas and applications much further by designing some prototypes which will demonstrate their potential. The research also identifies their unique characteristics in more depth, giving us a better understanding of the problems involved in fabric structures.
Introduction

The industrial and technological developments with new building materials, new constructional techniques and new structural forms have a profound effect on contemporary architecture, giving the architect the freedom to search for an optimum form and space. The trends towards fabric structures have been partly due to the reaction from traditional and standard tent systems. Their acceptance is rightly due to the realization of advantages offered by this novel method of construction.

The first part of this research has established the foundation and set the stage for much further development. It played an important role in providing our basic understanding of this unique new technology, and pointing out how this research influences later developments in this field.

The research undertakes variable analysis and design, integrating engineering elements with the architectural potential of those building systems. It develops new structural system that will be realized and anticipated as systems to find wide use in the future.

The development of various system of fabric structures is based on the exploitation of both the possibilities of efficient materials and the ability of the structure to cover large-spans with minimum support.

The major use of fabric structures achieved many goals and economically overcame most of the structural and design problems. They provide advantages over other structural forms such as:
- The excellent translucency options and architectural appearance.
- The very short installation time, comparing with other conventional structures.
- The visual effects both exterior and interior even at night.
- The excellent image profile and high functional potential.

The fabric structures, with the notion of speaking by itself will contribute to make architecture more attractive as it can facilitate an intuitive physical understanding of buildings. They also can lead the designer to a new gramer of structure, in a unique language.

However, the recent development and design of major projects such as public spaces are emphasizing the influence of fabric structure upon the architectural solutions.

The prime idea is to use a thin skin as an enclosure of habitable space and at the same time for load-bearing purposes. A flexible fabric is not easily suitable as a load-bearing element, it can only be employed when its capability to transfer tensile forces are utilized.

The material and system of structure are the main identity to architecture in a particular context. Throughout this study one can find that the construction of large-span fabric structures are evolutionary in nature and are updated with advancement in technology. This evolutionary nature of fabric structural systems are promoted with change in needs of the user, the application and
the times.
In relation to this understanding of the nature of materials and structural systems, the user and fabricator have understood the primary and secondary categories of materials and building systems as appropriate within the context and found almost universal applications.

The research also explains the development of fabric structures in current use, describing the influence of fabric materials and techniques towards the development of new structures. The new developments are based on new method of design and know-how, allowing us to explore the process involved in design and form-finding.

The computer based form-finding and design procedures are outlined in detail by designing a few prototype structures in order to achieve feasible use of computer aided design of fabric structures.

The new method of design, analysis and construction together with the variety of new materials have made possible various realizations. They are not only practical in use but also serve as prototype models for other structures. Fabric structures usually allow the realization of new and special structures, because they are in an experimental field, thus providing an opportunity to develop new ideas and to verify new ways of structural analysis. Most fabric structures are dismantled or reassembled, having a full-size model function for further realizations.

In addition, fabric structures can reduce energy consumption. The natural light from the translucent surfaces reduces requirements for artificial lighting, the reflectivity of the skin also reduces heat gain. The radiation of waste heat from the warm fabric surface to a cool atmosphere results in an energy efficient building in warm climates. In cold climates a second skin is normally used with glass fiber insulation in the cavity to reduce further heat loss.

Furthermore, fabric structures can be completed in a workshop, which will result in an increase of quality and decrease in real building time. In addition, this requires the contribution and close cooperation of all participants in the construction process.

To sum up, the fabric structures are usually used as a single component of an entire building; the space contain a single function, or only a roof and walls. If the other components are possibly constructed in conventional systems, then the space would contain a variety of functions.

Finally, the research will improve the professional performances of those who are involved in this field, and help readers who may be new to the field to gain a better understanding of fabric structures, their unique characteristics and the special requirements for design, fabrication and construction.
5-Introduction to fabric structural analysis and design

5.1-General principle of fabric structures

The historical development of fabric structures mentioned in the first part of this study, proceeds directly up to modern large-span structures. Tents and similar structures are fabric structures which are stabilized by a prestressing of thin skin with or without coating. They allow large-span efficiency, because of their low mass and their principle has remained essentially unchanged to date.

The fabric structures are usually considered as architectural, engineering and performances or ability of technology to a particular application. Many such structures indicate the form of origins of tent structures, which evolved as transportable shelters and as such were associated with particular site conditions. Many potential applications require consideration of very specific site conditions. It is an integral part of the design process to determine form and detail of fabric structures for particular design solutions. Fabric structures maintain many advantages in this connection as a result of their low-weight.

The main principle of fabric structures is tensile forces to hold the building down rather than up, unlike conventional building systems. This applies in particular to structures with open sides and large-span shelters, where winds can cause much greater uplift forces than gravity. Under these conditions, some forms of tension structures become impossible and uneconomic. The
fundamental principle underlying the design of fabric structures is simply that the surface must be maintained in a state of tension under any load condition.

The design of large-span fabric structures is also influenced by ground conditions, due to its major differential settlement that needs a bearing foundation and friction piles. They are usually more costly than structure itself. Fabric structures offer the possibilities of eliminating heavy foundation by using a proper way of designing and appropriate system of structures. The flexible fabric can also absorb movement, both within and between their structural components.

There are different systems of structures using fabric materials with many principles. The common principle among all are the light weight ratio and the ability to transfer tensile forces.

5.2-Structural principle

The structural principle in large-span fabric structures lies in the introduction and maintenance of prestressing forces, and the ability of specific forms and materials to transfer tension forces.

One of the important subjects in fabric structures is the prestress introducing system. The initial prestress can be introduced by tightening, clamping and other mechanisms. The additional prestress should also be introduced to the fabric surface by introducing tension force in the cables, which are attached to the fabric. The additional prestress is considered to be very effective for decreasing deformations. If by any chance the initial prestress decreases by a long term creep or relaxation of the fabric material, than the prestress can be recovered simply by the retensioning of valley cables.

Pretensioning in the surface envelope will be developed, by using anticlastic forms or saddle shapes in opposite directions. Tension along one curve is resisted by tension in an opposing curved element. Therefore, a mechanical means to stretch the fabric is incorporated into the design.

In air-structures, the stress developed in the thin surface of the spherical pressurized walls, having orthotropic properties, would be uniform at all points on the surface. The pressure differential acting on an air-supported structure is very widely due to aerodynamic pressures under wind conditions. The fabric materials used for air-structures are also non-isotropic which can greatly influence the stress distribution and design.

Experience has shown that the highest fabric stresses usually occur across the crown area. It is recognized that extraordinary care is required in patterning and assembly to prevent stress concentrations developing in this area.

In fabric structures, external loads are also fundamental subjects to be considered carefully in design process. Fabric structures require load-bearing
components for both upward loads from wind and downward loads from snow. Air-structures have no such components to carry downward loads. Their capacity to carry downward loads is equal to the level of the internal air pressure. They cannot carry substantial snow loads, they are dependant on snow melting equipment to avoid snow loads.

In tent structures, it is the valley cables that resist the upward load. The downward load is carried by cables, arches, masts, frames and special geometrical design methods. The components for upward and downward loads are usually arranged in a configuration to keep the structure stable at all time.

Cables are also used in air-structures in order to ensure the stability of structure. In this case the structure is called cable air-supported. The cables must be able to move through positioning sleeves on the envelopes during the pretensioning. Also stretching the surface fabric out as necessary to establish equilibrium conditions along the cables.

The important factor in the design and construction of fabric structures with cables is the positioning of the sleeve on the envelope. It must be able to slide along the cable during pretensioning, in order to allow equilibrium conditions to be established at every point on the surface under pre-tensioning loads.
The factor which contributes to the problem is the high temperature conditions, by developing friction in the sleeves and restricting its movement when loads are applied. In order to solve such a problem, it is advisable to use lubricated cables, which accelerate the movement at all times.

In addition, cable-net structures are also used and belong to this category of construction. They do not differ in principle such as form and load-bearing capacity from fabric structures. Their surface is made of open meshed nets of cables, having higher dead-weight and suitable for large to very large-span structures.

5.2.1-Large-span capability

The large-span capabilities of fabric structures is obviously far greater than any known structural schemes, with their unique systems and a variety of form and flexibility in term of function.

There are few materials suitable for and capable of large-span purposes, which is a result of their low-weight ratio, and behaviour under applied loads. The cables with a high ability to transmit forces under a particular load as a one dimensional element are associated with thin fabric as a two dimensional element, providing the lightest habitable spaces.

Fabric structures exist in every size, from a few square meters covered area up to several kilometers, and more than that can also technically be realized. Another fundamental difference between fabric structures and other structures is that, for membrane structures, there is no theoretical maximum span as determined by strength, elasticity, specific weight, or any other property.
The large-span capability of fabric structures are largely dependent on the following factors:
- Improvement in materials
- Advanced technology and equipment
- Development of new geometrical form giving possibilities
- New computer aided design methods
- Building budgets

The above-mentioned factors have greatly influenced the acceptancy of fabric structures for large-span applications, due to its cost effectiveness. In fact, the cost of any structural systems rises with the increase of span, but the cost of fabric structures is independent of span. They can be built as a single function by covering a large area as an envelope. Even an entire city can be realized in this way. Also as individual units, in any desirable configuration, in order to fulfil multi-purpose functions.

In general fabric materials are impractical for large-span structures, as a result of their low-strength. Therefore most manufacturers in this field try to develop a cabling system of structure, to reduce the fabric stress. The transverse loads should be carried by the cables, which can be anchored directly to the ground.

5.2.2-Light-weight efficiency

Fabric structures are the lightest structures of all, because they have a very low dead weight. The low dead weight materials are very efficient in large-span structures. The capability of any structure to cover a large area depends on its weight ratio.

The variety of possible forms is infinite, the forces which act are generally known, and the number of available materials are limited. If an attempt is now made to increase the load bearing capacity of a structure or to reduce the amount of material required for a particular structural task and for given forces, knowledge of the interrelations between the form and the mass of the structure and of its ability to transmit forces is vital. Form, force and mass are directly dependent on one another and together determine the efficiency of the structure.\(^\text{19}\)

The weight of the roof materials used in these structures usually lies between (0.5) up to (1.5) kg/sm for small and medium structures, and from (4) up to (6) kg/sm for large structures.

Obviously, the dead weight of fabric materials are largely associated with the

type of coating, yarn strengths, fire and weather-proof substances. Therefore, the dead weight of fabric materials will increase with the above mentioned factors, which will increase the quality and durability of structure.

It is difficult to mention the exact dead-weight of fabric structure, which also depends essentially on the kind and design of structure, the cladding, additional strengths, and insulation materials. However, in general the dead weight of those buildings executed with cladding and insulating materials measures between (40) and maximum (80) kg/sm.

5.2.3-Functional requirement


It is important to take under consideration the requirements of the application and the function of the structure in order to determine an applicable system of structure. It will meet the need of its users, such as space requirements or column-free requirements, occupancy task, duration of exposure, regional norms and standards, and other specifications in connection with the application and the site condition.

The air-structures are generally employed for enclosed spaces and offer the opportunity to control the internal environment.

The tension structures are generally more suited for open space structures, where a limited environmental control is concerned, such as protection against rain and sunlight.

There are other sub-types of large-span fabric structures, falling under both an air-structure and a tension structure. They will meet all functional requirements of a specific application. Thus, sub-types of air-structures are also suitable for open spaces, and sub-types of tension structures for enclosed spaces.

In fact, it is reasonable to say that for small and medium size structures, suitability goes to tension structures, where the additional costs of mechanical air handling plants, including backup facilities and regular inspection and monitoring would not be required. For large closed structures, the air-structure and cable air-supported structures are more suited than any type of tension structures.
5.2.4-Form and structure

The form of tension structures is the result of external forces, unlike the air-structures which are maintained by the internal air pressure inside the structure. The external forces that stretch the membrane into the desired shape imposes various limitations on the shape that can be formed, such as spherical surfaces which are very difficult to pretension, but can easily be generated by internal forces as air-structure. Other forms such as hyperbolic paraboloid are peculiar to tension structure and can be generated easily.

The freedom of form in tension structures arose from the nature of fabric materials to be curved positively and negatively: by placement of low and high points forces and the ability of fabric surface to be formed under compression and tension forces.

The form of fabric structures is dependant on the applied prestressing forces associated with the intended structure. The fabric materials used in these structures normally have no rigidity. They are flexible, but as soon as the loads are incorporated by means of rigid elements or cable anchors, the fabric tends to become rigid and will obtain its predicted form. The flat areas can generally and have to be avoided by paying close attention to the geometry of the surface. In this way, the structure falls under various categories, according to the type of loads, constructional materials, form and other mediums, having the capabilities to transform loads and stabilize the structure.

The subject of form and structure in this field is the core of the design process. They are dependent on each other and cannot be considered separately. The following pages will fully discuss the subjects with their problems and prospects that influence the overall aspect of design and construction of fabric structures.

In addition, the form and structure are essentially influenced by their boundary conditions. Irregular boundaries require precise geometrical configurations of form, and are usually suited with tension structures. The application with regular boundaries can be accomplished with air-structures. The complex boundary conditions are technically possible with both systems of structures, when the computer system is appropriately integrated in the design process. Most air-structures have extremely simple, regular and symmetrical boundary shapes rather than any tension structures. In general, it can be said that the larger the structure the more regular and symmetric it becomes.

The form of fabric structures is an equilibrium surface which is obtained by the introduction of prestress. In form-finding analysis, one must assume an initial surface which has an equal tension surface, considering only the geometrical rigidity to specify the surface tension in proportion to the responsibility or replacement of the surface fabric. Form-finding methods, model techniques and measuring techniques are well developed. The accurate geometry, cutting patterns, force and deformations can be obtained through the analysis of a physical model. On the other hand,
available computer systems offer comprehensive possibilities for the
determination of cutting patterns, forces and deformations, and for the
generation of forms.
In order to approach an optimum form and structure, one must acquire a
knowledge in the analysis of the following subjects:
- The form-finding analysis, which is the initial surface.
- The stress and displacement analysis to confirm the static behaviour against
  snow and wind loads.
- The analysis for installation and construction.

The construction and performance of large-span fabric structures must be
within the experience and skill of constructors. It is important to take into
consideration the erection method during design procedures, such as the
methods of tension control in general, and the methods of adjustment of fabric
or cable anchors in specific, that influence the performance of a successful
form and structure.

5.3-Air-structures

With our recent technological developments, it is possible to create a fully air
conditioned environment without using conventional elements. This is the
architectural essence of an air-structure. It is a thin flexible fabric stabilized by
small pressure differentials created by the application of environmental
energy. Although pneumatic elements so far have seldom been used in
architectural structures, it is conceivable that they might soon become popular,
because of the availability of thin plastic membranes with exceptionally high
tensile resistance.20

Technically the air-structures are defined as a pressurized construction. The
structure is stabilized by means of pressure differentials, but throughout the
world they are defined as pneumatic, blow-up, inflatable, air-dome, air-house,
air-supported etc. We can apply the concept of air-structures with tensile-
stressed skins not only to envelops subjected to positive, but also to negative
pressures, and adapt the air pressure to the applied loads.
In general, obtaining a structural form from flat sheets of woven fabric, a
uniform stress level can be achieved if the form is maintained under pressure.
This can only be accomplished with careful patterning and by compensating
the variation in initial elasticity of the material in the warp and weft directions.
The resistance to the pressure differential can be shared equally in the warp
and weft direction only if the elastic behaviour in the two directions is
approximately equal. Observation and experience have shown that if
compensation for the greater initial elasticity in the warp direction were not

20 Mario Salvadori, Robert Heller. Structure in architecture, New Jersey,
1963. pp. 278-280

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provided, the inability of the weft yarns to pick up their share of the load would result in most of the load being carried by the warp yarns. This would result in a flattening in the crown area, increasing the radius of curvature in radial direction, sufficient to accommodate the higher stress levels and result in a deformed shape. If the circumferential yarns are not capable of picking up share of the loads, there would also be a high concentration of load along the seams.

The deformation under load depend to a large extent on the elasticity of the material. For example, the shape of a rubber structural form will change much more than that of a glass-fabric form subjected to the same load under identical conditions. The rigidity of the structure increases with the modulus of elasticity.

At the crown of a domical form of air-structure, where all of the panels of fabric come together, a problem of concentration can be noticed, due to the close overlapping seams. Therefore, a crown panel of some kind is usually used to prevent a build-up and handle the termination. This could be accomplished by installing a rigid panel to which the ends of the fabric panels would be clamped. But this is difficult, as the fabric should be stretched out circumferentially. The alternative would be a panel of fabric which is essentially isotropic in character. With equal initial stretch in the warp and weft directions, that the crown would be circular under normal inflation stresses. With this construction, loads can be carried across the crown with minimum distortion and stress concentrations. It is very important to avoid such circumstances, by proper design methods. They are usually accomplished as parallel panels of fabric, in a cylindrical and low profile form.

The sphere is the most perfect form for an air-structure, the membrane being stressed equally at every point and in all directions. If it is possible to anchor the membrane, not merely at the edge, but also at one or several points in the center, the spans and radius of curvature are reduced with a consequent decrease of the membrane tensions. The resulting structures (pinpoint or drainage) are highly economical. All air-structures anchored at internal points or along internal closed lines require roof drainage. As a rule, the smaller the central supports, the greater are the membrane tensions.

The cylindrical forms on rectangular plans, with or without spherical ends have become most popular. Spherical ends on cylindrical forms are often used since the longitudinal membrane stress in the cylinder is the same as the stress in the spherical end. The circumferential membrane stress in the cylinder is twice that of the sphere, resulting in distortion and local folding of the membrane at the junction between the two forms.21

A conical form of air-supported structures is also possible; the tensions vanish at the apex of the cone and are greatest at its base. The apex of a cone is soft and subject to considerable deformation by external loads. A conical surface is simply curved. This has the advantage of being simple to cut with little waste of material even when the apex of the cone is slightly rounded off. The

rounded off, conical form is suitable for the stabilization of warm air in winter and snow slides off the sloping surface. The interior acoustics of conical membranes are notably superior to those of hemispherical domes.

The proper patterning, careful arrangement and placement of panels, and proper compensation for the non-isotropic characteristics of materials are necessary. These can assure proper distribution of loads across the lap joints and to avoid local stress concentrations, which can damage the fabric materials. However, the fabric materials with high strength will not meet all requirements of large-span air-structures. Therefore, air-structures are classified under various categories according to their function and structural mechanism. They have been outlined in section 5.3.1.

In addition, cables as intermediate elements are usually integrated to the design of air-structures, in order to reinforce the structure and distribute the loads uniformly to the ground.

The cable air-structures for spherical forms are different and present more difficult problems. Using radial cables will result in an unequal shape in the surface of the structure which will result in unequal pressure on the cables. Also the concentration of the weight of the cables and fittings would result in a deep depression of the envelope. Some manufacturers are using secondary circumferential cables.

However, in order to maintain an essentially spherical form and uniform cable loads, there is the need for approximately equal size cable spacing over the surface. The cable must be arranged in equalateral triangle grids, to maintain the uniform stability of structure and load distribution. The cables on a cable air-structure must be continuous ground to ground and clamped together at the intersections to take the small wind differential loads. Cable air-supported structures are usually built in low profile, in order to withstand high winds with minimum stress concentration and distortion.

5.3.1-Basic classification of air-structures

The air-structure refers to structures that are stabilized by air, gases, liquid, as well as architecture and technique. Therefore, there are a few principal types of air-structures, each of which has its own characteristics and unique mechanism in terms of function and structural behaviour. They are classified as:

1- Air-controlled structure: A structure whose position or movement is controlled by the action of air pressure differentials, which is not generally associated with architectural applications. The best examples are the pneumatic tubes to transport messages in stores, air braking systems, and ground effects machines, such as hovercraft.
2- Air-stabilized structure; an air-stabilized structure has a space enclosing mechanism, by means of fabric materials. It is usually anchored to the ground or supporting boundaries, and kept in tension by internal air-pressure that can support applied loads.

2a- Air-inflated structure; an air-inflated structure consists of a self-enclosed fabric, inflated with air to form a stiff structural member, such as columns, arches and walls. They are capable of transmitting applied loads to their points of support, in this way high and low pressure systems can be realized.

The structural capability of inflated members depend on the volume of air contained within the fabric envelope, the excess pressure differential exerted in the envelope, the characteristics of the fabric materials, and the structural form. However, there are three main types of air-inflated structures:

2a.1-Rib-inflated structure; the form made of a framework of pressurized tubes, which keeps a weatherproof fabric in tension. (see Fig-64,65)

2a.2-cushion-inflated structure; consisting of two layers of enclosed fabric in which the air is contained. The large volume of air in cushions will give a much more significant spanning potential than rib-inflated structures, and is usually used as roofing.(see Fig-66)

2a.3-Webbed-panel structure; a further possibility for obtaining flat, pneumatic cushions is to insert interior connections between the membranes. Cushions become especially rigid when the internal struts form a lattice.

2b- Air-supported structure; The weight of such structure, including external compressive loads, are supported by the large volume of pressurized air within the structural envelope.(see Fig-67) This structure is usually accessible through air locks or pressure balanced doors, and considered to be the most efficient structural system for large-span applications.\(^\text{22}\)

Air-supported structures need some of the following requirements in order to perform successfully:

- The need of a constant air supply mechanism, to maintain the pressure differential across the fabric envelope.
- The need of accurate fabrication to minimize leakage.
- The need of appropriate jointing and anchorage systems to resist up-lift forces.

2c- Hybrid structure; generally the air-structure, both air-inflated and air-supported structures would not cover all structural types within their wide range of applications. Therefore, another type of structure can possibly fulfil this demand, which is the combination of both air-structural types.

\(^{22}\) Frei Otto. Tensile Structures; Pneumatic Structures Vol.1, the MIT press, March 1979, pp. 10-11, 19-21

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a: high-profile rib-inflated structure

b: low-profile rib-inflated structure

c: domical form of rib-inflated structure
d: semi-cylindrical form of rib-inflated structure

e: semi-polygonal form of rib-inflated structure
f: typical form of total air-hybrid structure

Fig-64. Showing various possible forms of rib-inflated structures and their assemblies.
Fig-65. Showing various possible form of rib-inflated structures, using cable reinforcement.

Fig-66. Showing typical air-hybrid structures, integrated with other conventional elements.
Fig-67. Showing the possible type of air-supported structure, with low and high profile and their assemblies.
and some conventional elements. (see Fig-66)

2c.1-Total air-hybrid structure; which is the integration of both an air-supported and an air-inflated structure into one structural system.
2c.2-Partially air-hybrid structure; which is the combination of an air-structure with some conventional forms of structures.

However, structures lighter than air-structures are able to span large areas, when they contain a gas lighter than the surrounding air. Because such light gas or warm air within the envelope and together with its weight will weigh less than the air displaced by the volume of structure.

5.4-Tension structures

The main difference between a tension structure and an air-structure, besides their structural mechanism lies in functional efficiency. An air-structure is usually employed for a totally enclosed system of applications, unlike tension structures which are mostly involved with open side applications. The open structures will receive more suction on the surface by the two-fold action of the wind than a closed volume. Open prestressed tent structures can therefore be attached by higher wind loads than closed off tent structures and inflatables.\(^\text{23}\)

The form of tension structures cannot be determined in an arbitrary pattern of form. It is rather the result of form-finding methods and procedures, that are based on physical laws. The applied loads create a particular form, by using cables, rigid elements, and suitable boundary conditions together with the height and span of structure. The amount of prestress force that is applied for stabilization must not create membrane stresses in excess of the capacity of the material used. For large-span structures, it is necessary to use membranes that consist of steel cables which are capable of carrying the relatively high prestress.\(^\text{24}\)

There is some basic knowledge to be taken into consideration before starting the design and form-finding of tension structures, which can be described as:
- Familiarity with the wide range of forms and knowledge of restraints to ease manipulations and configurations.
- Experience of form-finding methods, using physical models or computer systems, in order to obtain an optimum form.
- Knowledge on structural design, in order to approximate stress distribution


\(^{24}\) Vinzenz Sedlak. Architectural Design with membrane structures; recent projects and feasibility studies. Membrane structures, second seminar; Practical membrane structures. 3-4 june, 1982, Sedney. pp. 256-257
within the variety of forms.
- Knowledge and experience of available materials, their behaviour under
  prestress load, characteristics, fabrication and cutting patterns.
- Knowledge of structural form and techniques within a particular environment,
  including internal comfort and external appearance.
- Knowledge on supporting and fitting techniques, including different types of
  anchorage, which are dependent on the structural form and ground
  conditions.
- Experience of methods of handling and installation, as well as maintenance.

Tension structures have a variety of geometric forms, which appeal to
architects as a new tool of design and structural schemes.
They are stabilized easily under applied loads, by prestressing the surface
fabric. As a result of these load requirements, the structure must utilize edge
cables, rigid elements, masts, arch, etc., to produce a moderated form and
optimum curvature.
Tension structures can be supported by masts, poles, and arches from
underneath, or by suspension cables. In order to distribute the stresses
several methods have been used, and classified under various categories
which are explained in section 5.4.1.

5.4.1-Basic classification of tension structures

Fabric structures are generally classified as air-structures, tension structures,
skeletons or framed fabric structures. All three types have their own specific
characteristics and sub-types, emerging as a powerful building systems.
The method for classifying structural elements and systems is simply
according to their shape and basic physical properties of construction.
Classification implies that complex structures are the result only of additive
aggregation of elements. The significance in aggregation is only the additive
nature of the elements. The significance in structure is that the elements are
also positioned and related with the intent of giving the structure certain load-
carrying attributes.25

Through careful design, the tension structure is made to operate
independently of gravity, stabilized only by its geometric form, and the ability
to spread all environmental loads throughout the structure in purely tension
and compressive forces. Since actual membranes cannot develop
compression or shear, they carry loads by tension only, and act essentially as
a network of cables. When the load changes, the shape of the membrane also
changes and adapts the curvatures to the values needed to carry the new
load. Membranes are unstable; they must be established by the action of an
inner skeleton, by the tension produced, by external forces, or by internal

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pressure. 26

The form of fabric structures is largely dependent on boundary conditions. The structural boundaries may be defined by the curves of catenary cables, poles and masts, valley cables and arches or straight beams. (see Table-i) Therefore, association of such intermediate elements will change the form of structure, each of which will fall under sub-types, having their unique character and can be classified as follows:

1- Self-supporting structure; when the fabric materials are capable of transmitting tensile forces with single or multi-mast as compressive elements, the structures are usually called self-supported fabric structures. (see Fig-69,71) They are the most simple form of fabric structures, and usually they use very little compressive elements, some cable reinforcement and anchorage are an essential part of design. When the anchorages cause some functional problems, their elimination will change the form of structure, by using some intermediate rigid elements. In this case the structure is called braced fabric structure.

1a-Braced fabric structure; the braces and struts are used in order to eliminate anchorage and cables which are the essential elements in designing a specific form of structure. They are usually stabilized by cables and ropes, offering re-adjustment during installation. The predominant elements in such structures are the column and mast, which need to be stabilized by appropriate foundations, unlike other forms of fabric structures. (see Fig-76)

2- Cable stayed structure; the most attractive systems among all are cable systems. A system of cables is attached to the fabric, in order to shape the surface by tensioning. (see Fig-75) It will deform the fabric surface, which may occur in one or two directions, considerable stiffness will be obtained which will enable the fabric to become a very efficient structure. When the cables are tensioned, they may lift the structure until they provide the desired shape, or they may be restrained to deflect the structure into any required degree of curvature.

A cable carrying only its own dead weight will naturally deform into a catenary shape, and a cable carrying a load that is uniformly distributed will deform into a parabola. The cable carrying concentrated point loads will deform into a series of straight line segments. Combinations of different loadings will produce combined forms. The cable-stayed structures typically use vertical or sloping compressive masts, from which straight cables run to critical points.

2a-Suspension-cable structure; a surface can be spanned by cable-mesh in a variety of ways in order to span a large area. They are typically sub-classified as:

-Single-curvature structure; in which roofs are made by placing cables parallel to one another, and using a surface formed by membrane to span between cables.

<table>
<thead>
<tr>
<th>Support system</th>
<th>Structure</th>
<th>Variation of forms and features</th>
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<tbody>
<tr>
<td>Self-supported structures</td>
<td><img src="image" alt="Structure" /></td>
<td><img src="image" alt="Variation" /></td>
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<tr>
<td>Cable stayed structures</td>
<td><img src="image" alt="Structure" /></td>
<td><img src="image" alt="Variation" /></td>
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<tr>
<td>Skeleton structures</td>
<td><img src="image" alt="Structure" /></td>
<td><img src="image" alt="Variation" /></td>
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</table>

Table-i. The basic classification of tension structures and their variation.
A. Hai Yousufi

-Double-curvature structure; in which a field of crossed cables of different and often reverse curvatures make up the primary roof surface.
-Double-cable structure; in which interconnected double cables of different curvatures are used in the same vertical plane.

2b-Composite cable structure; the high strength steel cables are widely recognized as being efficient structural members, having high ratios of strength to weight. The fundamental problem with the use of cables as structural members lies on the tendency to change their shapes whenever the load changes, for they are capable of carrying only tension forces. Therefore, a composite cable structure is introduced to overcome this problem by utilizing a secondary structural system, composed of rigid members such as space frame structures or braces. They will limit the change of shape of the primary cable system. In this way the cables are formulated as intermediate elastic supports and remain under tension at all time.

3- Skeleton fabric structure; skeleton or framed fabric structures are the most abundant of all structural systems. (see Fig-70) They offer the possibility of modifying the form of structure by changing the geometrical configuration of the compressive elements. The structure may be reduced or increased in size, by adding or removing elements. Finally, changes of utility or function are possible by removing or adding fabric materials. The main advantage of these structures is due to easy transportation on account of the compactness of packing in bundles. However, there are three types of framed fabric structures:
3a-Geodisic frame structure; a frame structure can be stabilized by a specific form such as dome, arch and shell, using rigid elements and producing a resistant system.
3b-Space frame structure; a structure can be stabilized by aggregations of three dimensional space frames or truss units, which will provide a variety of form, using rigid elements and producing a resistant system with large-span capability.

The above two types of frame structures are used exclusively in fabric structures. The fabric materials are incorporated simply as cladding, in order to provide an enclosed space. In addition, they would not meet all structural requirements, therefore, the following new structural system has been developed to realize new structural capabilities.
3c-Hybrid frame structure; the structure is characterized by using combined materials such as cables and fabrics with rigid frame elements, struts, beams, and trusses. In this way the structural systems will have the following advantages.
- The high adaptability in terms of function and high flexibility for various architectural applications.
- The reliable system of construction, pretentioning and retensioning after installation.
- The efficient use of material and the creating of a new style of habitable space.
a: frontal view

b: side elevation

Fig-68. The hyperbolic paraboloid form, generated by using tension fabric structure.

c: realistic form

Fig-69. Showing a typical self-supported tension structure with fixed boundary, and stabilized by externally applied jacking forces.
Fig-70. Showing two typical framed tension structures, front elevation, side elevation and perspective.
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**a: optimized form**

**b: realistic form**

Fig-71. A high point tension structure in its initial stage of development, generated as self-supported tension structure.

Fig-72. Showing the realistic form of a typical tension structure, stabilized by one central mast and perimeter poles.
- The new development in architectural form, and unique architectural appearance.
- The simplicity and easiness for different combinations, flexibility in terms of function.
- The efficient utilization of prestressing, which is usually presented by cables or steel rods with high strength.

4- Tensegrity structure; these structures are usually associated with the design of special structures, and partially incorporated in the design of fabric structures.

A tensegrity system is established when a set of discontinuous compressive components interact with a set of continuous tensile components to define a stable volume in space.

The tensegrity system of structures is a special form of structure, with high load bearing capacity and a very low-weight ratio, which is formed by tensile stressed systems and compressive elements. The tensile stressed elements which are mainly rope, cable and fabric form a continuous system which are stabilized by discontinuous compressive elements, such as poles, struts and braces. The tension and compression forces remain within the structure, unlike other forms of fabric structures, where forces have to be transmitted to the ground by anchors or foundations.

4a-Composite tensegrity structure; when the flexible fabric materials are integrated into the supporting and the transmitting tensegrity forcing systems, it is called composite tensegrity structure. The fabric material is not just a covering system, but is rather undertaking the function of supporting loads, the load bearing system is the fabric itself.

In general, fabric tension structures might be composed of different materials such as concrete, steel or timber, and may be formed in flat, single curved or double curved surfaces. Many different systems of structures are well known in this field, and have been experimented.

The tension structures are composed of cables, braces, struts or other rigid elements, their prestressing forces are maintained automatically by a mechanical device in the rigid elements.
6-Analysis and design of fabric structures

6.1-Design principles

The principle of design is usually based on the method of planning and process to establish a three-dimensional form of reality. There are many useful procedures developed towards designing and form-finding of large-span fabric structures, and simultaneously developed new tools in order to overcome the problems associated with complexity of forms and structure. However, the method and process are different in both, following physical and computer modelings, than most conventional structures, and based on statical patterns rather than evolutionary. On the other hand, the design of large-span fabric structures requires a knowledge based on the understanding of the following subjects. They are the main principles of design to be taken into consideration:

- The form-finding analysis; using physical or computer model.
- The patterning analysis; using special tools of measurement for a physical model or a three-dimensional computer model.
- The force analysis; requires the cooperation of the architect and the engineer.
- The fabrication and installation analysis; requires knowledge in jointing techniques and experience in installation processes.

In addition to the abovementioned considerations, it is also important to consider the geometrical nonlinearity, due to the large-displacements of the fabric and the cables. The material nonlinearity is usually caused by the wrinkling of the fabric material which is a mechanism in material properties.
The underlying principle that contributes in the design of a fabric structure is the introduction of patterns to the intended form. As it was mentioned earlier that precise patterning is essential to develop the desired form under load, and to avoid stress concentrations. Therefore, the designs of fabric structures are restricted to geometrical shapes, or shapes that would be patterned analytically or by regular layouts. Besides the main principle associated with design of fabric structures, there are other factors that played an important role towards form-finding and design procedures, and can be described as:

- Fabric structures are stabilized by tension and sometimes compressive loads can be imposed on the fabric, in order to reduce the overstress, and balance the initial prestresses. Thus, prestressing should be high enough to preserve the tensile force in the fabric under all load conditions.

- The choice of fabric material is as important as form and structure, therefore, materials with low creep are usually used, because creep is the ability of the material to deform under load conditions and exposure time. Thus, under such circumstances, special details must be developed, allowing retensioning during the installation process.

- The maximum forces used to select the material is the sum of the pretensioning forces and the maximum tensile stress from the associated loads. First the initial stress pattern should be determined, then the ultimate strength of the fabric which is based on fabricator standards.

- The safety factor in fabric structures is dependant on the load, the site conditions, the tear strength of the material and the exposure time.

- The direction of fabric material has to be selected, it is different in strength and elongation under load conditions. The warp direction is usually stronger than the weft direction. In addition, fabric will stretch under diagonal loads. Thus, the warp and weft of the material should follow the principal curvature of the structure.

6.2-Design of fabric structure

A variety of ways and methods have been developed for designing large-span fabric structures. Numerical procedures such as the finite element methods and interactive Computer Aided Design systems have in many cases replaced physical models as the primary design tool. Such methods provide a general systematic procedure for analyzing the complex behaviour of fabric structures. One of the fundamental problem in design procedures is the subject of form-finding. Since the fabric structure must be subjected to tension stresses at all time. In general, they possess no assembled unstressed configuration. In order to find a valid initial configuration one must determine a set of applied
loads, a structural geometry, and an internal stress distribution that satisfies the equilibrium conditions.

Although computer systems are emerging as a powerful tool in designing and form-finding processes, they have still not entirely replaced the empirical methods. The performance of physical model in the form-finding process is much more than a model in a normal design process. The form-finding procedures are the core of design in fabric structure. In order to accomplish the process, different kinds and qualities of models are needed, in regard to the system of structure and the complexity of form.

However, there are a few types of models used in form-finding processes which are different in regard to the material of the model and the method used to build the model for a certain purpose, such as:
- Preliminary model
- Measuring model
- Geometrical information model
- Cutting pattern model
- Force and deformation model

It is also possible to make a model useful for different purposes that would define the form and details and fulfill the measuring task. In this way several stages of form-finding can be accomplished step by step with the modified model.

Experience has shown that the physical modeling in regard to structural behaviour of fabric structures is of practical use. In addition, the models with cables and cable mesh are very effective and useful, they follow the same principle as fabric materials. The cable mesh model is also effective in helping to understand the structural design and analysis of large-span fabric structures, and their rigidity in relation to structural size and boundary conditions.

In fact, the design of large-span fabric structures is based on physical models, to understand the complexity of forms, the nature of the materials associated with the design and the special forms of these structures. Today computer systems also generate forms in three-dimension and they can be compared to the physical model. The advantages and procedures are different and explained in section 6.2.1, 6.2.2, 6.2.3. The attempt is to provide a model of form-finding and design, using three-dimensional computer models as a tool for design that could be comparable to a physical model.

6.2.1-Computer Aided Design

The usefulness of computers as numerical devices oriented towards graphical output is not new to the architect and engineer, who have some experience working with computers; the methods of approach are now well established and supported by scholars around the world.
Besides the ability of graphic techniques now possible with computers and the visual feedback of computer-generating three-dimensional models, computers have the capacity of handling and storing information, which makes it possible to explore more design alternatives than any empirical method of physical modeling normally used, as all scholars believe that the design function is essentially an analytical one in which Computer Aided Design CAAD systems are able to provide a natural extension of the complex resources currently used by architects.

A complex object such as a membrane structure must be generated by solid modeling, which maintains the three-dimensional structure of the object, and provides a hierarchical representation which is useful in the representation of complex objects. The current CAAD system provides a tree-modeling system, which is open for any further manipulation. In addition, it guides the designer for further analysis and re-use of object components. The quality of a geometric modeling program appears to the user as he/she uses a computer model of an object or interacts with the actual physical object in his/her hand. This is one of the primary aims of solid modeling, to provide a computer model comparable to the model of reality. The operation of each model and their movements in space indicates the process of building an object from a concept to details. Thus, such modeling and operations in a systematic and hierarchical order give the opportunity and flexibility for further design intuition and creativity.

In the field of CAAD there are two main different extremes of design input; either the software program can offer a pre-generated model, which can simply be processed or the user can sit at the keyboard with nothing except the ideas in his/her head, and translate those ideas into the computer via the keyboard. The current Ariadne program realizes both methods simultaneously; for the computer to be used as a genuine design tool, it must be used interactively. Today many users have become aware of this advantage and try to generate a full working model through the keyboard, which is an interactive ideal.

The design usually gives a brief outline of the scope of each component used in a complex structure in a sequence of geometries essential to a particular design. The first geometrical form is generated to control the conceptualization of forms in a sequential and hierarchical order. The subsequent combinatorial geometries are simultaneously engaged and control every level of the design process. In order to design efficiently with this system, one must acquire a knowledge of the following subjects:
- Topology; which is the first conceptual stage in morphological design, and studies the most fundamental properties of configuration, such as

27 The ARIADNE software program is used for form-finding and design, allowing to generate alternative forms, by means of easy manipulation of a computer model. In fact, design is a process related to possible other structural aspects such as functionality, adaptability, space allocation, fabrication, investment, cost and aesthetics.
combination, connectivity, etc.
-Projective geometry; which is more specific than topology, studies the properties of geometrical form, such as points, lines, and faces.
-Affine geometry; which is more specific than projective geometry, introducing affine considerations, studies the most important morphological aspects of form and space.
-Metric geometry; which gives the most important geometrical information of a form such as angle, length etc.

The process is the concept of structural design, in which a complex or special structure is represented as an object and expressed in terms of subcomponents, forming a tree-structure. The combination of an hierarchical design approach with pre-programmed models, permits complex objects to be synthesized by using operations such as subtraction, rotation, translation, etc. These operations tend to be very useful in designing complex structures. Each component can be visualized in 3D, which makes it easier to understand its function and properties. The generation of complex objects and their relationship in term of connectivity and visualization has always been an obstacle in architectural design activities.

The system which is still in its initial stage of development, includes the following sub-systems, each of which is programmed to have various graphical computation capabilities in 3D such as:
-Manipulation and analysis of building components
-Pre-programmed generation of building components
-Generation of a complex form
-Combination of building components
-Architectural drafting, presentation, and visualization in 3D

In each of these steps, the operation will take place by the selection of one or more commands. The graphical feed-back will permit some correction; volume configuration can be changed or modified at any time. The architect with some experience can use this capability almost like a physical working model. It is important to have a clear notion about design requirements and definite ideas before beginning with the computer. Through an underlying data file, operations and manipulations with interactive graphical inputs and commands, the entire process from concept to detail is integrated. The current program has a high quality interactive graphical device, which can compute, compare, transform and display three dimensional working models. However, working with 3D computer graphics, the user has many options within each option, and to a certain extent, among options, there is a significant flexibility for the designer to choose his own path of conception, analysis, and design alternative.
There are many advantages achieved by CAAD besides the main benefits related to the cost reduction in the design and drafting process. They can be described as:
-Accuracy, quality and visualization
-Reduction of time in the design process
-Ability to produce alternative design
- Avoiding the inconsistencies of complex structures and forms
- The speed and control of design modifications
- Estimating the precise components, materials and quantities.

Another advantage of this system lies in the generation of mesh in three dimensions. The interactive procedures, which allows the user to specify finer gradation in three dimensions are associated. The mesh generation is fully automatic by inserting parameter values to specify the tolerance of information and to change the tolerance whenever desired. (see Fig-74) Such automatic mesh generation as a basis of information in space is the key for a design that can easily be substituted by proper materials. The number of nodes indicate the number of joints and their position in relation to the relative components. The lines indicate the size and place of components in tension or compression to be substituted. These techniques lead to a new structural grammar by programming special patterns.

6.2.2-Computer based form-finding

The significant factors to be considered in the form-finding process are form, force, and material characteristics, besides the contribution of functionality, adaptability, fabrication and aesthetics. The problems of form-finding have been strongly considered in different ways. Many scholars have developed methods of surface form analysis, which enables the architect and the structural engineer to find the resulting form of the surface in equilibrium under given conditions of stresses and boundaries. Most fabricators have also developed new tools in the process of surface design, which depend on the mode of prestress and boundary conditions. However, today the electronic computer system and software application for form-finding analysis as an adaptable tool in design process has replaced up to some extent the empirical methods used previously. The application of software computer graphic has made it possible to generate a complex structure and form. The output of the program is a set of point coordinates which describe the form, from this all other values can also be determined such as the ground plan, elevations, sections, perspectives and a three dimensional working model. The process is like dealing with a real physical model, because modeling progress is seen continuously in three dimensions on the screen with its data value. The most common models are pre-programmed and can be used by pressing a corresponding special command and inserting limited values. All the parameters of these common models are open for change, the user has an infinite number of possibilities to gain an optimum form and structure.28

28 The performance of this method largely depends on characteristics and userfriendliness of the software, as well as on the performance of the computer configuration. The form-finding has been considered as multi-
By using the computer, it is easier to generate the initial form which is far from an ultimate or realistic form, but it also gives the possibilities for modification towards the final form. Sometimes a form consists of a few sub-parts to be generated and put together in order to obtain the ultimate form. These forms can be generated by automatic mesh topology that have some relationships in anticipating cutting patterns. The points and lines outlining the surface may be adjusted interactively in a three dimensional working model.

The initial form is usually generated as an algebra-form which is a mathematical system, used as a tool to represent and process computer models. The term model is used in a general sense to refer to a collection of any kind of physical and/or abstract objects. From a physical viewpoint a structural form may be seen as a collection of individual structural elements interconnected in space. The interrelation between the components in a structural form constitutes a fundamental aspect of the whole system. Hence, an approach for describing a structural configuration in a basic form is to represent the interconnection pattern of the system with an abstract model. This model can then be used as a skeleton to which other aspects of the system, such as geometric particularities, material properties and loads may be related.29

In each of these steps, the operation will take place by the selection of one or more commands. The graphical feedback permits corrections, and surface configurations that can be changed at any time. However, the form-finding method and analysis consist of the following procedures: (see Fig-73.a)

-Pre-generation of form; which is an ideal form, generated by one command and promises easy modifications towards the ultimate form.

-Analysis of form; which is the interactive operation, for modification and manipulation.

-Manipulation; the general square mesh for three dimensional surfaces is used to generate initial geometries for the form optimization procedures. The interactive form-finding process is very attractive, since the architect has the possibilities to modify structure and form, and at the same time will obtain a fast representation of alternative forms.

-Configuration of form; enables the designer to find a feasible configuration of form, which consists of various model represented as an object. This object is essentially open to be modified, if unsatisfactory results are obtained.

-Equilibrium form; The equilibrium form depends on the prestress level, the cable layout and the bearing support conditions. It can be assumed, in order to obtain the desirable form. This architectural form permits the structural engineer to analyse the form with additional properties, such as

disciplinary problem, linking geometry, statics and material characteristics.

Fig-73.a. Showing the process of formfinding, using CAAD method, that the output is an equilibrium form towards a realistic structure in the design process.

Fig-73.b. The design process and method, following CAAD, that the output is a realistic structure.
<table>
<thead>
<tr>
<th>Pre-generation of Form</th>
<th>Operation; Optimization and Modification</th>
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<tbody>
<tr>
<td>Equilibrium Form</td>
<td>Configuration of Form and Components</td>
</tr>
<tr>
<td>Satisfactory Structure</td>
<td>Materialization</td>
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Fig. 74. The form finding and design process using general mesh topology.
displacement and boundary conditions, material properties and behaviour, loading and prestress levels.

The output; is a set of co-ordinates, determining the value of each element in space. From these values all other working drawings will be obtained, from any angle, even the rotation of form in real time.

6.2.3-Design procedures

As has previously been discussed, the determination of realistic form of fabric structure is based on initial equilibrium, which is a combination of shapes and prestress, that balances the applied loading and satisfies the boundary restraints. When the equilibrium form is obtained, which is the core of the design procedures, other components must be incorporated to the form such as compression elements and tension cables. These elements will be manipulated and modified towards a satisfactory structure. At the same time an appropriate material can be employed to determine the response of the structure to various states of loading. If the response of the structure under a particular material is thought to be unsatisfactory, a new initial configuration must be determined. This process must be repeated until a satisfactory design is obtained. (see Fig-73/b)

As soon as a satisfactory structure is obtained, it can easily be materialized, which is an approach towards a realistic structure, by substituting the data value in space, that are presented as points, lines, and faces into selected proper materials and details. In this way the object is open for further substitution of details and components at any time, providing the opportunity for alternative detailed design. Once the satisfactory structure is achieved, an appropriate material can be employed to determine the response of the material to various states of loading. The specification and the material direction must also be made on the stressed three dimensional surface.

The next step in design procedures is the issue of cutting patterns. Fabric structures are fabricated from separate fabric panels that are cut from rolls of fabric, joined together in different ways and means, and ready for assembly. The patterning procedures are aimed to determine the two-dimensional cutting patterns for the fabric panels, which will meet the desirable form and intended stress distribution of a structure. Obviously, the result of the patterning process has a direct and substantial bearing on the performance of the structure.

By using interactive computer graphics, it is possible to determine the cutting pattern of the fabric under following procedures:
- Determination of geodesic lines on the surface of the equilibrium form.
- Determination of the surface into strips enclosed with geodesic lines.
- Flattening of the strips into the planer pattern.
- Determination of material direction under prestress.

The final step that CAAD permits is the visualisation of a realistic structure, which can be compared to a real physical model. If by any chance, the final object appears unrealistic, then the intended structure must be redesigned. The design procedures in most cases should start from form-finding, but sometimes it can also be accomplished within a wide range of possibilities. The software offers the possibilities to change essential elements, which is obvious in the course of design activities.

The realistic structure is the result of form-finding and design procedures that can be presented in a variety of ways, in order to satisfy the client for its successful performance. In addition, the three dimensional models presented by computer are useful to both the architect and the engineer. They help the architect to explore spaces, proportions, clearances and aesthetic, they help the engineer to determine the flow of forces in a complex three dimensional structure.

The following designs (see Fig-75, 76, 79, 80) will show large-span fabric structures generated in different ways. It will further demonstrate the various possible forms and their variations. There are three elements used to shape the structure, besides the fabric materials that can be described as:
- Vertical or inclined main masts, which can be a cylindrical steel pipe or laminated wood and concrete in the form of a column.
- Suspension and stabilizing cables attached to the braces.
- Horizontal bracing at the roof level, stabilized by cables or reinforced woven fabric.

These structures are designed under the effect of the load symmetrical in regard to the columns. (see Fig-76,79) The structures are designed as cable-stayed structures, or simple tension structures in square and polygonal plans. The surface fabrics are either reinforced by means of cable or only braces stabilized by cables and the covering fabric used without any reinforcement.

In the case of reinforced woven fabric the contour cables are carried in special sleeves to restrain the movement of the fabric in the cross sectional direction of the contour.

Each unit of the tent is stable by itself, and can be erected as a single unit or as many as required. (see Fig-76,79) Multi-storey textile buildings are also possible, by using fabric for ceilings and roofing, this will change dramatically the interior space. (see Fig-81) The structure can be erected by either prestressing the contour cables or the surface fabric upon upper and lower part of the supports. When the desired prestressing is achieved, the cable or surface fabric can be clamped to the supports and will remain prestressed by the constant prestressing forces.
Fig-75. The various possible types of cable stayed membrane structures generated by CAAD, bottom; a prototype of a tent designed for Haj Terminal at the Jeddah airport in Saudi Arabia.
Trends of Fabric Structures in Architecture

Fig-76. Braced membrane structures, as alternatives of the tent of Haj Terminal at the Jeddah airport in Saudi Arabia. top; single curvatures, bottom; double curvatures.
Fig. 77. The mechanical details of double curvature fabric structure illustrated in Fig. 76.
Fig-78. The mechanical details of single curvature fabric structure illustrated in Fig-76.
Fig-79. Double layers, single curvature fabric structures, top; based on hexagonal plan, bottom; based on square plan.
Trends of Fabric Structures in Architecture

a: process of component's configuration

b: assembly of components

c: cutout membrane

d: assembly of membrane

e: frontal view

f: realistic structure

Fig-80. An office building: shows the building process and integration of woven fabric to conventional building system.
Fig-81. The column system building; shows the integration of woven fabric to conventional building system. It can dramatically change the interior space by using geometrical forms as roofs or ceilings. The design is based on additive aggregation of identical units, which is open to modification in the course of architectural design activities.
6.3-Geometry of surface

The factor that has contributed to the design of many new structure is the introduction of computer geometry or patterning. As was mentioned earlier, precise patterning is essential to develop the desired form under load, and to avoid stress concentrations. Prior to this, most designs were restricted, primarily to geometric forms or forms that could be patterned analytically or by layout. To arrive at a suitable form it is desirable to be able to measure or define the shape so that other subsequent detailed activities can proceed. An accurate surface shape is required for an engineering analysis by computer and for the generation of cutting patterns.

Originally, geometry included large scale mapping in cutting pattern plans of the boundary strips of the special curved surfaces in a distortion-free manner. The geometrical data were derived only and directly from a physical model. The photo of the strips were taken from equal distances with optical axes approximately perpendicular to the model surface. These photos were enlarged to scale, mounted and traced on tracing paper. All lengths and angles in the irregular strips were then graphically measured. The full length of a seam is found by counting the number of equal meshes in the model. 30

The determination of surface geometry in fabric structure follows the same principle as cable-net structures, the fabric strips run on a given surface following the principle direction of load. In this case the fabric material and total length of the seams should be as minimal as possible in regard to its shape.

In fact, as has been mentioned before, a form must be based on geometry to determine its surface in space, which is a fundamental subject during the form-finding process. The geometrical lines must run in such a way that they have smallest possible total length.

With regard to the different patterns in geometry of a specific form, the geometry of surface might be independent, but there is one or two directions among all possible directions for which the sum of the lengths of the seam lines are minimal. Therefore, the best approach is to make the directions of the seamlines the principal direction of load, which is structurally optimal and needs the least outlay in material.

However, it is also necessary to select the direction of fabric fibers, usually the weft fibers of fabric extend more under load than the warp fibers. In order to obtain the fiber direction of fabric in a certain form, consideration of external loads such as wind and snow, their distribution over the form and the system of structure are essential.

6.3.1-Cutting pattern

The cutting patterns of a surface must be developed from the form either by hand from a physical model or by a numerical model through a computer. Physical models and hand methods are much more reliable for simple and small structures than a computer simulation with a cutting pattern which is rare and uneconomical.

The conclusion of F. Otto in this regard was that the quality of cutting pattern is of decisive importance for the usefulness, economy and appearance of pneumatically stressed membrane structures. This conclusion can also be used in tension fabric structures in general. However, as was mentioned before the design of fabric structure is characterized by its form, structural systems and geometry of surface which is defined by the method of cutting pattern. The methods of patterning are being incorporated into computer programs, as mentioned earlier. The actual coordinates are stored and the user is able to specify points and lines which are suitable when flattened out, rotated and converted into strips. Therefore, before evaluating the method and determination of a cutting pattern, one must consider the following parameters:

- The geometrical pattern of a surface must be determined in order to find the order of fabric strips. These strips of fabric can be arranged in a parallel or radial, and the combination of both in special cases is also possible. They depend on the form and the system of structure.

- The fabric strips must be arranged in such a way that the warp and weft directions follow the directions of principal stresses and principal curvatures.

- The width of the cutting strips must be determined, they depend on the following factors:
  - The width of the fabric material.
  - The maximum width of a strip for the minimum length of seams.
  - The greater the curvature of the surface the smaller the stripwidth will have to be, in order to limit distortion when the strips are flattened into a plane.

- Minimizing the waste of material by boundary strips, which must be straight and as parallel as possible. It can be fulfilled by geodesic lines as seam edges.

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6.3.2-Determination of cutting pattern

Essentially, the problem is to select a portion of the three dimensional surface and to flatten it into two dimension so that it fits within the available width of fabric. Such a strip in the surface may appear straight or curved, or twisted or a combination of these.

However, the computer system opens new possibilities for the determination of the cutting pattern of fabric structures. The accurate form can be generated so that the physical and geometrical properties can be treated adequately. The geometry of surface is usually described by the coordinates of points representing the structural fabric in space. The coordinates might also be calculated by using the physical model of a cable network and applying a form-finding procedure. The fabric material is approximated by a square grid structure, which is an adequate model for form-finding and statical evaluation.33 The following steps are believed to be a valuable method for the determination of cutting patterns:
-Form-finding; obtaining the equilibrium form of fabric structure through a physical model or computer generated three-dimensional form. (see Fig-82)

-Substitution under stress; the substitution material must be of smaller dimensions than the model material, in order to allow for the required build up of stress due to stretch of the material. The stretch ratio of a material differs according to circumstances, and requires further stress and strain testing to ensure its accurate stretch ratio under the intended applied loads.
It is important to mention that the substitute of material under stress is also largely dependent on the experience and skill of the constructor in a particular form and structure.

-pattern finding; the determination of a strip pattern on a fabric surface, which are oriented along geodesic lines within the surface of an equilibrium form. Their development into the plane will be the straightest possible.

-Cut-out pattern; cutting the substituted strips of fabric material under tension, in order to obtain the relaxed pattern. This pattern will be free of stresses.

-Pattern flattening; flattening the relaxed and substituted patterns in away to avoid wrinkles.

-Assembly; assembling the flattened patterns to the intended form using stitch


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Fig-82. The determination and processes of cutting pattern.
or welding techniques to ensure its efficient use under applied loads.

6.4-Design analysis

The significant and fundamental subject in installation and fabrication of large-span fabric structures is the introduction of tension to the fabric structure. It depends on the type and form of structure, and the elongation of the materials at the time when tension is introduced. In the period of exposure, creep and relaxation will also occur, due to sun radiation, wind and snow loading. The elongation of fabric material necessitates a reviving of tension forces, because fabric materials have orthotropic properties and show non-linear characteristics. Therefore, it is important to understand the elongation behaviour of fabric material under biaxial stress conditions.

In fabric structures various methods of introducing tension can be employed, because tension stabilizes form, resists loads, and will establish the form of the structure. It is difficult to obtain a curved surface with similar stress in both directions during the construction of fabric structure, because fabric material wrinkles very easily. Therefore, the following facts must be taken into consideration during fabrication and installation.
- The precise cutting pattern.
- The proper method and technique of fabrication.
- The installation method and procedure.
- The method of introducing tension forces.
- The possibilities of reviving tension forces during exposure time.

In order to consider the above procedure, one must analyse the following important aspects:
- The elongation characteristics of fabric material, in relation to the applied tension forces.
- The variation of stress during installation.
- The relaxation and creep, due to loading.
- Determination of cutting patterns.
- The evaluation of installation, and tension adjustment system.

In practice, loading caused by snow and wind may cause repetitive increases and decreases in stress. Thus, adjustments are required for the re-introduction of tension forces. By understanding the relaxation and creep characteristics, determining cutting patterns, methods of installation and tension introduction, one can acquire knowledge applicable to practical design details.

In air-structures especially, the air-supported system of structure needs to be constantly inflated and stable under various natural conditions. Therefore, they need a control system which maintains internal pressure. This control
system must consider the main sub-systems for structural safety, which is air-supply, snow melting and internal pressure control. They are usually based on structural behaviour and can be determined by analysis and experiments. The following findings are believed to be useful in design and installation processes:

- The air-supported structures are usually fabricated in the form of double-layers of fabric in order to allow warm air-circulation to melt heavy snow.
- The roof can be supported by a normal operating pressure, based on structural characteristics and can be obtained through analysis and experiments.
- The air-supported structures also need a pressure control system for necessary action, such as changing the number of operating blowers, the rotational speed of blowers, and the opening of release dampers.
7-Fabric structural properties

7.1-Structural characteristics

The main characteristics of a structure are defined primarily by the material used to shape the structure and the structural system on which the form is based and can be distinguished. Thus, the fabric material is an important element in the field of fabric structure because it is not just a covering material or protection against outside forces, but is a part of the structural mechanism that transmits loads to the other structural elements, creating a fully integrated structural system. It is the characteristic of fabric structures, both tension and air-structures, that the form and construction are not independent from each other. The form depends on the type of material, boundary condition, fixing and prestress loading. Therefore, it is not an automotive step in exact form-finding during design procedures, but is rather an interactive way of designing, which will be followed step by step until the realistic form is achieved for the actual construction.

As well as being a flexible material, fabric structures are also characterized by the opportunities they provide for creating aesthetically appeal structures. The advantages for architects working with these structures are well known, and the difficulty of devices arising in design process are the representation and communication of typical complex forms.

Fabric structures including air-structure have various characteristics, but there
are two main characteristics, which are as follows:
- They can create a semi-outdoor space environment, that permits soft and homogeneous sunlight through the structure.
- They have a mechanism, requiring a constant air-supply (air-structure) at all times. Therefore, maintenance and control of this mechanism are as important factors as the concept, such as design, structure and execution.

The air-structure, especially when air-supported, is usually designed to have an appropriate rigidity by means of a required internal pressure. They have a curve line always allowing equal distribution of tension forces to each part with the internal pressure to balance its own weight.

Most manufacturers today design air-supported structures in such a way that they are slightly higher than the floor level for the sake of safety, when the surfaces of the structure are deflated. By using high boundary elements, or compression rings, there will be no obstacle in design and execution of these structures.

The fabric material used in these structures are usually non-combustible and fire retardant, such as teflon-coated fiberglass and PVC coated polyester. However, the fire safety is measured in fabric structures according to the other combustible materials used in structures, such as conventional building materials, furniture etc. Therefore, the supporting structure, including arches, struts and masts should be non-combustible or independent, which will remain stable when the fabric is removed or damaged by fire or other acts of vandalism.

In general, it can be said that the fire safety of fabric structures is almost similar to conventional structures, and as a major fire has not damaged fabric structures up to now, research has been limited in this respect.

The problem related to acoustics in fabric structures is a fundamental subject to be carefully considered during the design procedures. The fabric has very low mass, and there is very little sound absorption and reflection. Therefore, designers usually use sound absorbent materials and acoustical liners.

7.2-Structural systems

Fabric structures are characterized by their unique systems, enabling the structure to withstand internal and external forces in the exposure site conditions. The structure usually possesses a system on which it is stabilized and ensures the form depending efficiency on the particular application. They were classified particularly as three main systems of structure, having their unique sub-systems which depend on the usage of additional elements and mechanisms, that can fulfil the requirements of a specific form and function. The three main system are as follows:
- Air-structures
- Tension structures
  - Skeleton fabric structures

These system of structure are very special in terms of form and function, each of which has the efficiency and flexibility to create the following unique environments:
- The total enclosed-space environment.
- The open-side space environment.
- The semi-outdoor space environment.

A multi-functional system of structure is possible, when two or more systems are used together and integrated in one new system. In most cases a skeleton fabric structure is integrated with tension structures, providing durable and permanent structures. The air-structure and tension structure are in principle two different structures but a composition of both is also possible. Thus, any change in force bearing would change the system and the character of a structure.

Apparently, the abovementioned systems could not fulfil all requirements associated with the new applications. Therefore, a composite system of fabric structure is essential to maintain the efficient use of fabric materials. These new systems are usually accomplished with existing building, or new applications, that require a certain degree of conventionality in terms of structure and space. However, it is the fabric material integrated with other conventional systems that provides a unique environment peculiar to fabric structures.

7.3-Material properties

The success of the structure is largely dependent on the performance and serviceability of the fabric material. The fabric material used in large-span structures should have high strength and a high modulus of elasticity in order to maintain stability under all load conditions.

The materials used in fabric structures are much more important in terms of their properties, because it is not only the envelope which encloses everything underneath, it is also the essential medium on which the structure is stabilized. Thus, the material must be of high quality and each batch and joint must be examined and tested in relation to its stress elongation behaviour under internal and external load conditions.

Large-span fabric structures require the use of sophisticated coated fabric materials such as PVC coated polyester or Teflon coated fiberglass and Kevlar fabrics which are dimensionally much more stable. These materials need special jointing methods and techniques such as high frequency welding, or heat sealing as well as sewing and cementing.

In fact, the relationship between form and structure in regard to the fabric
material depends on load bearing behaviour, which is influenced by material properties and structural details. The determination of material properties that influence the structure are not idealistic assumptions, but respond to the actual acting loads and in the realistic understanding of the load bearing properties of the individual structural elements. Also in their behaviour within the whole system, such as biaxial stress strain curves of fabrics, compensation or reduction factors applied to the cutting pattern for the fabrication of an unstressed fabrics, short or long-term creep, module of elasticity of fabrics and cables, temperature influences, influences of different structural details, boundary conditions, joints and seams, etc.

The choice of fabric material greatly influences the detail and design of fabric structures. There are different kinds of materials, consisting of uncoated synthetic threads through nylon and polyester base cloths coated with PVC to fiberglass fabric. The properties of the material in the warp and weft directions are usually different particularly in respect to the elongations, and they need to be prestressed, which requires some means of readjustment by incorporating proper details into the design. It is desirable to have these points of adjustment easily accessible at the anchorage or the base of supporting masts.

The creep characteristic of fabric materials will tend to relieve highly stressed areas to a certain extent, particularly at the edge cables. The creep characteristic can be expected, which is dependent on the bio-axial stress state, the relative magnitudes of the principal stresses and the orientation with respect of the warp or weft direction.

In general the fabric properties can be characterised by the materials used as filament yarns and coating materials, which are explained in section 7.4.

7.4-Material characteristics

The most common material for large-span fabric structures are coated woven fabrics, which are usually with polyester fibers and PVC coating or fabrics with glass fibers and PTFE coating such as Teflon. The main stress will be carried by fiber yarns, and only a smaller part with coating in the diagonal directions. The important fact in fabric structures is the fabrics life and its performances during exposure time. The role of coating in fabric material is to protect the base fabric from degradation, due to the ultraviolet radiation of the sun. The coating can vary in content and number of layers on either side of the base fibers.34

There are a few filament yarn materials used exclusively in fabric materials for large-span structures, having unique characteristics such as:

-Nylon (polyamid); as a synthetic material it offers high strength characteristics, but resistance to ultraviolet degradation is low. In addition, it has a low modulus of elasticity and creep, thus the yarns stretches when wet and shrinks when dry at high temperatures.

-Polyester; it has the same strength as nylon, but more resistance to ultraviolet degradation and less creep.

-Fiberglass; it has been used for permanent fabric structures, due to its high strength, high tear strength, and high modulus of elasticity. Fiber glass is much stiffer then synthetic fibers and cannot withstand sharp folds. Therefore, it must be handled carefully.

-Kevlar; is a high strength material with low elongation and resistance to high temperature. It has poor resistance to ultraviolet degradation and must be coated with an opaque material.

The most common coating materials used for the above mentioned fibers are as follows:

-Polyvinyl chloride (PVC); this coating material can easily be jointed by thermal or dialectric heat sealing. It can be economically assembled to provide high-strength panels, and is available in a wide range of colours. Flame retardants are required to achieve flame resistance, and ultraviolet absorbers to improve weathering characteristics. This material is usually coated polyester, and recommended for temporary and semi-permanent structures.

-Fluoracarbon (Teflon); is flexible and remains uniform under different temperatures. It is usually bleached white in the field by ultraviolet radiation from the sun, has a long life, is translucent and self-cleaning, and is considered for permanent structures.

-Silicone coating; it has the same characteristics as teflon, long-lasting, self cleaning, more flexible and more translucent. The main problem associated with coating is the assembly of large panels and not being flame resistant.

With the above mentioned materials, other more improved composite coated fabrics are developed having their own unique characteristics for specific applications.

Fabric materials gained popularity through their unique characteristics with regard to weather durability, transmission and reflection of light and behaviour in fire. These fabrics were developed and patented by chemical fabrics

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corporations to serve as both an acoustical and thermal liner for fabric structures. They are commercially known as FABRASORB thermo-acoustical fabrics.

7.5-Material behaviour

The different materials and different structural systems are used in a variety of ways in various site conditions. They greatly influence the performances and behaviour of the material with regard to the structure and site conditions. In addition, the material also tends to behave differently in the course of time due to the degradation of coating material and loss of fiber strength. Therefore, some chemical substances by means of painting have been developed to promote the behaviour of fabric material during exposure time.

In particular the degradation of PVC coated fabrics results in brittle colours and in most cases are quite dirty with loss of their strength, which needs to be considered in design and cutting procedures. The Teflon coated fabric has a bland colour with excellent long term protection, it quickly bleaches to a brilliant white after a few months of exposure. The disadvantage of Teflon coated fiber glass lies on its sensitivity to damage due to careless handling and needs to be designed as accurately as possible, because once it is erected there is no readjustment possible to avoid wrinkling.

In general, it can be said that there is no protection against the acts of vandalism in fabric structures. Therefore, the designer should make the fabric materials and essential elements such as anchors as inaccessible as possible in order to avoid this problem, which in most cases will result in the failure of the whole structure.

In addition, fabric materials need a certain degree of protection during fabrication and installation. They should be handled carefully, especially during transportation and erection. One of the disadvantages characteristic of these materials lies on their behaviour against sharp rigid elements, to be avoided at all time.

7.6-Fabrication and jointing

One of the important of problems in the field of fabric structure is the stress concentration in the fabric surface under the prestressed forces. Although fabrics are reinforced in those places where stress concentration can obviously be determined, such as joints, anchors, and openings, it is still difficult to determine the magnitude of the concentrated stress in the above
mentioned places. The result is that the fabric wrinkles very easily and the overall structure remains in equilibrium after wrinkling, retaining its load carrying capability, but the stress in the tension fields is concentrated. Experience has shown that the stress concentration is greatly affected by the geometries of form, material properties, fabrication and jointing. The fabric mainly is fastened by heat-sealing and different types of stitches, together with rope or cable, which can be fixed to other rigid elements by means of clamping systems. The load can be transmitted by the cable edge bearing against the edge of the clamp element. Failure may develop when inappropriate fabric material is used in the joints. Tearing also will occur when the low modulus fabric materials are used in the joints. In general, it can be said that the fabric materials can be reinforced where the concentration of stress is determined, but the strength of the joint is usually higher than the strength of fabric materials. In this case the jointing techniques and methods are essential to ensure the permanent stability of structure.

When the design arrives at the stage where materials should be specified for fabrication, then material must be fully inspected by visual and laboratory tests, in order to determine the biaxial load characteristics and to ensure that they meet the stress-strain characteristics required by structural analysis as well as other specifications.

There are different ways to regard the connection of fabric surfaces to the load bearing elements. There are a few practical systems that have been used to stabilize the surface fabric, and are mainly based on the location of joints and the large potentiality of structure that can be described as:
- Sewing joint method; used with the aid of thread, especially for synthetic.
- Welding joint method; used for coated woven fabrics and metallic sheets.
- Glueing joint method; used for coated woven fabric and metallic sheets.
- Rope joint method; uses rope and cable together with metallic sheets.
- Plate joint method; uses metallic sheets by means of bolting.
- Clamping joint method; used with mechanical jointing techniques.
- Combination; The effective connections are sewing and welding, sewing and glueing, and bolting and glueing.

It is easier to join two fabrics with low weather resistance, such as fabrics made of cotton and translucent polyamids, by means of threads which have a higher weather resistance than the membrane itself. In contrast, it is difficult to join high strength fabric material with seams which do not reduce this operating time. It can be said that as the durability of the materials increases, the structural problems of the seams and joints become greater. Anyway, experience shows that, in the design of connections and joints, practical experience plays a primary role.

In any case experimentation suggests that reinforcement of fabric materials will be required according to the circumstances, by doubling fabric material which means doubling the strength of fabric and anticipated fabric stress, since stress tends to concentrate around supporting sections. In addition, it is necessary to reinforce the joints with rubber, when the fabric is
sandwiched between plates, because the tear strength of fabric is low.
In general, the edge cables and joints must have the ability to rotate freely in
order to adapt to complex curved surfaces, so that fabric tension may be
introduced afterwards in order to improve further adjustments and avoid
surface wrinkling. Therefore, the details of joints and the use of proper
methods of jointing in designing fabric structures are a fundamental subject,
which needs more research, experimentation and testing.

It is also important to mention for both air-structures and tension structures,
and those with cable edges, free edges and fixed edges, that the panels
should preferably be assembled warp to warp and weft to weft, avoiding sharp
angles of intersection. However, where necessary to join warp to weft, the weft
panels should be stretched out during assembly in order to assure uniform
distribution of the load at the joints. Most fabricators determine the bio-axial
characteristics of the materials being used, which may vary from roll to roll,
and take its characteristics into account in developing fabric patterns.

7.7- Anchoring and supporting systems

The design of anchoring and supporting systems are largely dependent on
the system of structure. Some complex forms of structure need more detailed
and complex anchoring systems to be readjusted, such as open sided fabric
structures and cable-stayed structures. Others require much stronger and
special compression masts or poles to determine the form and stabilize the
structure, such as self-supported fabric structures.
However, the anchors and supporting systems need to be jointed to the fabric
according to the type of loads subjected or going to be applied on a specific
area. Thus, each design and form needs a special method of supporting and
anchoring systems to be examined in order to fulfill their particular task. Some
supporting elements need to be moved freely and others should be fixed
firmly. It is difficult to develop standard joints and fittings for large-span fabric
structures, because all structures differ not only in size but also in shape. The
standard details are only possible in standard structures.

In general it can be said that, whether the design is an open or closed system
and may be both, they need special detailed supporting and anchoring
systems to be taken under consideration in the design process. There are
various detailed supporting and anchoring systems available that are well
known, but special structures need special details and techniques. The
anchoring and supporting systems are mainly used in fabric structures to fulfil
the following functions:

36 Vinzenz Sedlak. Aspect of detailing and component selection in mem-
brane structures. Membrane Structures. Second Seminar. Practical
Fig-83. The possible types of edge fittings of membrane; shows a variety of methods to insure the successful performances of fabric structures.
-in order to introduce prestress tension, to determine an optimum form.
-In order to provide a mechanism for applying prestress loads.
-In order to collect and resolve the forces resulting from the prestressed and external loads.

The type of anchorage provided depends on the position, direction and duration of the loads required by the fabric structure, whether it is above or at ground level, primarily vertical or horizontal, and if it is temporary or permanent.

However, the boundaries of fabric structures can either be formed by cables or membranes can be clamped directly to a beam or a perimeter frame. It is usual to run the edge cable in a sleeve formed by the membrane laid back on itself at the underside of the structure. At the intersection point of two edge cables, the membrane corner, details are required to assure the membrane to the cable. Also the two edge cables to a common fitting, which is then anchored to single or twin suspension cables. (see Fig-83)

The fabric corner and the edge cables can be clamped either between or onto a suitable steel corner plate fitting. The membrane needs to be suitably reinforced at the corner and this type of detail is recommended only for small to medium structures. The adjustment towards the corner is not possible with this detail. (see Fig-84)

As the edge cables become longer, tangential stresses increase and the membrane corner must be prevented from slipping back and creating monaxial stress conditions along the boundary. A continuous seatbelt webbing strip is sewn to the underside of the membrane along the sleeve parallel to the cable and suitably protected from ultraviolet radiation, allows the tangential stresses to be transferred and the membrane to be anchored directly to a corner plate fitting.37

Attaching a membrane boundary to a rigid beam or a perimeter frame requires highly accurate patterning and fabrication and correct determination of the reduction factor. The reduction factor is that percentage of the overall dimension of the membrane surface by which it has to be reduced, in order to allow for creep under prestress in the constructed building.

The boundary can also be formed by a straight pipe onto which the membrane attaches by a sleeve. This is a detail commonly found in air-supported structures and allows a larger amount of membrane adjustment than direct clamping to a frame or ring.

The problem in supporting a membrane by a mast or pole from underneath or by suspending it from an overhead suspension cable is the high stress concentration. In order to distribute the stresses several methods have been employed. The simplest method is by local reinforcement of the material. This

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Fig-84. Showing the methods of fitting membrane to the boundary support, avoiding the wrinkling mechanism and tear around edge supports.
Fig-85. Showing the mast foots, and supporting cap rings, which are suitable for tension fabric structures.
method is only suitable for very small or low stressed tents. On major support points, stresses can either be distributed onto rigid steel rings or to steel rings often formed from angle sections which allow clamping. (See Fig-85) Other points of support can be provided by using cable loops, either in the form of a rosette or in the form of a cable loop, which requires high accuracy in form-finding and detailing.

In fabric structures the simplest mast type is a pole used in small tents. These poles can be made of timber or steel, which are usually tubular. For the design of large-span fabric structures it is always desirable to place masts in a special position so that they are only subjected to pure compression forces, therefore allowing the section to be designed as economically as possible. The masts must also be hinged at their supports, depending on the expected movement. The hinge can be either uni-directional or multi-directional. (see Fig-85.a, b)

The perimeter masts and poles are also used to lift membrane corners off from the ground and thereby provide access underneath the membrane as well as considerably reducing the distance of the ground anchorage points to the building. (see Fig-72)
8-Fabric structural design evaluation

8.1-Environmental design

The primitive shelter of nomads created an environment in which one could live in different climatic conditions. Modern society expects greater indoor comfort and a higher degree of environmental control, which presents a new problem.

Environmental performances of fabric materials can be improved by passive or active layers of fabric to control thermal or lighting behaviour. Radiative properties of fabrics can be chosen to perform and suit different climates and functions. Measurements of transmittance, reflectance and absorbance are given for almost all fabric materials.

Fabric structures for heating and cooling require the knowledge of the amount of solar energy admitted to the structure. The energy is a combination of the solar energy transmitted through the fabric and the energy absorbed by the fabric. The absorbed energy is dependent on the material and climatic condition of the site, on average almost half of the absorbed energy will enter the structure. In addition, a windy climate will decrease the amount of energy entering the structure. In hot and sunny climates, white fabric with low solar gains are recommended.

The translucency or transparency of fabric material affects the thermal problem because low translucency means that more solar radiation will be
reflected and the heat gain will be lost, transparent or highly translucent materials will increase the heat gain. However, their degree of translucency can be controlled by means of pigmentation. Reflectivity of the fabric is another important aspect of temperature control inside, in particular under a hot solar climate. Experience has shown that white has better reflectivity than silver, grey and blue.

As far as natural lighting is concerned, it is important to transmit the visible radiation. This can only be achieved by increasing the value of solar reflectance of the fabric materials, which will result in a decrease of solar gain. In general, the problem of temperature control can be considered as shown in (Fig-86), the various ways in which heat enters and leaves the structure. When the solar energy directly affects the structure, obviously the external environment will be hot, there might be a flow of heat along with inflating air or just normal ventilation. There is of course an activity input, depending on what happens inside, people and their activities generate a lot of heat. Leakage and ventilation generally escape through the structure. Another significant aspect is the ground itself, where the temperature transfers into or out of the ground. These are the main components of the heat exchange with the structure itself.  

The principal comfort problem is heating and cooling, which can be described as the main sources of heat transfer into and out of the structure. These include the convective and conductive exchanges between inside and outside air, such as solar radiation, radiation from the ground and the surroundings, long wave reradiation, ground reflection, earth contact conduction, environmental shading, ventilation, lighting, internal occupancy and tasks. These sources can be considered with the following parameters, that the outside and inside thermal exchange is involved. Heat input and control:
- Direct solar radiation; shading the structure by artificial or natural means, such as trees, planting, awnings etc.
- Diffuse sky radiation; covering of the structure by any means.
- Ground reflected radiation; changing the ground reflection by using light or dark covers as required.
- Angle of direct solar incidence; orienting the surfaces to the sun’s rays, as required, by sloping the walls and roof according to the solar altitude.
- Surface properties; using proper fabric material, which differ in transparency, opacity, absorptivity and reflectivity.

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Fig-86. A passive heating criteria model; Shows the flows of heat into and out of a simple tent structure.

Fig-87. The double layers of tension and air-supported structures using insulation material and cavity in between with underfloor heat storing.
-Penetration of absorbed radiation; removing the penetrated heat by providing a ventilation system within the skin.

-Exposed area; exposing the site area of structure to the sun radiation, that usually depends on the form and size of structure.

The sources of heat output and control can be considered with the following parameters:
- Temperature differential; using or building in cool or hot site conditions, day or night, increasing or decreasing internal activities as required.

- Surface and layer conductances; removing the different air inflation around the structure by installing deflectors and using multi-skin construction, and internal furniture and design.

- Structural and insulation conductivity; using insulation material such as foam insulation, or reflecting foil between multi-layer construction.

- Area of transfer path; different exposed surfaces in relation to its volume with other temperatures, such as ground etc.

- Heat removal within the thickness of the structure; ventilation between double or multi-layers of fabric, using water cooling systems outside of the structure.

In fact, the fabric structures are like filters between the inside and outside environment. They are able to breath and allow selective exchange between the inside and outside environment.

In general, a comfortable environment within an enclosure needs a balance of energy, input and output. The input energy is continuously provided by using conventional energy such as electricity, gas, oil, etc., because the fabric has a high thermal resistance. On the other hand, this balance of energy has been achieved by using warm or cold air between multi-layers of fabric, or by using layers of insulation as a core to double-layer structures. (see Fig-87)

Fabricators in this field usually use double layers of fabric solution in the cavity wall, increasing thermal insulation by using an insulating layer of air to lower thermal response.

Fabric structures can be air-conditioned, by using multi-layers of fabric to actively control solar and sky radiation with an increase in cost and maintenance. Fabric materials with the increase in manufacturing techniques, combination of materials, together with gas heat transfer mediums, offers a wide range of thermal and light performances to meet different applications in various climatic conditions.

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8.2-Installation and maintenance

When the structure arrives at the stage where stress is imported to the fabric material, the role of sewing and welding techniques can be noticed. Manufacturers usually employ flat bar welding after the joint overlapped fabric by the width of elect-rod, which could vary from 25mm to 60mm. The importance for high frequency welding only in certain applications depends on the base strength properties of the fabric and the coating. In fact, by welding, the coated surface of the fabric will be joined together, but not the base of fabrics, where the strength of fabric lies. As a result of the varying thicknesses of coating and inconsistencies in the base strength, seams tearing can cause the failure of structure during installation. Therefore, it is advisable to examine all details, including joints and seams before installation on site, and take into account the behaviour of structure and material under the particular site conditions.

However, there has been a series of tests which were carried out by the companies producing the fabric materials. These tests cover an extensive range of possibilities, and from this range a test of certification is usually issued by official authorities for building equipment. During recent years, some air-structures and tension structures were entirely welded, quite a number of very large units were machined only. Tension structures were sewn and then welded with a clear strip patch over the sewn seam, increasing the seam strength and ensuring its performance. This method minimizes the labour involved in constant checking of the different patches of material for variations and ensuring a seam or joint with a durability at least equal to the anticipated life span of the fabric materials.

In fact, a careful detailed planning is required since it is generally necessary to completely install and make the whole structure secure in a continuous uninterrupted operation. If the fabric material is exposed to strong winds before being tensioned, it can flap and tear easily. Thus a working place is needed to be considered close to the project to speed the installation process, and all workers need to be self contained with the necessary tools. The edge cables and fitting steel must be able to be attached to the fabric without completely unfolding the surface material, and during operations these fittings should be tied to the anchor points to prevent being blown back on to the fabric material. Any defects in the prestressed surface may have structural consequences. Therefore, a regular inspection of the whole structure is required, particularly the fittings, anchorage and the places where rigid elements are concerned.

Maintenance is required for fabric structures at regular intervals to ensure that structural problems are not developing. This includes the inspection of the framework and the fabric material, and repairing any tears that might develop during exposure. Air-structures need special care, and must be regularly monitored. The valves, back flow dampers and air-ducts must be checked regularly. The backup unit
needs to be started and run occasionally and fuel levels maintained in case of primary power failures. Additional stand-by operations must also be considered, taking into account the environmental fluctuations, in order to increase the pressure, if necessary to resist strong winds.

8.3-Cost evaluation

With large scale development of resources, large-span enclosures that could provide different indoor climates are possible. Before starting a very large scale project, it has always been useful to become an expert through a number of smaller scale structures, thus obtaining experience and gaining knowledge of the know-how in detail techniques and design practices, where successful structures in connection with cost and economy are dependent on such factors.

The total effort required in large-span fabric structures are certain factors of knowledge that will contribute to further developments, such as design, material, fabrication, assembly, installation and time. These factors are largely dependent on the type of structure, expertise of designers and fabricators, and particularly on the size of the structure. Every step towards further development, and new experience during designing, fabrication and installation will promote the knowledge to estimate the total cost of a structure.

The standard unit costs of enclosed space such as cubic meter or surface as square meters are not applicable in fabric structures. Because the tension and air-structures are not constructed from standard building elements, there are no walls, ceiling and roof. The structure is all considered to be one total enclosure. Fabric structures classified under various catagories, maintain their unique systems that cannot be compared with traditional methods. A tension structure and air-structure are in principle two completely different structures. The span of tension structure and air-structure for an identical surface might be the same and having the same height, but the enclosed space can be different, and can not easily be compared. In fact, the cost of fabric structures are directly related to the complexity of surface and structure as a whole, rather then their large-span. It is also obvious that as the structure becomes more and more complex, the need for special detail technology such as supporting and anchoring are prerequisites. Thus the cost of structure is largely dependent on such new technology to be developed in order to insure its successful performances.

However, the cost evaluation of fabric structures needs proper management and organization to be taken under consideration during the design process. It is very difficult to estimate the cost of new fabric structures, which are not identical, each design and construction having its own quality and unique system. The effort in one structure might be different then the others.
8.4-The design analysis of the tent of Hajj terminal

The research has arrived at the final stage to justify various fabric structures in practice by evaluating their unique properties associated with form and structure, and the mechanism involved to be extended to a much broader variety of buildings. The development of new application in practical use gave opportunities to originate new design approaches and new methods, and to exploit new alternatives.

The tent of Haj Terminal at the Jeddah Airport (see Fig-75) has been chosen for evaluation as one of the largest tension fabric structure in recent years. The main idea for the Haj Terminal was to cover a large free space for almost two million pilgrims from Islamic nations coming to Saudi Arabia during the six-week of hajj season.

8.4.1- Feasibility study

The Jeddah International Airport in Saudi Arabia is located approximately 70 kilometers west of the Holy city of Mecca. Jeddah is the only large commercial city close to Mecca so all air traffic bound for Mecca arrives there and pilgrims proceed by land to Mecca. The airport facilities can normally handle this traffic, except at the time of the Haj pilgrimage when, during a six-week period, 70,000 Muslim pilgrims arrive and depart. Saudi Arabia became aware of the attention that the Islamic world pays to it, because of its religious homage. They are sensitive to the responsibility this creates for their country, the need to be a gracious host to the world of Islam, the need to guarantee a safe, healthy pilgrimage. Because the Hajj is performed in a specific season, large masses of Muslims must move into and out of the country in a short time. Foreign pilgrims have increased seven fold in number since 1950, and this quantity is expected to continue to increase through the end of this century.

There is greater affluence for Muslims and greater flight accessibility to more countries. These are factors combining to increase the number of pilgrims who come to Saudi Arabia by plane. In fact, the number has reached three quarters of a million who must enter the country for the Hajj then leave. The combination of so many people gathering at one time in such extreme heat created an urgent need for shelter of a very specialized nature.

It was apparent that Saudi Arabia had to prepare for these extensive future needs. It was decided by the Saudi government to construct a terminal facility at the King Abdulaziz International Airport which could handle the processing of the pilgrims. A separate terminal facility of 500,000 square meters was needed to process
the Haj pilgrims. It was expected that by 1985 the terminal could handle approximately 950,000 pilgrims during the six week period, and accommodate 50,000 pilgrims at one time for a period up to 18 hours during arrival and 80,000 pilgrims for periods up to 36 hours during departure. This time was required to transfer between air and land transportation. The facilities consists of a linear, air conditioned terminal building adjacent to the aircraft parking aprons and a large shelter support complex adjacent to the terminal building. This scheme provided minimum walking distance for the pilgrims from the planes to the air-conditioned terminal where all formal processing and baggage handling is accomplished. Pilgrims then move into the naturally ventilated support area where they will organize for land travel to Mecca. Because of the severe environment in the Jeddah area, the support complex must be protected from the sun.

The architectural firm Skidmore, Owings & Merrill (SOM) was asked by the Saudi government’s International Airport project office to create a structure large enough to accommodate thousands comfortably, and at the same time, the terminal design had to be kept simple to control construction, operation, and maintenance costs and to allow easy and rapid travel connections for the pilgrims.

The architects explored many concepts, including several concrete and metal roof systems, but the tent and fabric structures became the most applicable structure for this application.

In history, the tent provided a protected resting spot and a sense of unity, solidarity, and security for most Arabian nations. The shape and form of tent shelter is deeply ingrained in the life and culture of the vast majority of the Islamic world. It was not unlikely or unusual then for the basic double curves of tent-like structures to be considered for the design solution of a Hajj facility at Jeddah Airport. The parallel between the long standing use of tents and that of tent-like fabric structures was not lost on the architects.

In designing the Hajj Terminal, the architect (SOM) had to solve the challenge of providing a structure that was not a building, but rather a kind of shaded village. In a very real sense, they had to create an environment which could allow for the spiritual transition from weary air travel to holy pilgrims. The SOM architects explored many concepts with the International Airport projects office, which called for a minimal number of columns to allow for the movements of masses of pilgrims and for a simplicity of design. The idea of having a single building to enclose processing and waiting areas required such an enormous structure, it would have been almost impossible to build, maintain, and air condition. Therefore, SOM decided to design two kinds of space. A series of enclosed, air conditioned terminal buildings would be used for customers, baggage handling, and their processing tasks, while much larger waiting areas would shelter the pilgrims.

To achieve the shaded environment or the vast waiting area, SOM considered several approaches that included concrete "mushroom" and light metal and concrete roofs. However, the quantities of building materials needed would have been so huge that the architect turned to fabric structures as an alternative. SOM decided Fiberglas fabric coated with Teflon which is the most
suitable material due to its high strength, weather resistance, not being sticky during sand storms and long life. Working with this fabric, the architect was able to generate a design that is highly efficient in terms of erection construction materials, and costs. Thus the feasible use of fabric material in specific and fabric structure in general was achieved, which was also as result of their large-span capability over other structural systems.

8.4.2-The design considerations

The consideration of fabric as a suitable material for Hajj Terminal at the Jeddah Airport brought SOM on the conclusion to consider various fabric structural system, in order to evaluate the most feasible structure among various structural schemes. The first structural system to be considered was a light-weight, portable, and large-span air-structure, and its sub-types. The SOM architects did not consider the air-structure for Hajj Terminal, because they are suitable for a fully enclosed environment and the mechanism involved to withstand their longterm performances would be much more costly than tension fabric structure. They offer the opportunity to be able to control the internal environment in an integrated fashion and the structure was also considered to conform with local custom and traditional heritage.

Finally the tension fabric structure was considered which is generally suited for such cases, in which a limited environmental protection is sought, such as rain or direct sun light where side walls can be omitted. Part of the preliminary design consideration was to examine alternative forms of construction, principally tension fabric structure. An exercise was carried out to test the feasibility of various forms of tension fabric structure. But results indicated that the combination of costs, site constraints, tradition, aesthetic factors and configuration of existing buildings, pointed to a tent-like structure as the best solution.

The designer task with a tent-like structure in this stage was; choosing a suitable system and formulation of the geometrical arrangement of each unit in the whole structure. The next steps were the specification of loads and the formulation of individual load combinations, and at the same time stress analysis of the structure on the level required.

In order to achieve a suitable system of structure, SOM considered a system that should be based on the following qualities:
- The consideration of a successful tent structure in terms of public acceptance and commercial performance for Jeddah Airport.
- The consideration of architectural needs of the building such as form, function, translucency, weather control and the efficient coverage of the plan configuration.
- The unique appearance of tent structures compared with other building system.
The need and provision of an open environment that should not be hostile for pilgrims.
The need of creating a focal attraction within the airport area upon arrival of pilgrims.

8.4.3-The design conditions

As all designs are based on certain requirements in terms of performances, aesthetics and functionality, the Haj Terminal tent is also subject to the conditions to be taken into account during design developments. The conditions are usually outlined by architects in order to increase the quality and functionality of the structure for a specific application. On the other hand such conditions or parameters will allow the designers to narrow their path of conceptions towards an applicable system of structure which is peculiar to the present project.

In general, looking at any form and system of structure the following aspects were considered to be parameters for a successful design:
The structure must be open sided and should have good access to pilgrims.
The structure should be free of anchors and unencumbered to prevent blockage or obstacles which might cause accidents especially during night use.
The structure should be based on additive aggregation of individual units, offering repetitive installation of the identical unit that might be needed in the future.
There should be a minimal use of masts to avoid the obstruction of the flow of pilgrims.
No part of the membrane should be lower than 3 meters to eliminate potential vandalism.
The structure should be manufactured outside the airport and must be able to be readily transported on site.
The structure should have a symbolic meaning, peculiar to Arabian tradition and accordingly should be aesthetically excellent.

8.4.4-The development of design

The form of large-span, lightweight structure with translucent material can adequately respond to the overall environmental needs of this space. The most common form of this system has been the two-way cable-net structure with a covering or skin. This system was used on the Olympic stadium in Munich, Germany for the 1972 Olympics. However, this system was not
economical for the Haj Terminal because of the large number of cables and numerous connections between cables to create a grid network. The new and improved membrane materials allowed development of an appropriate structure using the fabric membrane with cables in a two-way interactive system of cables and membrane.

The level of expertise at the time suggested a simple symmetric structure of reasonably high curvatures. The architect Fazlur Khan developed the present form, by using a center posts system of tent. The original form was based on the traditional tent concepts, which uses center posts, but SOM and the project team eliminated such posts in order to avoid the proliferation of columns which obstruct the flow of pilgrims. This obviously made the support structural system somewhat more expensive, because the central posts are a more direct approach.

In order to accomplish this project from design development to installation and maintenance, SOM set up a multinational team of expertise. The contracting division of Owens Corning Fiberglas was asked, if they were interested in a very large project using Fiberglas fabric coated with Teflon to be constructed in Saudi Arabia. The Owens Corning immediately named a task force to review the project, analyse the performance criteria, determine what aspects could or could not be achieved, determine if the application of a fabric roof system was appropriate, and develop a potential schedule for accomplishment.

The task force which Owens Corning assembled was comprised of personnel from a wide range of disciplines within the corporation. They generated detailed information that made it possible to prepare the scope of Owens Corning’s capabilities based on the performance requirements presented by SOM.

They developed and promoted the present design solution for the Haj Terminal fabric roof system which would speed up the construction and lower the cost of the project. They had the experience in designing and erecting fabric roof structures, as well as the background in developing and working with the fiberglas fabric.

In response to a positive to the architect, Owens Corning asserted its desire to handle the project and to be included in all of the attendant recognition of design and involvement which would come from presenting their design ideas to the Saudi government. Through meetings, presentations, and discussions, the concept for the fabric roof system was accepted by the Saudi Ministry for Defense and Aviation, International Airports projects, in August 1977.

However, since the design called for structural engineering expertise, the Maddigan Praeger and Geiger Berger Associates were engaged. These consulting engineering firms would help with the design, fabrication, and construction of concrete masts, and the rigging of support and tension cables in conjunction with the fabric material. Other consultants would help with the lifting and tensioning capabilities as well.
The proposal team worked very intensely to pull together the necessary information, details, calculations etc., Mitsubishi corporation, representing Nippon Kokkan steel, approached Owens Corning requesting discussions about a steel alternative to the concrete columns. At the preliminary stage of design, the steel columns had not been considered, because of the corrosive environment near the Red Sea. However, Mitsubishi Nippon Kokkan had developed an epoxy coating for the steel column to make them a practical choice. The steel columns were included in the proposal as an additional alternative to the concrete columns. A great deal of time and money would be saved if the Saudi Ministry decided to use steel. It was during the design clarification process that concrete was substituted by steel as the column material.

8.4.5-The final design

The final design decision was made on the basis of the above-mentioned consideration by the multinational experts in the field of fabric structure. The original idea of center supported conical roof had been evaluated, and replaced by cable-supported roof units. In fact, the inherent long-term characteristics of the cable-supported roof units allow columns to be spaced far enough apart to give the large support area a very open feeling and allow maximum flexibility for various support buildings located beneath the fabric roof.

The architects and engineers of SOM explored the present designs for the fabric roof system and, with the aid of a computer, determined that the optimum shape for the individual roof units would be a double curved conical form. The fabric form would be tensioned and shaped with cables radiating from a center support ring on top, to the four edges of the cone at the bottom.

For the purpose of planning, a module of 45 x 45 m was established as one unit. Each module is 3 units by 7 units for a total of 21 units per module. The overall plan is grouped by 10 modules which is five in a row on each side of a central roadway, with provision for an additional five modules on each side. The steel columns of 45 m high are located at the corners of each unit. The roof membrane forms the tent shape, springing upwards from a 20 m height at the columns to 35 m at the center tension ring. The radial cables extend from the center tension ring to edge or ridge cables connecting the columns at the intersection of adjoining roof units. The suspension cables are arranged in 4 pairs and extended down from the top of the columns to hold the center tension ring in place. Pairs of suspension cables were used rather than single cables to provide redundancy in case of failure. To further protect against collapse due to membrane damage, four stabilizing cables are provided for each unit. These cables extend downwards from the center tension ring to the lower tension ring at the column. These cables keep the center ring in
position if a particular unit’s membrane loses tension.

The overall stability and structural integrity of the entire system is achieved by a special arrangement of the columns around the perimeter of each module. Extending around the perimeter of each module, including the common row of columns between adjacent modules, is a row of very stiff double columns and portal frames. This stiff edge and separation between modules makes them independent of each other and allows modules to be added or removed. On the other hand, this system ensures that a failure in one module will be isolated and not transmitted to an adjacent module. The tent roof of Hajj Terminal thus provides structural stability, safety and redundancy at the following three levels of the systems:

- The individual members cables.
- The unit stability-stabilizing cables.
- The module stability-perimeter double columns and portal frames.

As part of the final verification for this structure, a full scale prototype of two of the tent roof units was built. The prototype was used to verify the results of the structural analysis and to demonstrate the constructability of the roof system to include its many connection details. On the other hand a test was also required during design procedures, in order to prove the integrity of the architectural design and the engineering analysis as well as check out the materials used and construction techniques to be followed. A prototype was built at the Owens Corning Technical center in Granville, Ohio, to represent one interior and one corner unit. It was anticipated that such prototype tests would also help the manufacturing of many of the components and improve erection tools, equipments, and procedures.

It was understood during the planning process that all components would be manufactured thousands of miles from the site, shipped to the Saudi desert near Jeddah, and assembled as a prefabricated unit. Therefore, all pieces must fit, all tools must function correctly, and all methods must work the first time.

However, a simulating apparatus was provided along the interior edges to simulate the adjacent units in the actual structure. The test columns were designed with tie-back cables in which column deflections could be controlled to approximate the behavior of the actual columns. All roof membrane patterning, compensation, fabrication and shipping techniques were carried out exactly as anticipated for Jeddah Airport. In addition, a series of tests were conducted to demonstrate the system’s safety or redundancy features. The roof structure performed as predicted with no loss of unit stability. The series of fabric rip tests demonstrated the system’s redundancy regarding loss of membrane stress and also the fabric repair procedures.

When the prototype units were being assembled, hundreds of strain gauges, strain sensors, and load cells were attached to their fabric, cables, and rings. This instrumentation provided the principal measurements which were recorded then fed to a computer for analysis. The computer analysis gave the
Fig-88. The tent form, and installation procedures for the roof of Haj Terminal at the Jeddah airport.
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Plan configuration

The flow of heat in the structure

Fig. 89. Showing the plan configuration of square-based units, and the air circulation from the structures open sides up through the open support rings at the top of each conical unit.
engineers a check of the structural behavior of all roof system components during raising and tensioning of the two prototype units. The simple hand-held device allowed them to measure the average stress in the fabric anywhere on the roof surface.

After the erection and final tensioning of the two roof units to a final stress of 1.226 kg/mm, a ground survey and air survey (photogrammetry) were conducted to verify the final shape of the membrane. Confirmation of the shape was not only visually important, but was required to analyze the cable and fabric stress data since shape directly influences the results. By analyzing the stress data together with the shape data, it was possible to evaluate the overall behaviour and performance of the structure with reference to the theoretical model and minor adjustments were made for the actual construction in Jeddah Airport.

However, testing verified the validity and reliability of the roof unit shape and also verified the accuracy of computer programs developed by consulting engineers hired by Owens Corning. The shape and prestress level of all prototype components agreed within three percent of the computer prediction. The computer programs were very sophisticated, the engineers could even simulate the effect of fabric rip.

8.4.5.1-The form of the tent

After the selection of the basic materials for the tension fabric structure (cables and teflon-coated fiberglass) and steel column, a comprehensive study of shapes and forms was undertaken to develop a shape both aesthetically pleasing and structurally feasible. In making these studies, the cultural heritage of Saudi Arabia was kept in perspective. The tent tradition is a familiar form in the Middle East. Throughout the history of Saudi Arabia, tent structures have provided comfortable shelters by shading, while allowing the breeze to flow through. From a structural design point of view, it is important that the design of the membrane surface of a tent shape must result in a double curvature shape to ensure stability for both upward and downward acting wind loads. In fact such a form guarantees tension in the fabric under any loading condition with only an adjustment in the level of tension in one direction or the other depending on whether the wind pressure is up or down. An appropriate initial tension can then be determined to keep the fabric taut and stable.

By studying various forms and proportions, the final configuration and form selected, which is a two-way grid of columns, from which the high point of the tent (tension ring) are suspended and the low corner points are anchored. (see Fig-88) The double curvature tensile membrane surface is created by holding the membrane at the column locations and raising the tension ring.
thus stretching and pretensioning the membrane. This form also provided rain drainage at the columns and also induced a natural flow of air out from under the tent roof through the opening at the high point at the center tension ring.

This large structure has a fairly low rise of roof relative to the span, but the roof itself starts at a considerable height. The suspended cables have been used to gain height cheaply, and the resulting overall form is very effective in resisting the strong wind forces.

However, a structural form having equally tensioned fabric is effected by cable tension and cable layout. The shapes of cable-reinforced fabric structures differ from fabric structures without cables. Therefore, the form determination of cable-reinforcement fabric structures is an important problem for the structural engineer in preparing the surface design. This task was achieved by using computer simulation and physical model test, and even a full-scale prototype to assure the accuracy of form.

8.4.5.2-The structural system

The design of the tent of Hajj Terminal appeared as a cable-stayed tension structure, in order to increase its long-span capability. The fabric roof was also reinforced by cables, strengthening its long term performance. In fact, the cables are stress relieving which reduce the loads on the membrane structure under design wind load.

Due to the unique structural behaviour of the structural system, analysis and design are closely related and have been an iterative procedure. Fabric structures rely on their skin to carry the external loads. They are constructed with enough initial tension, so that under any combination of loads the structure does not become slack at any location. These structures derive their strength from their shape and the amount of built-in tension or prestress. The combination of a double curvature surface together with prestress provides the stiffness and strength to resist external loads in any direction.

In fact, the surfaces with more curvature are stiffer than surfaces with less curvature for the same amount of tension. The membrane structures deform under load and change their geometry in response to external loads. Analysis of such structures must therefore take into consideration the large displacement they experience and the amount of curvature and prestress they have. The complexity of such analytical procedures therefore calls for heavy use of digital computer programs used for analyzing fabric structures, and must also have the capacity to accept nonlinear material behaviour, since fabric stress strain diagrams are nonlinear in nature.

The SOM decided to use the NONSAP computer program which was originally developed at the University of California at Berkeley. It was modified
for the purpose of analyzing the Hajj Terminal fabric roof. The NONSAP is a non-linear large displacement computer program that can perform static as well as dynamic analysis. The program was modified and expanded to avoid the difficulties encountered in membrane structural analysis such as form-finding, numerical instabilities and the huge amount of data stored, retrieved and displayed graphically during the iteration process.

In the computer model used for the analysis of the roof, the fabric surface within a 45 square meters unit was represented by a set of intersecting curved finite elements in the radial direction and in the circumferential direction. The properties of the idealized fabric, radial curved elements were modified to include the effects of the radial steel cables. The columns were considered as vertical mast elements. The steel tension rings were also represented by a series of beam-column elements.

wind pressure and model test criteria

The determination of wind loads are quite difficult specially for tension fabric structures which have nonconventional forms and sometimes allow the wind to impinge on the underside of the membrane. In this case the fabricator usually used wind tunnel tests.

The design of the tent of Hajj Terminal is also governed primarily by wind loads. The wind loading criteria were developed by a static pressure model test performed at the University of West Ontario, under direction of dr. Allera Davenport. The test established a wind load criteria of pressure on a localized 7.5 square meter area, pressure on one roof unit and loading patterns on an entire roof module. A finite element mesh depicting a 21-unit roof module was used to check the wind effects on the entire module. On the basis of a number of iterations, the final prestress level was set at 1.226 kg/mm in both warp and weft directions.

The suspension cables were designed so that, if one cable in a pair fails, the remaining cable will temporarily support the center tension ring until repairs can be made. Stabilizing cables were designed to pick up the tension lost by the fabric roof in the event that the fabric membrane should accidently lose tension. The cable size ranged from 15.25 mm diameters for a radial cables to 61 mm diameter for a ridge cable.

The membrane roof structures are sensitive to damage due to possible vibrations induced by wind. A dynamic analysis that consisted of frequency extractions was performed on a single roof unit and on a 21-unit model. The upward and downward movement frequency of the tension ring was calculated to be on the order of 1.3 hertz and was found to be associated with large damping characteristics thereby eliminating any possibility of resonance under design conditions. An aero-elastic model consisting of 3x3 units and closely simulating the dynamic properties of the full-scale structure was constructed and tested in a wind tunnel. It was found that the structure was

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stable and did not experience excessive vibrations during a simulated 95 mph wind storm.

8.4.5.3-The development of details

The important factor that has always been taken into design consideration during design development is the detail and manufacturing process. The detail development arose from structural systems and special forms. In fabric tension structures, the details are developed in such a way that they contribute in installation processes as well. In most other structural systems the details are only aimed to fulfill the static performances of the structure.

However, the manufacturing of the components for the Hajj Terminal fabric roof system was truly an international effort. This effort included integration of the industrial skills and plant facilities of firms in three nations. These manufacturing processes were based on findings resulting from the prototype, production facilities in France, Japan, and the United States. They had to manufacture and deliver their products to the site to match the design and building schedule requirements.

The columns fittings and bolting details, and the upper and lower ring details together with perimeter rings and cable sockets are designed, manufactured and tested. Other elements included thousands of pounds of fasteners, spacers, and brackets which are extruded, aluminum edge clamps that were etched, anodized, and nickel acetate sealed. The neoprene was used to sandwich the clamped fabric edge and to seal the roof joints.

As was mentioned earlier, each design needs its own details to be developed according to the structure and the force subjected. Thus the present structural details and fittings were also non-standard and had to be specially designed and manufactured.

8.5-The choice of material

An analysis on the determination of material properties was undertaken, which are not idealistic assumptions, but respond to the actual acting loads and in the realistic understanding of the load bearing properties of the individual structural elements as well as in their behaviour within the whole system.

In general there are three elements dominating the structural system which are the columns, the cables, and the fabric material.
The column

The key structural element of the roof system is the group of 45m steel columns. At a count of 440, they amount to over 30,000 tons of steel. The columns were fabricated at the Shipyard city of Tsu, Japan, at the southern end of Tokyo Bay.

The supplier Nippon Kokkan, had skilled workers that produced the columns from a cold-rolled process. The columns are not perfect cylinders, but are actually tapered almost 2.45m in diameter at the base, 1.22m at the top. The fabrication required expert ability to achieve the precise dimensions which is critical to the performance of the roof system.

The extensive welding was accurately performed to unify the column, add flanges to the column surfaces, produce the bottom rings, assemble the junction diaphragms for perimeter columns, and to fabricate the mated, two section support rings. The steel surfaces of the columns, rings, and diaphragms were cleaned, treated, and coated with a four layer epoxy paint system. Each column was wrapped, then placed in a special barge for ship transport to Jeddah.

The cable

The other important structural element is the network of special steel cables that tension and support the roof. The 246 miles of Hajj Terminal cables are not ordinary wire cables. The Beaujolais wine district of France manufactured the five different diameters of cable in a unique method of coating the wire strands with amorphous polypropylene plastic, as the wire strands were twisted into cables. This procedure protects the strands from the corrosive salt air of Jeddah.

The cables are then wound onto rolls so they can be fed through a process, which extrudes a polyurethane coating over their entire exterior surface. The final plastic sheathing gives further protection against the harsh elements of the Red Sea air.

After the plastic coating is tested, the cable is moved to other plants where sockets and fittings are attached. The fittings and other exposed cable receive a final coat of polyurethane before the cables are crated and shipped to Jeddah.

The fabric material

Another design aspect to consider is the expected life of the fabric material and its performance. The building regulation committee and the health
department did not permit the use of PVC coated fabrics for this permanent application, due to its degradation and loss of strength in the order of 15-20% over a period of 8-10 years.

The teflon fabric offered excellent long-term protection, initially it had a rather bland colour but quickly bleached to a brilliant white after a few months of exposure. The structures have remained very clean in appearance compared to comparable PVC coated fabrics. The disadvantage of teflon coated fiberglass is that it needs to be handled carefully on site. It is very prone to damage due to careless handling, creasing, abrasion by dragging over concrete on dirty sites.

The fabric material used in the tent of Hajj Terminal had to satisfy numerous performance criteria. In the past, fabric membrane materials had a relatively short life, consequently they were used in temporary structures. However, the fabric membrane for the Hajj Terminal needed a life of at least 30 to 40 years with minimum maintenance. The time requirement was extremely difficult because this environment is very harsh due to the continuous exposure to ultra violet degradation and a highly corrosive marine atmosphere. In addition to a long life span, the fabric material also had to be and should have the following qualities:

-Self-cleaning to ensure a lasting good visual appearance.
-Lightweight yet capable of carrying high tensile loads with little or no long term creep.
-Good thermal insulator to protect the pilgrims.
-Sufficiently translucent so that area is naturally illuminated during the day.
-Non-combustible and also not give off any toxic gases or fumes when subjected to fire.
-Easy to fabricate, transport and ship.
-Replicable on site during installation if required.

The fabric that meets these requirements is a heavy weight, teflon coated fiberglass. The fiberglass provides structural strength and the teflon coating protects the fabric. It is a major element in pure statics as well, and an amount of 1/2 million square meters of fabric were used. The yarn weighed about 0.68 million kgs.

The fabric was manufactured by Owens Corning at a plant in Rhode Island, this architectural fabric combines the benefits of Fiberglass "Beta" yarn, which is much stronger than steel, and less expensive with Dupont's Teflon. The Fiberglass fabric coated with Teflon is highly fire resistant, it resists many common chemicals and will not deteriorate over long periods of time. It is highly resistant to micro-organisms, moisture, temperature extremes, and the sun's ultra violet rays.

The Beta yarn is an ultrafine pure glass fiber developed for America's space program, which required strong, lightweight, fireproof fabrics for space suits and other applications. Though Beta yarn is six times finer than silk, it can withstand temperatures to 815 °C.
8.5.1-The fabrication

One of the fundamental subject in designing fabric structures is the pattern analysis and fabrication. The patterning analysis and experience in its determination and geometry did exist, because the form of the tent is a natural development of fabric structures. But the indeterminate system largely influenced the determination of cutting patterns, because a compensation for stretch of the fabric material in warp and weft direction have to be made. This task together with fabrication and careful packing, and handling procedures was fulfilled by the firm of Walter Bird.

A substantial testing procedure was conducted to determine the influence of jointing methods. Samples of welded, stitched and combined welding plus stitching joints were tested and from these minimum weld widths and procedures determined. Some test strips of the fabric have been attached to the structure and it was planned to test these at the prototype structure to ascertain any loss of strength.

However, various jointing methods have been experimented with, the fixed joint seam is usually used for tension fabric structures. Fixed seams can be made by glueing, welding or sewing. Seams always influence the stress distribution in the membrane and the elastic behaviour of a membrane structure.

By welding a seam the material is doubled in a certain area of surface. This means that, in order to deform the seam to the same length as the adjacent membrane, twice the force will be necessary. If the same force is in the seam and the membrane, the seam will only undergo half the elongation of the membrane, it will remain shorter.

The sewn seams are always over-welded with a narrow strips of membrane material of plastic foil. In fact, the stitch is a little hole in the membrane coating so that penetrating water and dust reduces the lifetime of the fabric and the structure.

After the fabric is tested and inspected, cut into panels and joined into the individual tent-like units. There are three different kinds of units for edge, interior, and corner placement in the module. The bonding is done with a sealing process that combines high temperature and pressure to create a joint that is stronger than the tensile strength of the fabric.

The finished fabric unit is carefully folded with cellular plastic foam inserted at each bend to prevent creasing. The unit is then crated for shipment to Saudi Arabia.
8.6-Installation procedures

The transportation and erection care decides above all the good quality and success of a fabric structure. In the erection procedures all relevant material, design and fabrication parameters meet together into the final product with the design intent. Knowledge and experience of prestressing procedures and operations together with erection preparations to guarantee shortest instability time of the fabric in the air could have been responsible for successful erection of the present fabric structure.

The design consideration allowed a suitable construction sequence and allowed a clean unobstructed available site for handling fabric structures. The manufacturers carefully rolled, folded, and crated the fabric for transportation. The mobile cranes were used to handle the large panels of fabrics. The aspects of site preparation and construction sequence planning as a mean of protecting the material are a prerequisite in design consideration. A careful detailed planning was made to completely erect and secure whole structures or large panels in a continuous uninterrupted operation.

However, the project team began to prepare the Jeddah airport site for installation of tent-like structures. They installed all utilities, sewage and communications systems, including roads, warehouses, office buildings, and housing to receive management personnel, labour, equipment, and materials. The installation of the Hajj Terminal fabric roof involved one of the most sophisticated and unique construction methods ever developed. Unlike other tent systems, the Hajj Terminal roof units are not attached directly to the ground, rather their lower edges are more than six stories above ground. In order to accomplish this, Owens-Corning developed technology exclusively for the project.

The lower corners of each fabric unit are attached to support columns and its highest point is attached to a large support ring suspended from the column by cables. The support ring is divided into upper and lower sections. During installation, the upper ring section is held stationary at 55m in the air, while the lower ring section raises the fabric from the ground. When the fabric is raised to its full height, the upper and lower section are permanently bolted together.

The project appears deceptively uncomplicated because of the free flowing lines of the fabric and the simplicity of the columns. The fabric roof system is intricate in detail, complex in assembly. The installation required a concentrated management effort to coordinate the manpower, materials, and equipment to bring all components together properly.

The labour force came to the jobsite with basic individual construction skills, however none had been involved in erecting a fabric structure. Training sessions were conducted to demonstrate the proper method for handling the fabric and pulling it into position under the support ring. They were also coached in use of the special hand tools, pullers, and accessory equipment.
With manpower, components, equipment, supplies, and support systems ready, the actual construction began with the erection of the columns.

Each of the large 68 ton support columns for the fabric roof system were carefully placed on a concrete pad in which giant bolts had been set. The accurate seating of the planged base for bolting to the footings is accomplished by a 28 ton crane, the largest of its kind in the world. There were three different formats used for column placement which are single columns, two-columns frames, and corner four-column frames joined by cross beams and height diaphragms. Double columns are used to attach the exterior edges of the fabric, while corners of the module are secured to the four-column units. Once each of the columns is in place and secure, the necessary diaphragms and cross beams are bolted and welded to them.

The two-section support ring is placed in the center of each unit area of the module and four pairs of suspension cables are connected to the upper section. That section is hoisted by crane to a level where the other ends of the suspension cables can be attached to the tops of the surrounding four columns. The crane then lowers the ring section until it is supported solely by the suspension cables. Stabilizing cables are drawn between the upper ring section and connecting points on the columns, 20m above ground. (see Fig-88)

A hoist cable is run from the mechanism on the lower part of the ring up over a pulley on the suspended upper section and anchored back down on the lower section. This arrangement doubles the mechanical advantage for raising the fabric unit. The lower section is then raised out of the way.

Another set of cables is rigged from column to column to hold the lower edges of each roof section. These cables are laid out on a series of scaffolds. Aluminum plates which will be used to clamp the fabric edges to the cables are then attached. After all of the cables support rings and clamping hardware are in place, the crated fabric is delivered to the center of the unit area.

The lower section of the support ring, which has been raised out of the way, is lowered until it is just above the uncrated folded fabric. The neck of the fabric roof is attached to the lower ring which raises the fabric off the crate into the air. The nets are placed around the fabric when secured to the ring so that wind will not whip it around before the bottom edges are under control.

The hoist then lowers the ring until the fabric reaches ground level. The workers attach tag lines to the four bottom edges of the fabric and pull all four sides of the unit outwards, as an umbrella being opened. As the workers are stretching the fabric towards the edge and ridge cables, the hoist ring continues to lower in stages until an optimum working level is reached. After the fabric has been spread to the edge and ridge cables, the four edges are clamped in place. Edge cables are used on the exterior sides of the fabric units, while ridge cables are on the interior. These cables are extended between the columns, from a 45 m by 45 m frame for the fabric bottom.
After the fabric has been completely secured to edge and ridge cables, the support ring holding the neck is again raised until the unit reaches full height without lifting the bottom edge. Workers then lace 32 radial cables reaching from the support ring through vertical sleeves and the inner fabric surface to the edge and ridge cables. These radial cables have sockets at both ends. They function as spines in an umbrella to shape and strengthen the material. The process is repeated until all 21 units of a module are in place.

The Hajj Terminal fabric roof system is comprised of 10 modules. Each module has 21 fabric units joined at the adjacent edges to form a single covering construction planning called for the raising and tensioning of an entire module at the same time. There were over 100 observers checking critical points of the roof system during the raising process, each person was connected by phone line to a central control. Periodic stops are made for careful inspection and any needed adjustments. The jack screws on the lower section of the ring are connected to threaded fitting on the upper section. These jack screws make the final draw of the units to tension the fabric. When the correct tension has been attained in each unit, the two ring sections are bolted together. Following the stage of prestress a survey was done to check the top of the columns and center of fabric ring, and the results were nearly perfect.

8.6.1-Economical performances

The present fabric structures for permanent use are not considered economic structures, particularly when the costs of design, cutting patterns, fabrication installation and maintenance are included. Consideration was given to the short and long term costs of the project, whether it is more economical to replace the fabric skin at regular intervals. There was no cost limitation from the Saudi government in this project, rather they concentrated on an outstanding structure to conform with the environmental context. The $2.5 million prototype testing program proved that the initial design required only very minor refinements. Everything learned at the prototype stage made the actual construction procedures easier, and safer. In fact, such a project could have been accomplished with other standard structures less costly and time consuming, but new and special structures need additional costs such as prototype testing etc.

In most cases expensive fabrics with a shorter life can prove to be a more viable economic solution for commercial installations where replacement of the fabric can take place after a given period. The cost of the replacement fabric is not as high as the original fabric because the same cutting patterns can be used and the structure and sub-structure will still be in place. The constant improvement in fabric technology will probably ensure that the
replacement roof will have a better performance and the economic circumstances of the installation may improve sufficiently over time to permit the use of more permanent fabric.

8.6.2-Weathering control

The internal comfort is one of the main problems in fabric structures to be solved by proper ways of designing. The membrane used is thin, does not have good thermal insulation, acoustics are difficult and certain techniques are developed to make this structure tolerable for such an environment. By utilizing the natural characteristics of the fabric forms, with inlet and outlet venting areas for different seasons and conditions many roofs can rely simply on natural ventilation.

The fabric structures were built to modify the external climate of this particular location. Many scholars refer to a membrane as being like a filter between the inside and the outside environment. The membrane filter makes it possible to specify the idealized performance requirement of a membrane. It should be able to breathe and allow a selective exchange between the inside and outside environment.

Fabric structures as shade from the sun or shelter from the rain, provide many opportunities for creative design. The climate under such a structure can only be at best a modification of the outside climate.

In creating this design, the architect made optimum use of the advantageous properties of Fiberglas fabric coated with Teflon. The white fabric reflects 76% of solar radiation from its upper surface, thus helping to ensure that temperatures do not reach an uncomfortable level. In fact, this reflective property coupled with the air circulation from the structure’s open sides up through the open support ring at the top of each conical unit, keeps temperatures in the 26.5 °C range, even when outside temperatures hit 54.5 °C. (see Fig-89)

The constant desert wind gives a natural venturi effect across the top opening of each ring. The fabric is also translucent and this permits shadowless natural light to filter to the area below. About 7% of available sunlight is transmitted, creating a softly shaded environment that eliminates the need for artificial daytime lighting.

Fiberglas fabric coated with Teflon on both sides will resist the effects of heat, ultraviolet rays, and salt air. It is also very strong and durable. Tensile strength of the fabric is 15 kg/mm, which meets the design prestress loads of 1,226 kg/mm. The roof has a life expectancy exceeding 30 years.

In addition to the advantages of the fabric itself, the acoustical problems created by the many thousands of pilgrims located beneath the roof are diminished due to the conical shape, the roof height and the material.
8.6.3-Maintenance

The regular inspection of this structure is obviously required since any defects in the prestressed surface may have detrimental structural consequences. Particular attention to fittings, regions where contact with rigid elements such as edge cables, roof rings etc. will greatly help in maintaining a practical structure.

Like all other structures these types of structures need a reasonable attendance by the owner, engineer and manufacturer. Prestress and damage control belongs to the maintenance program as well as preserving the coating from unnecessary climatic corrosion due to dirt patina and abrasion. The most important question of the ultimate strength of the joining seams of a fabric structure can only be answered with a substitute test, which could compare the deterioration of the fabric strength in comparison with the resistance of the seam.

The prototype test has proved that all fittings and seams strength are reliable in respect to the prestress forces and structural systems. As a result, up to date no severe damage has been sustained. The gradual deterioration of fiberglass coated fabric can hardly be noticed, the life of the fabric is expected to be between 35-40 years. The replacement of the fabric roof is within the maintenance program and the performance of this structure proved to be the most reliable structural system in this field.

8.6.4-The problems and prospects

The main problem arose from the tensioning procedures, because the 21 tents in each module must be tensioned simultaneously. The visual simplicity, and hence the interconnectedness of the tent structures made engineering analysis more complex and time consuming, than if the tents had been center pole supported and designed as independent units. The structure is a very large indeterminate system with ripple effects from unit to unit and module to module. Tensions or loads applied to one tent are induced into surrounding tents and columns.

As we mentioned before, the form analysis is a fundamental subject to be taken into account during design procedures. Thus, the tents of Hajj terminal required a large computer model analysis. Though several physical models were employed for form-finding and pattern analysis, in order to stimulate the behaviour of this indeterminate system a large computer system had to be developed.

The second fundamental subject in designing fabric structures is usually the
Interior view of Hajj Terminal tent. Source: J. Zils (SOM)
pattern analysis and fabrication. The pattern analysis and experience in its determination and geometry does exist, because the form of the tent is a natural development of fabric structure. But the indeterminate system largely influenced the determination of the cutting pattern, because a compensation for stretch of the fabric material in warp and weft direction had to be made. Although the pattern analysis and fabrication together with packing and handling procedures were fulfilled by the firm of Walter Bird, the experts at that time called for a full scale prototype to ensure its performances and acquire the necessary data. On the other hand such a prototype will create economical consequences that cannot be employed in every structure. This decision was made particularly for this project, where there were no economical consequences.

However, the structure is a marvelous melding of ancient and modern Islamic tradition and the centuries old use of tents are unified and symbolized by the power of today’s engineering technology. When the pilgrims emerge from the terminal buildings into the protecting shade of the fabric roof, they will find the accommodations of a village with an openness, which accents an environment of Islamic spirit. Then they will leave the protection of this modern tent form, which now symbolizes both the traditions of the past and today’s Saudi hospitality.

8.7-Alternative concepts

On the basis of the above mentioned structural system, the author searched for alternative designs, in order to overcome some problems incorporated in the design of tents at Hajj terminal and based on the following aspects:

- To reduce the number of columns, thereby reducing the total cost.
- To design a center-pole supported system as independent units.
- To avoid the ripple effects of tents from unit to unit.
- To provide a determined system so that the tension and compression process would remain within the structural unit.
- To be applicable to various climatical conditions, having equal architectural appearance.

The alternative design illustrated in Fig-76 shows a new system of structure, called braces fabric tension structures. They are designed under the effect of load symmetry in regard to the columns. The structure is compared with the tents of Hajj terminal which used 32 masts in 21 units and this system will use 21 columns in 21 units. The difference is 11 columns which is almost 35% of the total cost of the columns.

The second attempt was to design a tent unit as an independent structure, at the same time giving the opportunity for repetitive installations to cover large spaces. This independence of the structure as a self sustained unit avoids the
effects of one unit to another, and can be erected as a single unit.

The first alternative unit is based on a double curvature form, which is peculiar to a fabric structure and prestressed as an umbrella system. The braces or struts are incorporated with an uni-directional rotation for readjustment to avoid the wrinkling mechanism and a clamping system is provided at the lower part of the tent to be adjusted in the course of erection and installation process. (see Fig-77)

However, the unequally distributed load over the surface will result in tangential forces along the edge and such an edge can take those forces only by friction between steel cables and membranes. If the forces are getting higher than the friction forces, the membrane starts to slide along the steel cable. That will cause abrasion effects on the membrane material and the membrane can easily break. In order to avoid this problem, a textile belt along the whole edge line should be added, such a belt is sewn to the membrane parallel to the edge cable and cannot be changed in length any further. It means that the cutting pattern of the membrane has to be very precise. In the corner, the belt is clamped with steel plates.

The detailing of a flexible membrane edge in this way is perhaps the most common solution for tent structures. The textile belt is as sensitive to UV-radiation as the membrane itself, because of not being coated. Therefore, the belts have never been attached to the membrane from above, even if it is covered by a strip of membrane material. They should always be sewn underneath the membrane and be protected against water and any other direct attack.

The other advantage of this structure can be noticed in terms of collecting of water in a rainy season, unlike the tent of Hajj terminal which will flush the water around the structure, and in architectural appearance in terms of interior space.

The second alternative is based on single curvature form which will be maintained by the fixed boundary around the frame and the cable-sleeve along the contour lines. (see Fig-76) Though such form is not peculiar to fabric structures, the author tried to utilize the material in such a way that other possible forms could be found. As we mentioned before, apart from anti-clastic and syn-clastic form, the membrane can be built by zero-clastic and mono-clastic form as well. The single curvature can be overcome only by keeping the membrane stress up very, very high, e.g. for most normal structures a maximum 0.55 kg/mm prestress is needed. The author trying to keep the surfaces not flat but with well defined curves.

The single curvature forms were derived from patterning analysis through computer, and determination of boundary restraints by cables in sleeves. In such a form the cables along the curvature played an important role to prestress the form, otherwise the stress concentration on the surface will pull them apart. If the patterns have no curvature at the edges, the surface will be defined as a plane and the form as a cone. Thus, it is the cutting patterns and surface geometry that defined the form.

However, the structure is stable when a suspension cable is attached around the frame. The pretensioning is provided by the clamping system at the top of
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the tent with flexibility of readjustment in the time of exposure. (see Fig-78) The system is also designed to collect water in the rainy season around the frame and guide it for drainage in a proper location.
Conclusion

The aim of any fabric structure is to provide a large-span structure, or enclosure either for temporary or for permanent use. The material used is normally flexible, when a tension force is applied the material tends to find its own shape and become rigid. The shape and number of points where stress is applied play a crucial role in the overall performances, demanding careful calculation. The installation of such a structure is also a critical issue, and must at least be supervised by technical expert in this field. In general, the high stress areas shown by wrinkles could cause tear, while a low stress area always could collect water and result in degradation of fabric material.

This research ensures successful use and performance of fabric structures, and promotes the development and supply of more reliable materials, and equipment to provide better operating procedures. This research also reflects the possibility of applying these systems of structures to low-cost and large-span structures in seismic regions. The traditional system of construction reveals to be inefficient and dangerous for torsion, the fabric structures have developed structural design without torsion stresses. The fabric structures are designed with the same idea as minimal surface, that produces uniform surface tensions, free of torsion.

However, the important findings besides the main conclusion can be described as follows:
- The structural characteristic of fabric structures in general is understood and the property of the structural system is confirmed.
- Fabric structures have been classified in terms of their unique systems and the special mechanisms involved. Their principle and characteristics are essentially verified.
- The accuracy and validity of fabric structures together with analysis and design methods are verified.
- The underlying principle that contribute in the design of fabric structures is confirmed and the parameters towards form-finding and design has been described.
- The usefulness of computer and Computer Aided Design procedures together with form-finding has been explained. The design exercises showing the accuracy and suitability of computer program for large-span fabric structures.
- The geometrical reasoning of form and the determination of cutting patterns has been evaluated, using CAAD systems.
- The safety of the structure against external and internal loads has been
discussed, since these structures should be analyzed and designed by adopting the analytical methods.

- It is important to take into consideration a safety factor, in order to ensure the stability of the structure, which is a result of stress concentration and tear in membrane surface.

- In most cases a pretensioning load to the fabric and an anticlastic surface for the surface geometry must be used, in order to stabilize an optimum tension fabric structure.

- The fluctuation of internal pressure in air-structures is based on a change in air volume induced by the deflections of the entire roof which are caused by the wind load.

- The fluctuation deflections in air-structures during strong winds can be effectively reduced by increasing internal pressure.

- The re-tensioning and re-adjustment mechanism is essential in fabric structures, in order to avoid the wrinkling along the seams and surface of structure.

- The importance of fabric material, their characteristics and properties in terms of structural systems has been evaluated.

- The anchoring and supporting systems are used in fabric structures to fulfil many tasks beside their capabilities for carrying forces. These tasks and their performances have been explained.

- The new development in terms of fabric and insulation materials, such as translucent glass fiber will greatly promote the design and development of fabric structures in various site conditions.

- The heat transfer and control of single-layer fabric structures requires much more energy, compared with conventional structures.

- The heat transfer and control of fabric structures, by means of multi-layers of fabric and insulation material is almost compared to conventional structures.

- Unlike other building technologies, fabric structures gain advantages through manufacturing processes, which can be completed in the factory, involving considerable skilled labour with high quality and management

- Fabric structures require a close cooperation of architect, engineer, fabricator, and constructional manager to coordinate the entire procedure of design and installation.

- In order to prevent the act of vandalism, fabric structures should be protected by a conventional construction as perimeter walls. These perimeter walls are
sometime formulated within the base of the structure, and must be considered in design procedures.
Summary

This dissertation is focusses on the design and developments of various applications using woven fabric, ranging from habitable structures to large public spaces. It also emphasizes the influence of the fabric structures on the architectural solution, and feasibility of designing and constructing small to large-span structures by means of fabric materials.

The traditional tent as starting point leads the reader back to one of the problems in human habitation, that of preserving the identity of forms and principles of order. The earliest tents after cave dwellings are also meaningful today as temporary protection and places for meeting and living. Traditional tents are certainly the most impressive and successful form and structure of their kind, unique in the purpose they serve, unique in their magnitude, and also unique in the conflicts with natural environment. On the basis of the advantages offered by this novel method of construction, the traditional tent environment has been extended to a contemporary tent environment in which a detailed study of its applicability to emergency application has been realized.

The lesson has been learned, that the traditional forms of tents and settlement cannot deliberately be adopted to the functional requirements of modern society. Tent form and function related to its context, is the standpoint implicit in every section.

The study and analysis of "past and present" tent structures and the methods for evaluating their mechanisms, based on technical qualatative aspects resulted in a set of recommendations for further improvement. The balance between primary tent material in a traditional tent environment is transformed into secondary material in the contemporary tent environment, and an empirical building technique is developed to the context of building technology.

To define fabric structures properly, it is essential to understand how they differ from other building systems. These differences include structural theory, materials, form, weight, manufacturing and thermal performance. In fact, as a result of improvements in three key areas; materials, structural analysis, and environmental control, they can now be considered a mature building technology, offering an alternative to conventional construction, even for permanent buildings.

The dissertation studies the use of fabric materials in architecture as an integral structure. It analyses the functional justification of the use of such materials and their technological basis, studying its morphological type with different shapes and the suitable design technology according to their characteristics. It also studies fabrics as building material, with mechanical and physical characteristics, setting up processes, details, and solutions etc.
The scope of this study is not limited to the transmission of new knowledge and know-how but also looks into the process that has promoted such new knowledge. Fabric structures, like other optimum lightweight surface structures requires special design and construction methods which are distinctly different from normal construction and design practice.

On the basis of the architectural concept, the author illustrates the variables that influence architectural design and continues with computer based form-finding, which is a key tool in the development of membrane structures. Although physical model and hand methods are more reliable for simple and small structures than computer simulation, computer programs for membrane structures including cutting pattern, are rare and uneconomic.

The design of fabric structures is characterised by its three dimensional form and structural system to be defined and visualised, and the geometry of surface which is defined by the method of cutting pattern. The author developed a method and process to establish a three dimensional form of reality. The useful procedures are developed towards designing and form-finding of fabric structures, and simultaneously developed new integrated know-how within the Ariadne computer program in order to overcome the problems associated with complexity of form and structure.

The research has endeavoured to present some of the design and constructional factors to be considered when a fabric structure is contemplated. These are presented in a general fashion and then reinforced with more detailed descriptions of a recently completed project.

The reader may find useful the methodology used to identify the tent structures which implies a new fundamental approach in development of fabric structure. By acquiring a knowledge based on the understanding of the research, the study approaches the development of fabric structures in which small and large-span structure is utilized. New knowledge together with new know-how, confirms a multi-disciplinary spectrum of the trends of fabric structures in architecture.
Samenvatting

Dit proefschrift heeft als thema het ontwerp en de ontwikkelingen van verschillende toepassingen van textiele materialen. Het benadrukt tevens de invloed van weefsel structuren op de architectonische verschijningsvorm, en de mogelijkheid van het ontwerpen en construeren van kleine en grote overspanningen.

Wanneer de traditionele tent als uitgangspunt wordt genomen, voert dit de lezer terug naar een van de problemen bij menselijke woonvormen, namelijk het probleem van vormidentiteit en ordeningsprincipe. De eerste tenten die gebruikt werden na grotbewoning, hebben ook tot op heden waarde als tijdelijke bescherming en als plaats bestemd voor ontmoeten en leven. In hun klasse zijn traditionele tenten zeker de meest indrukwekkende en succesvolle voorbeelden van integratie van vorm en structuur, uniek in het doel dat ze dienen, uniek in hun grootte, en ook uniek in de conflicten met de natuurlijke omgeving. Op basis van de voordelen die deze constructiemethode bood, is de omgeving van de traditionele tent uitgebreid tot de hedendaagse tent-omgeving. Hierbij is een gedetailleerde studie van haar toepasselijkheid op noodtoepassingen uitgevoerd.

Er is aangetoond dat de traditionele vormen van tenten en nederzettingen niet zonder meer overgenomen kunnen worden in de functionele eisen van de moderne maatschappij. Tentvormen en functie in relatie tot de context is het impliciete standpunt in elk onderdeel.

De studie en analyse van vroegere en huidige tentstructuren en de methoden om de werking daarvan te evalueren op basis van technische qualitatieve aspecten, hebben geleid tot een serie aanbevelingen ter verbetering van de genoemde structuren. De balans tussen primair tentmateriaal in de traditionele tent-omgeving, is omgezet in secundair materiaal in de hedendaagse tent-omgeving. Ook wordt een empirische bouwtechniek ontwikkeld binnen de kontext van de bouwtechnologie.

Om weefsel structuren op een juiste manier te definiëren, is het van essentieel belang om te begrijpen op welke manier ze verschillen van andere bouwsystemen. Ze verschillen onder andere in structuur, material, vorm, gewicht, fabricage en warmte-prestatie. Als resultaat van verbeteringen in drie hoofdgebieden, te weten: materialen, structuur-analyse en omgevings-beheersing, kunnen weefsel structuren nu beschouwd worden als volwaardige bouwsystemen. Daarbij bieden ze een alternatief voor conventionele constructies, zelfs voor permanente gebouwen.

Het proefschrift bestudeert het gebruik van weefsele in architectuur als een integrale structuur. De functionele rechtvaardiging van het gebruik van dergelijke materialen en hun technologische basis wordt geanalyseerd. Hierbij wordt het morfologisch type bestudeerd met haar verschillende vormen en de toepasselijke ontwerptechnologie volgens de karakteristieken.
daarvan. Tevens bestudeert het proefschrift weefsels als bouwmateriaal, met mechanische en fysieke karakteristieken, waarbij processen, details en oplossingen etc. opgezet worden.

Het bereik van dit proefschrift is niet beperkt tot de overdracht van nieuwe kennis en vaardigheden, maar onderzoekt tevens het proces dat dergelijke nieuwe kennis bevordert. Weefsels, zoals ook andere optimale licht-gewicht oppervlakte-structuren, vereisen speciale ontwerpen en constructie-methoden, die duidelijk te onderscheiden zijn van de normale constructie- en ontwerppraktijk. Op basis van het architectonische concept illustreert de auteur de variabelen die architectonische ontwerpen beïnvloeden. Vervolgens worden middels een computer vormen gezocht die als gereedschap dienen in de ontwikkeling van membraanstructuren. Alhoewel fysieke modellen en handmatige methoden veel minder betrouwbaar zijn voor simpele en kleine structuren dan computer-simulatie, is een computer-programma voor membraanstructuren inclusief snijpatroon zeldzaam en oneconomisch.

Het ontwerp van weefsels wordt gekarakteriseerd door haar drie-dimensionale vorm en structuursysteem, en de oppervlakte-geometrie die bepaald wordt door het type snijpatroon. De auteur heeft een methode en een proces ontwikkeld om een drie-dimensionale vorm te bepalen. De bruikbare procedures zijn ontwikkeld voor het ontwerpen en het zoeken naar de vorm van weefsels. Tegelijkertijd wordt -geïntegreerd binnen het Ariadne computer programma - nieuwe kennis ontwikkeld om de problemen te overwinnen die geassocieerd zijn met complexiteit van vorm en structuur.

Het onderzoek heeft ernaar gestreefd om een aantal van de ontwerp- en constructiefactoren te presenteren die in ogenschouw genomen moeten worden wanneer een weefsels structuur wordt overwogen. Deze worden gepresenteerd op een algemene manier en daarna versterkt met meer gedetailleerde beschrijvingen van onlangs voltooide projecten.

De lezer heeft wellicht baat bij de methodologie die gebruikt wordt om de tentstructuren te identificeren, hetgeen een nieuwe fundamentele benadering impliceert in de ontwikkeling van weefsels. Door kennisverwerving gebaseerd op het begrijpen van het onderzoek, benadert de studie de ontwikkeling van weefsel structuren waarmee kleine en grote overspanningen kunnen worden uitgevoerd. Nieuwe kennis gecombineerd met nieuwe vaardigheden bevestigt een multi-disciplinair spectrum voor de trend van weefsel structuren in de architectuur.
A. Hai Yousufi
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