TENSILE FABRIC ROOF STRUCTURES-AN ARCHITECTURAL APPROACH

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF ARCHITECTURE

By

S. NITHYA

DEPARTMENT OF ARCHITECTURE AND PLANNING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the dissertation, entitled **"TENSILE FABRIC ROOF STRUCTURES – An Architectural Approach"** in partial fulfillment of the requirement for the award of the degree of **Master of Architecture,** submitted to the Department of Architecture and Planning, Indian Institute of Technology Roorkee, is an authentic record of my own work carried out during the period from July 2009 to June 2010 under the supervision of **Dr. Mahua Mukherjee**, Department of Architecture and Planning, Indian Institute of Technology Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Place: Roorkee
Date: 29/6/2010

(S. Nithya)

CERTIFICATE

This is to certify that the above statement made by the candidate **Ms. S. Nithya** is correct to the best of my knowledge.

Place: Roorkee
Date: 29/6/2010

Mahua Mukherjee

(Dr. Mahua Mukherjee)
Assistant Professor,
Department of Architecture and Planning
Indian Institute of Technology Roorkee
Roorkee – 247667, India

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(S. NITHYA)

ABSTRACT

The challenge of long span structures has appealed to many a minds involved in the construction field, be it bridges or roofs or any other structure. History has been witness to much experimentation with such structures, where innovative solutions have come up and some of which have stood the test of time and made a mark in the minds of people strong enough to be termed 'conventional'. Tensile fabric roofs are a comparatively new phenomenon steadily growing towards wide acceptance. In India, it has seen the light of the day in the recent past with some landmark structures, but is yet to be fully exploited, mainly due to the ignorance of the professionals involved in the construction field.

This dissertation is expected to help architects develop an understanding of tensile fabric roof structures, familiarize them with it's development through the ages, materials, design, construction and other necessary aspects involved. National and international case studies of a few prominent tensile fabric roof structures play an important role in this regard. Following which those aspects critical to the design of tensile fabric roof structures have been identified, developed and discussed in detail. The knowledge thus gained seeks application in the form of design.

Thus the roof of an existing structure has been redesigned using fabric, significant materials estimated and the approximate costs obtained and analysed for comparing the different roof structures. Conclusions have been drawn and recommendations made on the basis of the study of the subject at hand.

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The structural element is an aid, nothing more, to the fulfillment of a building task, the fewer elements of construction and material needed to fulfill the task, the freer we can be in total conception, in division of space and in adaptation of the building to our daily requirements.'

– FREI OTTO, German architect and structural engineer.

CHAPTER 1:

INTRODUCTION

The aims, goals, objectives and methodology are defined in this chapter, along with the scope and limitations. A brief outline of the dissertation is given.

1.1 PREAMBLE

Roof structures that stand by the force of tension rather than that of rigidity and gravity, are an unapparent reality throughout history. From the time cave men flung a goat skin over poles for protection from nature's elements; and American-Indian women built Tipîs wrapping animal skin over wooden poles tied as a cone; to the vast tensile fabric roofs now prevalent in many parts of the world, all form part of the phenomenon, 'tensile architecture'.

'Modern' tensile fabric roofing emerged in the second half of the 20th century as an antithesis of compression loaded vaults and domes. A combination of tension and compression members is required by any system to span a space; in tensile fabric structures this system consists of predominantly flexible tensile fabric members.

Being made of light and flexible materials such as woven, coated fabric and high strength cables, they lack the gravity and rigidity which are the basis of structural strength in conventional building support systems. Instead, curvature and internal tension – similar to that which determine the pitch of a drum or holds the shape of a soap bubble – are the properties which make a tensile structure capable of resisting loads.

Their aesthetics comprise of anticlastically curved surfaces, sweeping profiles, dominant hovering roofs and diffident walls. Such structures are light weight and eliminate the need for expensive, bulky and rigid structures to span large spaces.

Gravity is unalterable. Such structures make use of various shapes / configuration to distribute their own & other loads in different manner i.e. thro' tensile forces.

1.2 IDENTIFICATION OF PROBLEM

In the early 1950's attention focused on the tensile fabric structures, as maximum performance per kilogram was what everybody sought. It can be seen that most of the tensile structure projects that are considered a landmark in architecture have been developed by civil engineers as consultants, hence the component that sets it apart as a 'landmark' owes its existence not always to architects.

This is the case mainly because the design of a tensile fabric roof structure now requires profound knowledge and grasp of the behavior, strength and stability of the components that go into it. 'Form finding' an important part of the design of tensile fabric roof structures, is now generated with the use of computational methods, which is not a favored specialization among architects.

India is among the fastest growing economies in the world and is expected to reach the status of a 'developed nation' in the coming decades. This growth reflects in the building industry, with the necessity of structures like stadia, congregation halls, airports growing constantly. The future of design and construction also demands greater use of renewable materials and reduced carbon emissions. A tensile fabric structure significantly reduces the volume of materials required in construction, therefore reducing the carbon footprint of the project. Unlike many countries abroad, tensile structures are not used extensively in India. Time and resources are spent to a great extent on bulky conventional structures for long spans like stadia and industries, rather than use a tensile structure which offer speedy construction and is light weight. Creating awareness among architects and making the design of tensile structures easily approachable, will help to promote their use.

1.3 AIMS & OBJECTIVES

The objective of this dissertation is to understand the concepts, working, components and materials involved in tensile fabric roof structures to develop a better understanding of tensile fabric roof structures, and develop an architectural approach towards the design of tensile fabric roof structures. This involves;

- To study the evolution of tensile fabric roofs through history.
- To study the components, materials and the process of form finding.
- To understand the above through case studies
- To arrive at the basic tensile fabric roof forms.
- To broaden the approach of the architect in this field
- To apply the approach.

1.4 METHODOLOGY

The above mentioned objectives will be achieved by adopting the following methodology;

A. Review Of Literature To Understand Tensile Fabric Roofs

- Tensile architecture through history
- Characteristics
- Material
- Form finding
- Construction Technology

B. Study form finding in depth

C. Selection of case studies

D. Analysis of case studies

E. Discussion and interaction with relevant people in the field.

F. Visit to fabric workshops

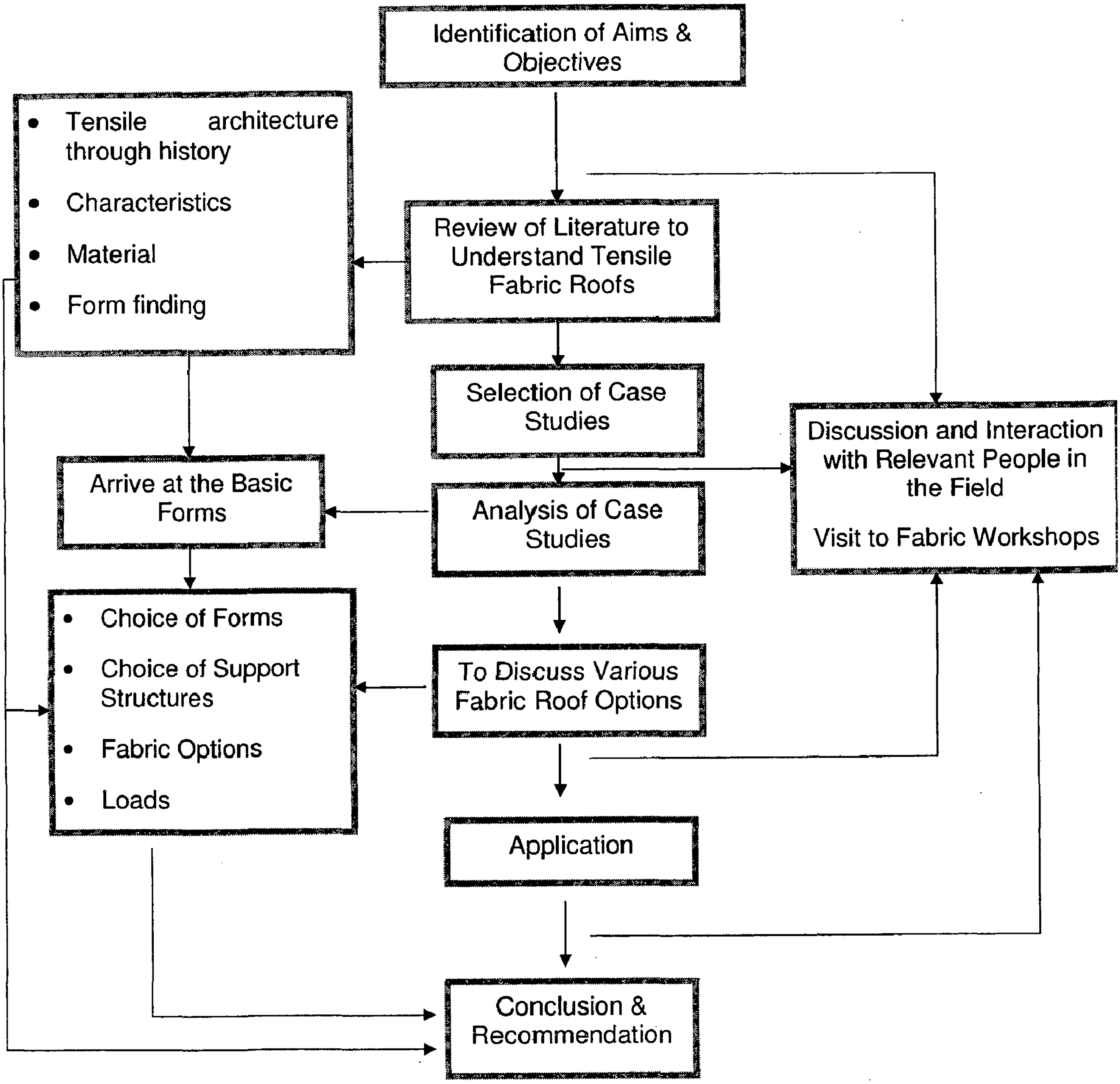
G. Arrive at the basic forms

H. To discuss the various fabric roof options

- Choice of Forms
- Choice of Support Structures
- Fabric Options
- Loads

I. Validating the same by application

J. Conclusion & Recommendation


Identification of Aims & Objectives
Review of Literature to Understand Tensile Fabric Roofs
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• Choice of Forms
• Choice of Support Structures
• Fabric Options
• Loads
To Discuss Various Fabric Roof Options
Application
Conclusion & Recommendation

1.5 SCOPE & LIMITATIONS

The scope includes

- Developing better understanding of tensile fabric roof structures.
- Study will concentrate on developing fabric roof options in the Indian context.
- Methodology will be validated with design.

Limitations of the study are that

- It is limited to tensile fabric roof structures; it will not include any other form of tensile or roof structures.
- Does not include dynamic, retractable tensile roof structures.

1.6 SUMMARY

In line with the above mentioned aims and objectives, an initial literature study was done to gain an in-depth knowledge of the evolution, and other aspects of tensile fabric roofs.

CHAPTER - 2

LITERATURE SURVEY

Understanding of the topic at hand, through its evolution in history and relevant ancillary forms; its main characteristics that set it apart from other structures and the materials that go into it has been attempted here.

2.1 TENSILE ARCHITECTURE THROUGH AGES

Tensile fabric structures were acknowledged in the 1950's as being entirely new and appropriate to the 'modern' age, as historical architecture in the west was closely identified with the compression modes of spanning interior spaces. Early tensile architecture arose among barbarian wanderers and invaders living outside the frontiers of the civilized world. The buildings of wanderers are the antithesis of architecture produced by civilization; they are light instead of heavy; transient instead of permanent; portable instead of static. The continual state of flux of wanderers' life deprived their buildings of the sense of permanence which indicates civilization.

2.1.1Tents, Tipîs, and the black tent

A tent is any supported structure covered by flexible material. Tents may not be as durable as conventional buildings, but they require far less material to create. This makes them more economical and portable. Tents arose where two conditions prevailed: a shortage of suitable building material and a need for mobility.

Fig 2.1:Reconstructed Tent. Moldovia, Russia. Made of Animal bones and Tusks.

The oldest tents known come from Siberia, Lapland, Iceland and Alaska. To shield themselves from icy winds, nomadic hunters hung animal skins over large bones (Fig 2.1). If trees were available, branches were used as supports. Sometimes birch bark was used to cover the frame. The evidence found thus far dates back at least 40,000 years. Thirty thousand years later, woven fabric was first incorporated into the tent. [1]

The ideal tent shape for shedding precipitation, withstanding extreme winds, and venting indoor fires is the cone. Cone-shaped tents are found throughout the Northern Hemisphere. Usually in a "cone", tree saplings were nested together to support a covering that sheltered the lower portion of the tent, leaving the top open to exhaust smoke.

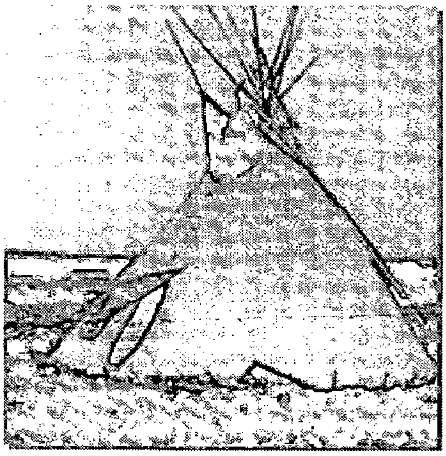


Fig 2.2: American Tipî

The American tipi (Fig 2.2) is considered a masterpiece of structural design. Native Americans improved on the simple cone shaped tent by adding smoke flaps and a wall liner. The flaps, which can be turned to take advantage of the prevailing winds, serve as an adjustable vent. The liner forms a double wall with the outer covering, creating an insulative space and helps draw out the smoke from a fire. The liner is wedged to the ground while the outside covering is above the ground to create a convection current of cool outside air that travels behind the liner and draws the smoke out through the smoke flaps.

In the summer, the base of the outer wall is rolled up to allow cool air to enter. On windless or especially hot days, a small fire will actually increase the cooling effect for natural air conditioning.

Native American ingenuity also extends to the support system. Tipi poles are shaved meticulously smooth, so that moisture that enters the smoke flap opening collects on them and runs down the poles to drain behind the liner.

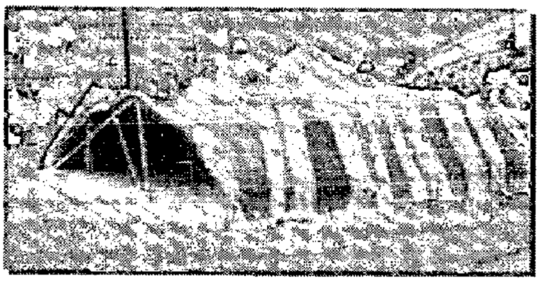


Fig 2.3: Black Tents

While Native Americans were perfecting the cone design, desert peoples such as the Bedouins, Berbers, Moors, and Kurds were developing the "black tents." The black tent (Fig 2.3) gets its name from the black goat hair used to weave its covering. This loosely woven cloth allows air to pass through while providing shade in hot and arid climates. Should this material get wet, however, its fibers will swell and repel rain.

Black tents utilize all the features that to this day allow tensioned structures to function. The fabric is draped over ropes, which are supported in turn by a series of poles. The ropes carry the load to the stakes, which tension the structure and anchor it down.

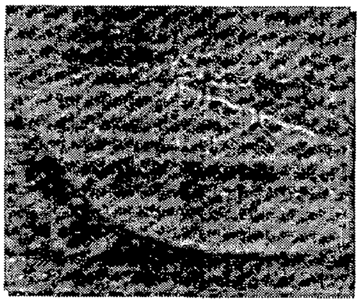
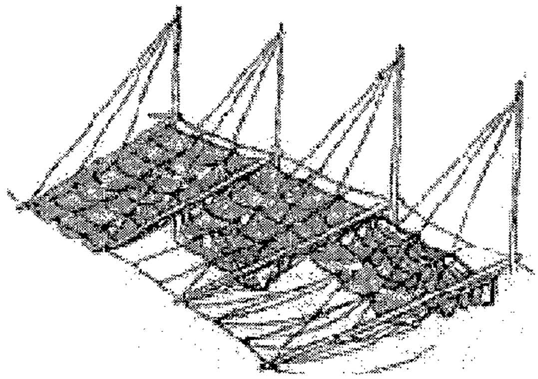


Fig 2.4: Circus Tents

Nowadays, the most familiar large tensile shelter is the circus tent (Fig 2.4). Early circus tents used a simple umbrella shape; however, they had the disadvantage of the central compression post being placed in the center of the performance space. By adding support poles, the center could be left free, and this led to the famous three ring circus. [1, 15, 38]

2.1.2 Ship Sails



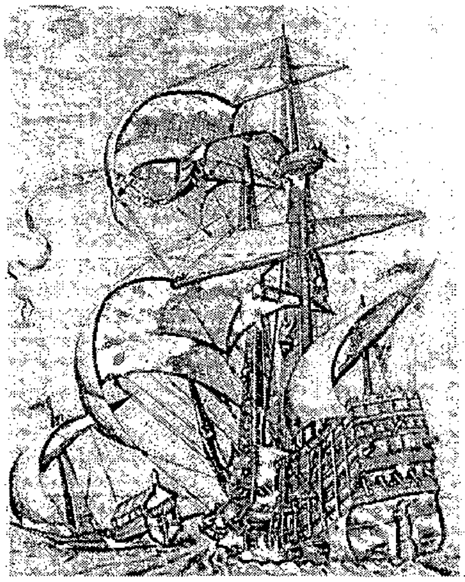


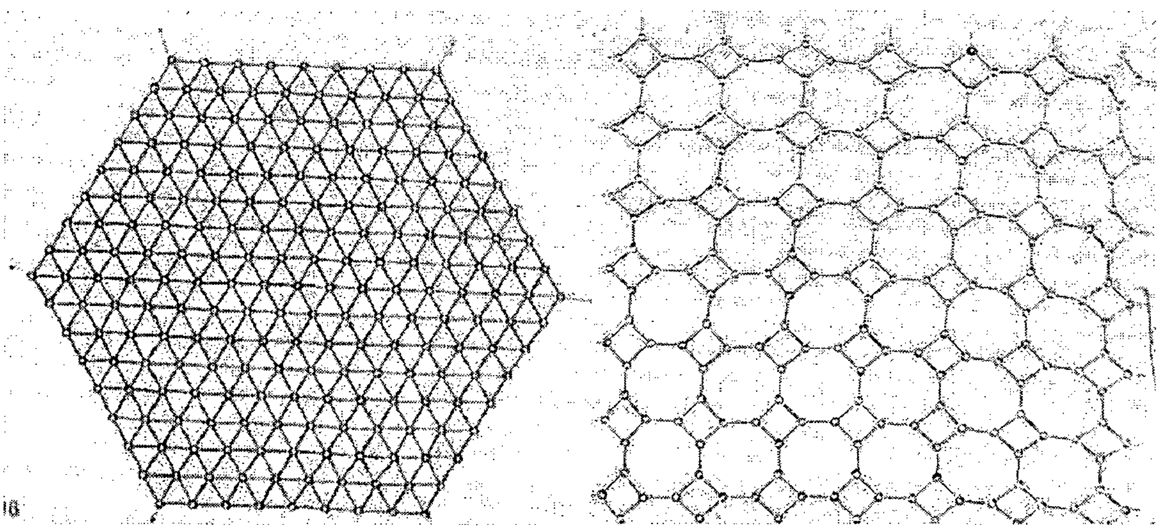
Fig 2.5 Top: Roman 'VELA'

Fig 2.6 Right: Ship Sails

The functional use of fabric and tensile strength do not form part of roofing alone, sailors have harnessed wind to move ships using the same components (Fig 2.6). Pneumatically stressed membrane sails become aerodynamic forms with the shape being determined by the boundaries; stayed masts form the compressive support which transfers the membrane tensions in the sails to the hull. This tensile technology of the ship transferred to the roman amphitheaters in the form of 'vela' (Fig 2.5), retractable fabric shade structures, they were inspired by the rigging of sailing ships and were worked by retired sailors.

2.1.3 Cable net structures

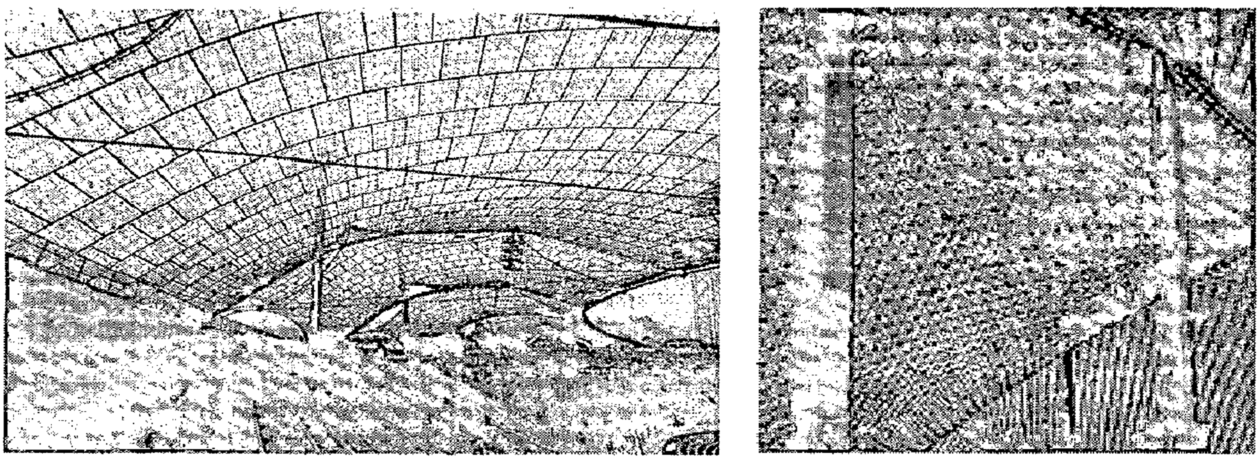
Cable net structures were made prominent by Frei Otto, **a German architect and structural engineer.** The first large-scale project was the sprawling 86,000 square foot German Pavilion for the Montreal Expo in 1967. At the time, there was no fabric strong enough to withstand the tension required for such a huge structure. Instead, Otto designed a network of interconnected cables to form the surface structure with a fabric membrane hung just below the cable net. It was the first structure to introduce the organic and free flowing shapes of tensile architecture. The secondary fabric skin hung below it- an arrangement that made it vulnerable to the accumulation of snow, which could be dammed by the cables.



(a) Fig 2.7 Developable Mesh (b)

The supporting system consists of all those members including the boundary elements – usually edge cables- which do not belong to the net. The internal net geometry is given by the conformation of the net elements. A net is called developable (Fig 2.7) if it can be severed from its boundaries and laid out on a plane surface without dimensional distortion to the net. Spatially curved triangular mesh nets are not developable because the triangulation of the net grid prevents angular distortion of the meshes. The great advantage of developable nets for prefabrication in a factory away from the building site, prior to erection, is fairly obvious. Sections of the net can be transported to the site, assembled on the ground and connected to the supporting system before being hoisted into position and prestressed.

Cable nets (Fig 2.8) may be fabricated from a variety of materials having high breaking strengths. The best known are steel wires, parallel wire bundles, steel cables or ropes, bars, chains, organic and synthetic fiber ropes, and laths of wood. In cable nets which acquire their rigidity by prestressing there is no advantage in using an infilling or weatherproof sheath with high dead weight as this merely increases the forces in the cables and reduces the structural economy.



(a) Fig 2.8 Cable Net. (b)

The inherent flexibility of prestressed tension-loaded nets creates a severe weather proofing problem which calls for careful design of the pattern and scale of panel systems and detailed consideration of the joints and fixings. Of the host of possible materials and details, few have proved very satisfactory in terms of construction and aesthetics. The Montreal solution which used a PVC-coated polyester fabric suspended from the cable net was rejected for Munich because the exposed cable net was insufficiently durable. Finally, standard 2.90m x 2.90m acrylic glass panels were used, attached at single points to the cable net intersections. Since the original angles between the mesh cables vary up to 6° under loads and temperature changes, the glass panels were supported on neoprene pedestals which assured freedom of movement. The joints between the panels were sealed with a continuous neoprene profile clamped to the edges of the panels, wide enough and thin enough for wrinkles to form, not a pleasing detail. Munich stadium roof (Fig 2.9) for the 1972 Olympic Games was Otto's crowning achievement.

Fig 2.9: Munich stadium roof for the 1972 Olympic Games

This elegant cable net structure with acrylic panels covered over 40,000 square feet. It has been hailed as one of the greatest landmarks of the century. A powerful catenary forms its interior edge. Flying masts ride on suspension cables reaching down from the tall masts and running on to the catenary. They help create high points and so generate the vaulted volumes of the undulating ceiling which soars over this great space. Despite the interfering geometry of the rigid acrylic panel cover, these powerful tensile forms make this structure one of the great landmarks of the history. [1, 2, 3]

2.1.4 Pneumatic structures

The Chinese developed the first hot air balloons from paper. In the eighteenth century, lightweight, close weave cotton fabric made the first passenger hot air balloons possible, and this led to the giant gas-filled airships and zeppelins of the early twentieth century. The development of synthetic fibers such as nylon and improved coating techniques led to a barrage of innovative balloon designs, and the appearance of the first pneumatic buildings during the Second World War. Pneumatic structures are flexible membranes which are stressed by the differential pressure of a gas, normally air. While in theory limitless spans are possible with non-prestressed pneumatics where the pressure differential exactly balances the self weight of the floating membrane, in practice, prestressing of the membrane is mandatory to stabilize it against dynamic and unsymmetrical loading and this severely curtails its real span potential.[1, 2]

Frei Otto published exhaustive studies of the possibilities of utilizing air-supported structures. Walter Bird formed Birdair, which along with Geiger Berger designed and implemented several large air supported shelters. These low-pressure air-supported structures maintain a fabric membrane in tension by supporting it against the lower outside pressure (Fig 2.11). In this sort of structure, this difference in pressure can be quite small and internal occupants can safely breathe the air. Pneumatic shapes are characterized by double curvature surfaces of predominantly synclastic curvature although single curvature and anticlastic surfaces are by no means impossible. Plane surfaces are impossible in practice. Undoubtedly, sphere is the most perfect form for a pneumatic membrane, being uniformly stressed in all directions.

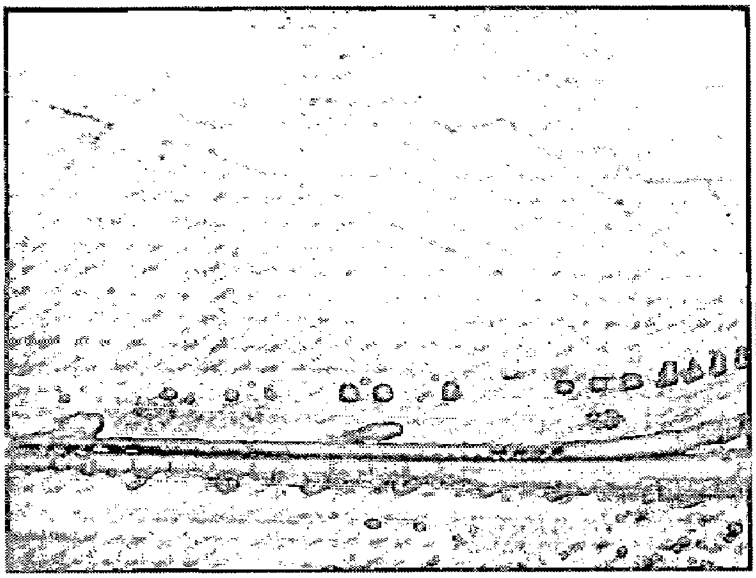
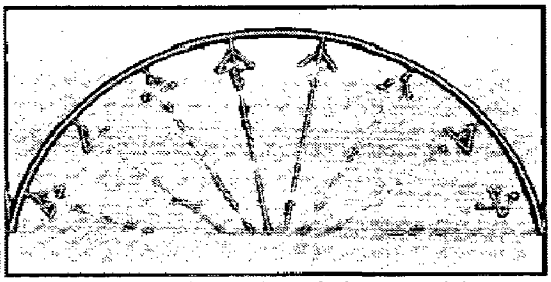


Fig 2.10 Left: Tokyo Dome

Fig 2.11 Bottom: Principle



By giving the surface a low profile curvature and reinforcing the fabric with a grid of high strength cables, large spans could be achieved at a fraction of the cost and construction time required for conventional structures. However, their dependence on mechanical devices has proved problematic and has led to a number of disturbing deflations. Still, pressurized buildings led the way to a greater acceptance of fabric structures and opened the way for a new, less controversial structural system of tensile fabric architecture.

2.1.5 'Modern' Tensile Fabric Roofs

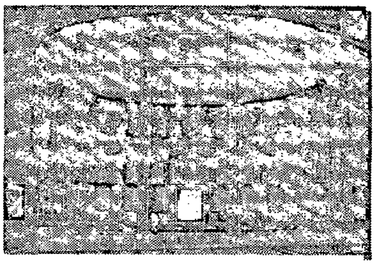


Fig 2.12: Shukhov's Structure

Russian engineer Vladimir Shukhov was one of the first to develop practical calculations of stresses and deformations of tensile structures and membranes. Shukhov designed eight tensile structures and thin-shell structures (Fig 2.12 & 2.13) exhibition pavilions for the Nizhny Novgorod Fair of 1896, covering the area of 27,000 square meters.

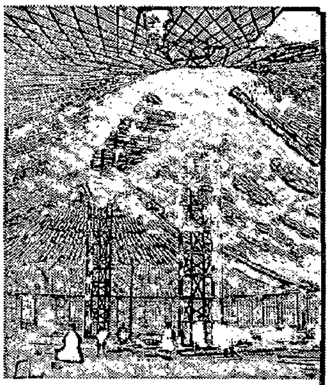


Fig 2.13: Shukhov's Structure

This is an outstanding example of early tensile building. Shukhov patented a suspension system of nets made of steel strips covered by thin steel members. Daylight was admitted to the interior through hexagonal and diamond shaped lights in the roofs.

Frei Otto, a German architect and structural engineer, was the seminal figure in the development of tensile architecture. He was the first to lead away from the simple geometric solutions to the organic free forms that could respond to complex planning and structural requirements. The secret of Otto's success lies in his study of the self-forming processes of soap bubbles, crystals, microscopic plants, animal life, and branching systems. He found that natural objects will create forms that are very efficient, wasting nothing and use a minimum of material. [1, 2]

In the 1950's in Germany, Frei Otto began building cotton fabric canopies using tent technology. Otto realized that structural and architectural forms are inseparable. He argued that flexibility is strength, not a weakness. He proved that large tensile fabric buildings were possible, even though the materials and construction methods necessary were not yet available.

Today, tension membrane structures finally benefit from fabrics stronger than steel, with a guaranteed life span of over thirty years. These provide an elegant, energy efficient and economical solution where large open spans are required.

The second major challenge in tensile engineering was solved by **Horst Berger, a civil engineer**. Berger put Frei Otto's theories into practice and is thus made enhanced the feasibility of introducing tensioned fabric structures into modern architecture. In 1974, Berger figured out how to mathematically describe and determine the shape of a tensioned fabric structure. Until this breakthrough, tensile forms could be determined by painstakingly building models that could be dipped into a tank of soap. [1, 28]

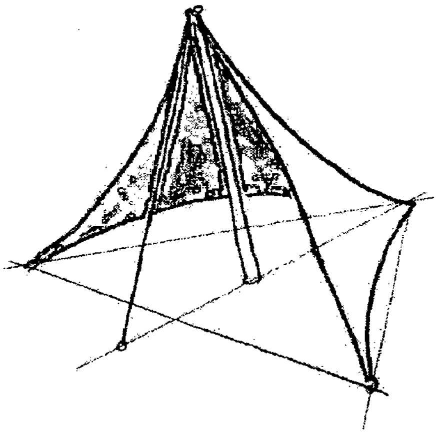
Berger has also deigned some of the first, biggest and most beautiful tensile structures in the world. The largest is the Haj Terminal Building in Jeddah, Saudi Arabia (Fig 2.14). This massive structure accommodates over 700,000 pilgrims on their way to Mecca each year, all in the space of one month. Its 210 cone shaped canopies cover 105 acres and can shelter up to 100,000 people.

India has also shown interest in the fabric roofs in the recent past. Dhananjay Dake and his firm Construction Catalysers, Pune, have been instrumental in creating many significant fabric roof structures around India.

Fig 2.15: Denver International Airport

Fig 2.14: Haj Terminal Building Jeddah

2.2 CHARACTERISTICS



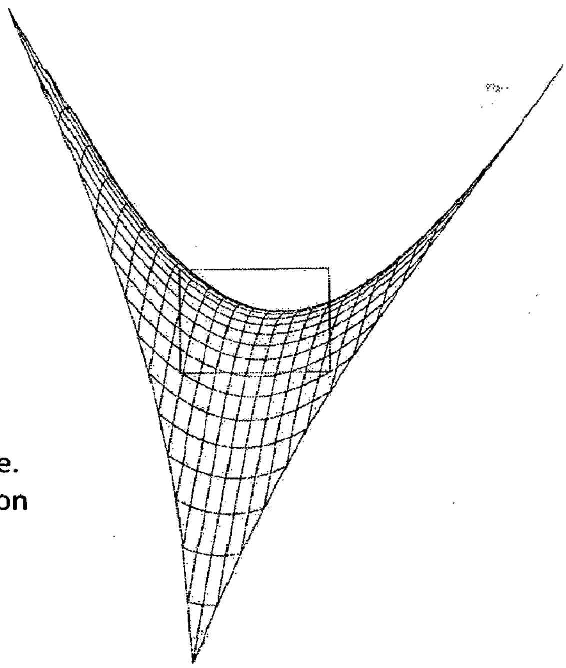


Fig 2.16 Top(a): Single four point structure. Three points share the ground as a common plane. The fourth is created by the pole.

Fig 2.16 Right(b): Anticlastic Surface

The term, 'tensile fabric roof structures' refers to those structures which have flexible fabric materials as its primary components and whose strength and stability is harnessed from their geometrical form that require a specific pattern of internal stresses. Tensile fabric structures are dynamic anticlastic surfaces (Fig 2.16b), meaning the curvatures at any point in the surface, in the two major axes are in the opposite directions, and they flex their shape with the changing loads. Four is the absolute minimum number of anchor points for a tensile fabric structure(Fig 2.16a). A surface generated by connecting only three points will be a flat triangle. Four support points are needed – with one of them in a different plane than the other three. In other words it is always a combination of high and low points, with a minimum of atleast one high point.

The characteristic form sets these structures apart and is a necessary aspect of their capability to carry load. The curved surface needs to be stretched between support points above the surface, below it, and on all sides around its periphery. These geometrical requirements are common to all tensile fabric roof structures and give them the shape. Curvature, following scientific laws, is a critical aspect of the structure; the shape of the structure cannot be arbitrary but derives from the structural function; form and function are one. These principles seem to echo what the roman architect Vitruvius, almost two thousand years ago, considered the primary qualities of a building, utilitas(function), firmitas(structure), venustas(beauty). [1, 2]

A structural system consisting of predominantly flexible members needs to have ways and means to harness stability and strength; their components require arrangement in a specific geometric form, while being subjected to a specific pattern of internal stresses.

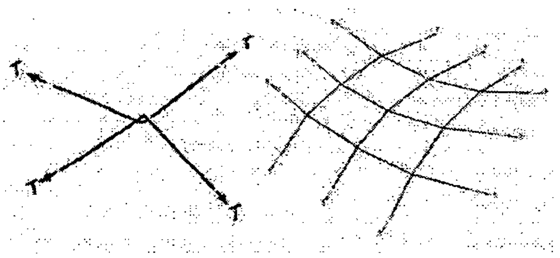


Fig 2.17: Force diagram of a typical node in a tensile saddle surface, and part of a typical anticlastic surface net.

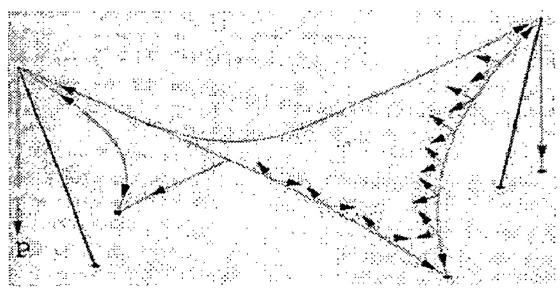


Fig 2.18: Force flow as a result of pulling down with prestress force P at one of the struts.

The geometry of tensile structures is therefore not arbitrary but follows strictly the rules of engineering mechanics. Once the boundaries and support conditions have been fixed and prestress pattern selected, there will be only one three dimensional shape under which the structure is in equilibrium at all points. The exact configuration of this shape is calculated in a mathematical process called form finding or shape generation. When we put a fabric net into tension, we increase the internal pressure at each point. The higher the initial tension or pre stress level, the more stable and stiff the fabric will become. Prestress can be introduced by just pulling a corner outward, this is achieved my means of various supports which will be discussed later.

2.3 MATERIALS

A tensile fabric roof structure primarily consists of three key structural elements, the structural fabric, the rigid structural elements and the cables. For the tensile structure to function properly there must be a hierarchy of elasticity of the materials. The membrane must be more flexible than the cables. They, in turn, must stretch more than the rigid members which support them. When such a hierarchy exists, the structure will be easy to build, and behave in a predictable and efficient way under load. [20]

2.3.1 Structural Fabric

Structural fabric is the material that defines lightweight tensile structures. For the fabric membrane three factors are important:

- Structural strength;
- Behavior during construction
- Surface properties.

The fabric consists of a structural base material, such as fiberglass or polyester cloth, covered with surface coatings such as polyvinyl chloride, Teflon or silicone. The surface coatings determine characteristics of the fabric such as, dirt resistance, translucency, water resistance etc. the structural base is characterized by the tear resistant weaves, strength etc.

Fabric tensile structures are inherently much less vulnerable to fire damage than most conventional enclosure structures. Fire tests have demonstrated that the seams of most fabric materials will open up and exhaust hot fumes and smoke long before enough heat develops to harm fabric, cables, and other structural components. The continuity of tensile elements, and the extreme light weight of the actual structure, will greatly reduce both the risk of injury and damage to the building as a whole.

Because fiber glass fabrics fail abruptly when they reach their tensile limit, safety factors need to be conservative. The softer polyester fabrics are much safer in this respect because, long before they break they will reach a yield point, beyond which they stretch extensively.

Further critical factors that contribute to the structural reliability of the fabric material include a fool proof seaming method compatible with the full strength of the material. Quality and economy of the structural membrane is: greater width of material, and therefore fewer seams; softer materials, that are therefore easier to handle; and compatibility with gasketing and clamping devices. The choice of coating material not only has a considerable impact on these factors, but is also critical to the durability and fire resistance of the fabric when the structure is part of a permanent building.

The seams can be sewn, glued, electronically welded, or heat-sealed. Seam styles can be parallel or radial to a mast. Butt seams are joints produced by placing two adjacent pieces directly beside one another and covering the joint with a strip of material. Lap seams are joints made by overlapping the edges of the material. All the materials come in some shade of white; some are also available in a limited range of colors, depending on supply and demand.

- **Requirements**

As a primary structural element, it must have the strength to span between supporting elements, carry snow and wind loads, and be safe to walk on.

As enclosure element, it needs to be airtight, waterproof, fire resistant and durable.

As daily use element, it requires transmitting daylight (translucency), reflecting heat, controlling sound, and being easy to keep clean, this will depend on the specific building application and combination of base fabric and coating. This may lead to significant energy savings by means of light and air-conditioning. Surface properties which avoid the accumulation of dirt, or facilitate its removal, not only help in its appearance but also help retain the translucency and reflectivity levels required for the efficient functioning of the building.

Tear failures start at an open edge or at a hole in the fabric. It is critical, therefore, that fabric panels are contained continuously all around the edges, it can be achieved by edge ropes in continuous sleeves which are connected to cables or other structural members by clamping devices.

After patterning when the fabric segment has to be fabricated, it has to be done after the computation of the compensation i.e. fabric panels have to be created shorter by the exact amount that they stretch under stress during the construction process. When the fabric members are subjected to stressing, the fabric might stretch in one direction; or in the case of biaxial stress it might stretch in both the directions (Fig 2.19 & 2.20). The kinks might form or reduce in the fill and warp threads depending on the stressing.[1, 9]

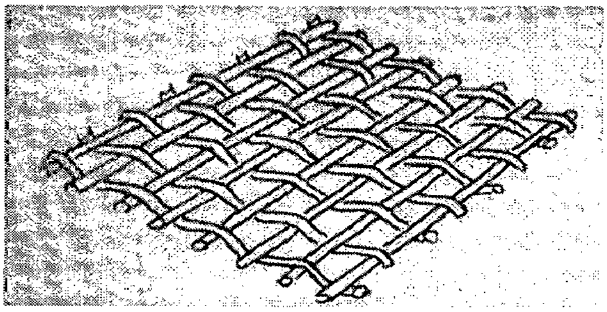


Fig 2.19: Warp and Fill configuration before stressing.

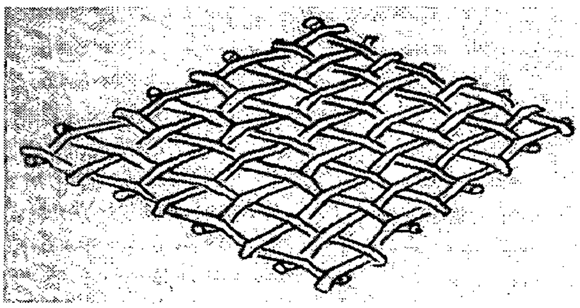
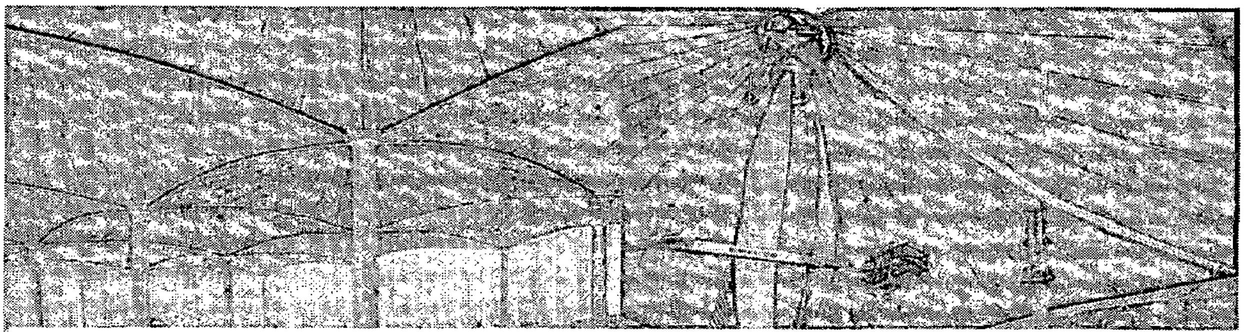


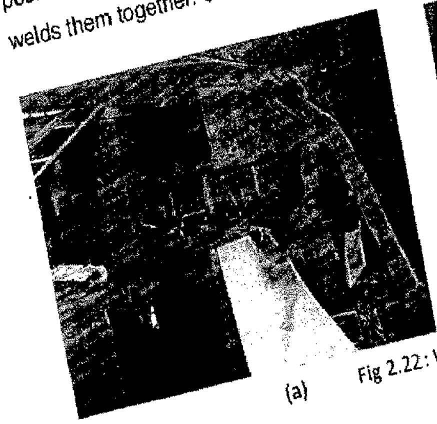
Fig 2.20: Warp and Fill configuration after stressing.



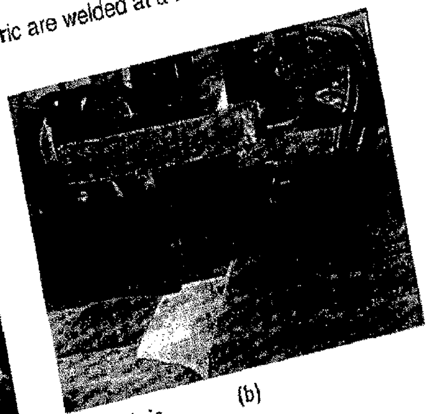
(a) Before (b)After

Fig 2.21: Rip Fabric failure of a roof unit in the Haj terminal, Jeddah due to faulty compensation. Before and After respectively.

In the early days fabrics were stitched together, now fabrics are welded. They could be lap or butt jointed in welding, the overlap is usually in the range of 20-100mm. In India the welding machine used usually requires handling by three people. The platform on which the fabric is placed for welding is slightly higher than a table. The welding mechanism raises and the fabric is overlapped appropriately and placed in position on the platform, and then it comes down, holding the fabric in place and welds them together. Small lengths of the fabric are welded at a time.[11]



(a)



(b)

Fig 2.22: Welding of Fabric.

2.3.2 Rigid Structural Elements

Rigid structural elements, such as masts, struts and arches, are to support the flexible fabric and cable membrane, generate its peaks, form its edges, and create the anchors that hold it down. The materials include steel, reinforced and prestressed concrete, laminated wood, aluminium.

Requirements

The rigid elements in tensile structures must be strong, light, reliable, readily available, easy to fabricate, transport and erect.

Fire protection measures like components prone to fire can be located at a safe distance from the potential source of fire, or encased with protective materials, or the adjacent area can be sprinklered.

Sample Materials

The materials include, Steel, Reinforced Concrete, Pre-stress Concrete, Laminated Wood, Aluminum, Composite Synthetic Materials. Structural steel suits excellently, the drawback of steel, however, is the need for protection against corrosion, either by painting or galvanization. Aluminium is a prime candidate to replace steel in light weight structures. It weighs one third, comes with similar strengths and does not corrode. Fiberglass, carbon and other synthetic materials have begun to appear on the market as alternative structural framing products. Structural lumber in the form of laminated wood is suitable for use in arches, frames or columns.

2.3.3 Cables

Cables serve a number of functions in tensile structure applications: reinforcement of the fabric where the spans and stresses get too large; linear tension support elements along ridges, valleys and edges; tie-backs and stays to stabilize rigid support elements and redundancy members, which provide alternate routes for the flow of forces, and assure the integrity of the overall structural system should a fabric panel have to be replaced. [1, 20]

Requirements

The cables need to be light, high-strength and flexible.

Sample Materials

Cables made of strands of high-strength bridge steel wire cables have high tensile load capacity; they are twisted slightly so that under tension the wires press against each other. They can be fabricated to almost any desired length, are flexible enough to be coiled on large, transportable drums, and are provided with reliable, standardized end fittings which make it easy to connect them, either to each other or to rigid structural support components. They can be galvanized to protect them against corrosion, and can be placed outside the building skin exposed to natural elements. Other new alternative materials are Kevlar, fiberglass, polypropylene and carbon.

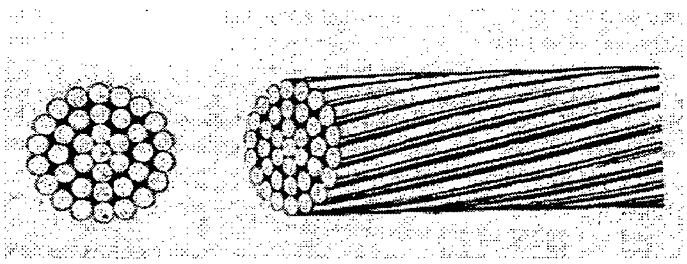


Fig 2.23: High-Strength Bridge Strand Steel Wire Cables

2.4 FORMFINDING:

2.4.1 General

'Form finding' is to tensile fabric roofs, what column and beam is to a frame structure; i.e. finding the form of a tensile fabric roof is more to do with the structure than with the aesthetics, though the latter also forms a significant part of the decision making process. When frame structures are designed, the architect is not necessarily involved into sizing and detailing of the structure. But the architect checks that the placements of these structural elements should not spoil a particular space functionally or aesthetically; without compromising on the structural stability. The role of the architect in the process of form finding of tensile fabric roof structures should also be similar. He should have a basic idea about the evolvement of the form, knowledge of the fabric and the support structures.

Form finding is that important and decisive part of the design process, which determines given the space function, what kind of form the roof will take, the respective support structures and the necessary stress required for the roof to carry its self weight, precipitation load and the weight of a man if required for maintenance. As already mentioned tensile fabric roofs are the top most portion of any structure, no construction is possible above it.

In most cases, since the tensile member forms only the roof, the consultant is given the plan and asked to develop a design complementing it. Though it has worked quite well so far, it would be very convenient if the use of tensile fabric roof has been decided at the conceptual stage. There would be more options to explore, if the conceptualization of the plan and roof happens side by side, this way there are less constraints on the support conditions.

The objective is to find a geometric form for the structure which satisfies the functional requirements of the building while conforming to a prescribed pattern of force flow in perfect equilibrium.

2.4.2 Soap Film

For defining and exploring various forms of a tensile structure, mathematically generated computer models are used right now, but the initial study and development of various forms and solutions started with the exploring of physical three dimensional models, of which the soap bubble technique is significant.

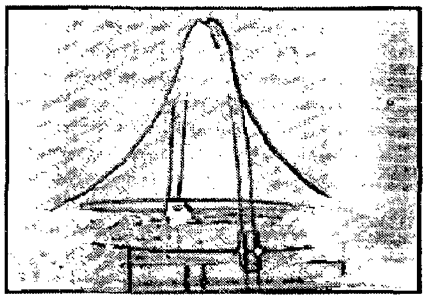


Fig 2.24: Soap Bubble

The surfaces of soap bubbles have a very important feature. These surfaces which have minimum surface-tension potential energy also have minimum areas. That is, soap bubbles or clusters have a natural tendency to minimize area for the volumes they enclose. [26]

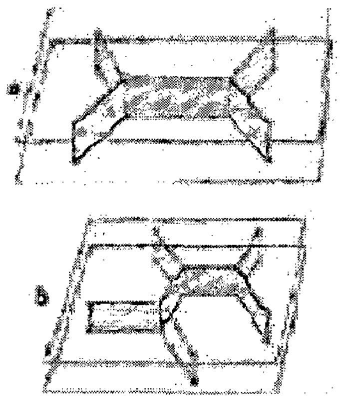


Fig 2.25: Soap Film

To understand the minimum surfaces formed by soap films, the solution to the Steiner problem can be mentioned. An elementary problem in mathematics, the Steiner problem can be solved by the application of the 90° and 120° principles. The Steiner problem investigates how 'n' points over a surface can be united in the shortest way by a web. Two transparent surfaces are connected with thin and parallel pins of equal lengths and then dipped into a soapy solution. When it is taken out, soap films will form. These films have a 90° angle with the supporting transparent surfaces and when three soap films come together, they connect at 120° angles with one another. When observed from above, the intersecting lines between the soap film and one of the surfaces give the shortest web which unites the points in n numbers.

Soap bubbles have the property of enclosing the maximum volume in minimum possible surface area; as the surface tension is uniform at every point and in every direction. In the generation of tensile forms, if a set of high, low points are given, and dipped in a solution of soap water, a soap film will naturally form the minimum surface area attainable between these points, giving the ideal working shape for a tensile structure, this model was then photographed in front of a grid and transformed into workable data generating the feasible form. In the soap film method, hairy thin threads, pins etc are used, in the structure; steel cables replace the threads, tensioned fabric replaces the soap film and masts and struts replace pins. Frei Otto made extensive use of the soap film technique, while Horst Berger preferred physical models to soap bubbles. [2, 21]

The following experiment is cited as an example of a solution being developed for tensile structures. In 1964, in the Development Centre for Light Weight Construction, Berlin, Larry Medlin investigated more advanced techniques for applying points of support and restraint. In his soap film studies he discovered that the umbrella like apparatus for pushing the membrane up, and a parachute like rig for pulling the membrane down, could be simplified to a single tensile loop for support and restraint. In a plane soap film, the uniform surface tension will draw a loop of thread to a circle. If the loop is then raised from a point on its edge above the plane of the film, the surface is spatially deformed in an anticlastic curvature and the loop acquires an equal radius arc curvature in space. The loop shape and stress distribution are identical regardless of whether the film plane was deformed upward or downward. A series of studies in mesh material followed to investigate the application of the single loop in large-span cable nets.

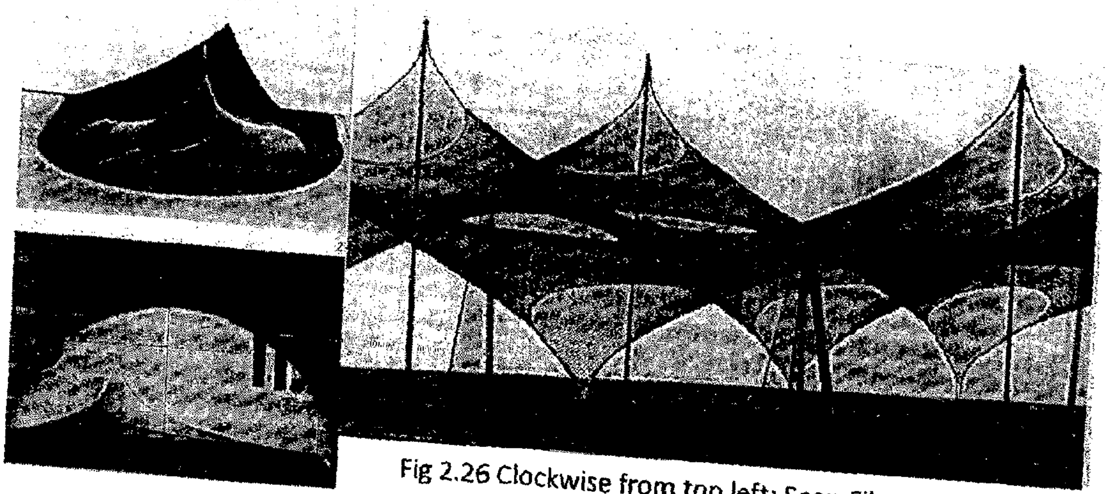
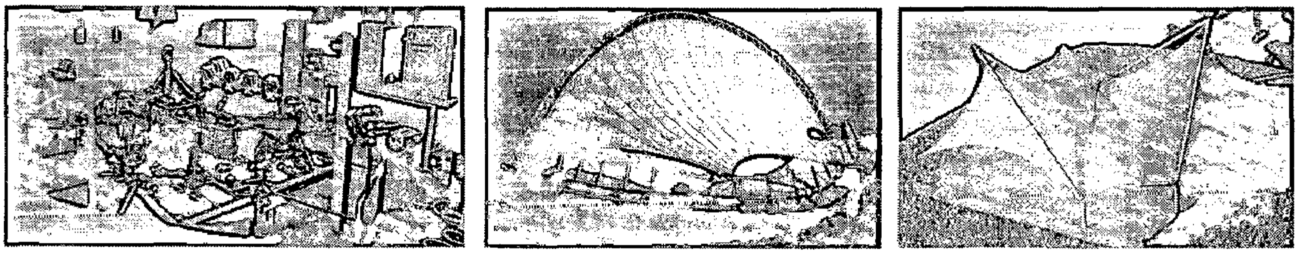


Fig 2.26 Clockwise from top left: Soap Film Technique

In a soap film it is practical to develop a surface with a loop configuration that acts simultaneously as a point of support and restraint. In such a surface configuration, the tensile resultants of the support and restraint apices are axially opposed. A compression strut must be introduced to hold these points apart and induce a self contained equilibrium of surface prestress in local areas of the membrane. This obviates the necessity of external suspension or tie down points, except where they are required to support the dead load of the membrane or to ensure overall stability. The Munich games roof is a development of this solution.

2.4.3 Physical model

Soap film was almost always followed by a physical model, in the study of tensile architecture. Before the advent of computer modeling, scaled model study was conducted to meticulously determine the prestresses required at the necessary points. Spring steel mesh was used for the study of cable net structures earlier. Nowadays foam board, stretch fabric, soldered steel wire, flexible silver string form the main materials of physical modeling. [1, 2, 15]



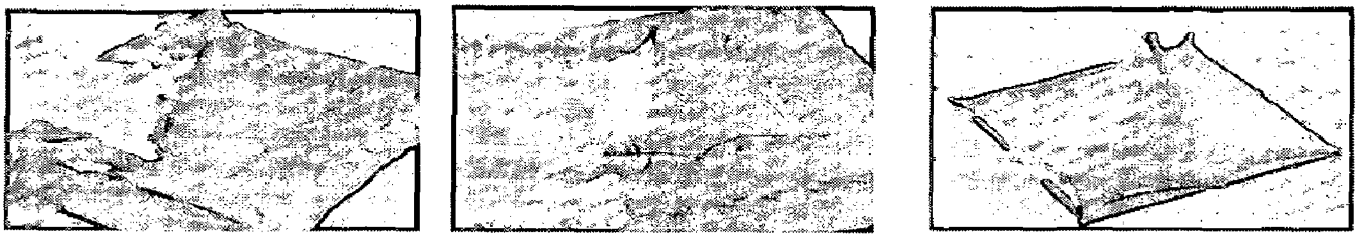
(a) (b) (c)

Fig 2.27: Physical Models

Stretch fabric models are an excellent means of exploring shapes, testing the behavior of the structure and also form good presentation models. Models made with this material are most realistic in their structural behavior. Once the high and low points of the structure have been fixed to a suitable scale, the points are established by means of brass tubes or any other linear element made of a material sturdy enough to stress the fabric to the required level. A light and highly stretchable material, with similar elasticity in both directions is an apt material for the fabric, one such stretch fabric is spandex. The base is usually foam board or wood as might be required. At places where the fabric has to stretch over the mast, a small object with more surface area like a button is placed on top so that the mast top does not puncture the fabric.

A generous piece of fabric is draped over the supports and the fabric is stretched in gradual steps and pinned to the foam board. Starting with just a few pins on the periphery the process is repeated till the fabric is taut and held with pins not more than 2-3 cms apart. As the stress increases, the fabric becomes more transparent, and the position of any interior supports becomes visible. A triangle can be held behind the vertical support elements to check on its vertical alignment.

Installation of cables can be done through double threading a needle and attaching the end to an anchor point with a knot and then guiding it around the model; the needle can be guided under the fabric also if needed, working with its elasticity. Winding the thread around the anchor pin a few times will usually wedge it sufficiently until it is fastened with a few knots, glue can be used to further secure the connection.



(a) (b) (c)

Fig 2.28 Physical Model.

To model the edge catenaries, the outlines are first drawn with a felt tip pen or a soft pencil, a stable free hand sketch will be sufficient. The elasticity of the stressed fabric will ensure that the catenaries reshape into smooth continuous curves when cut. A double thread is used to make small stitches approximately 3mm long and about 2mm inside the line drawn on the fabric. After the stitches are completed the thread is pulled tight till the catenary curve is a little shallower than the desired final sag and then tied firmly around an anchor pin. The fabric pins all around the structure are removed leaving the anchors in place. The surface tension will pull the edge catenaries into tight arcs. The last step is to cut off the loose fabric. Sharp pointed scissors of good quality should preferably be used. The cut should be continuous and smooth, cutting just 1mm outside the thread wherever needed. The excess fabric is then removed and the model cleaned up.

2.4.4 Computer Model

Digital modeling helps in designs of greater precision, taking less effort and time (once the appropriate software is available) is more versatile. In the present world almost all tensile structures are computer aided designs. These programs allow the designer to create a three-dimensional model that can be viewed at various angles; they also allow customization to provide information for facilitating fabrication and installation. The programs can calculate the amount of fabric required; the dimension of each fabric piece; the size and length of structural members; the size, length, and tension of cables; and the necessary hardware. With a software program, the designer can modify the shape more easily than with a physical model.

Computer generated digital models serve three particular purposes;

- Form generation.
- Performance of the structure under different loads
- Precise geometry of every part and the cutting pattern generation of the fabric.

The basic mathematical process involved in the digital modeling, will give an output as a geometrical form which is in equilibrium with all the forces, it will help in illustrating the design, dimension and quantify its components and help in further structural analysis.The shape generation process takes three distinct steps towards achieving the final form; the plan shape, the isometric shape and the geodesic shape. In all these three levels form is generated by the process of iteration; a mathematical process by which the solution to a problem is found in incremental steps applied to a small portion of the total system. The resulting surface is a minimum surface, meaning that it has the smallest surface area possible to cover a space with the given fixed support points.[1]

The geometry and forces are interrelated. In the process of design the assumed shape and assumed forces should be iteratively correct to be in equilibrium. Equations of simple static equilibrium are required to be used. More important for the economy of the structure is that the membrane strips of fabric, called 'gores' in the fabric industry, resulting from this design approach fit into the parallel boundaries of the long rolls of fabric coming off industrial looms. In the geodesic shape, the shape is optimized to minimize the forces and allow patterning of the membrane fabric with a minimum loss of material.[8]

LISA is one such application developed by Dr. E. Haug of SL Rasch Special & Light Weight Structures GmbH., Stuttgart, Germany in 1986.

- Form finding methodology using LISA – the procedure as described in catalog for Sl Rasch Special and Light weight structures GmbH, and as shown in fig.2 involves following steps
- Two dimensional auto cad drawing input is fed in the software, specifying the exact co-ordinates of the 'high' and 'low' points of the structure to be constructed.
- The software then creates a three dimensional mesh which consists of number of 'Numerical Membrane elements' coordinates of which are stored.
- LISA then performs number of iterations to this three dimensional mesh to develop an optimum surface which can be made by joining at the 'high' and 'low' points.
- Thus the optimum 3D surface generated is then transferred back to Auto Cad as a 3D model, which is then analyzed for structural stability.

The design process is thus totally mechanized involving combination of CAD linked Finite Element Program and Computational Fluid Dynamics (CFD) Program. In final stage of the design process the generated idea is allowed a direct link with controlled manufacturing machinery (CNC) devices, like the milling machines, laser and water jet cutters and 3D printing devices thereby providing high precision design output.

2.4.4.1 Cutting Pattern Generation:

This step involves the conversion of the surface, generated after form finding into a set of planar cloths for fabrication i.e. they define the cloth subdivisions of the surface generated. Cutting Pattern Generation includes the determination of the distortion and stress free lengths of all cable and membrane pieces as a prerequisite for the cutting of cable and membrane materials and their knotting and sewing together to form the tensile fabric roof. In the cutting pattern generation real material values are used. Moreover this step becomes important because the slack lengths determine the prestress in the structure when the structure is analyzed and checked under different loading conditions. [16, 22, 31]

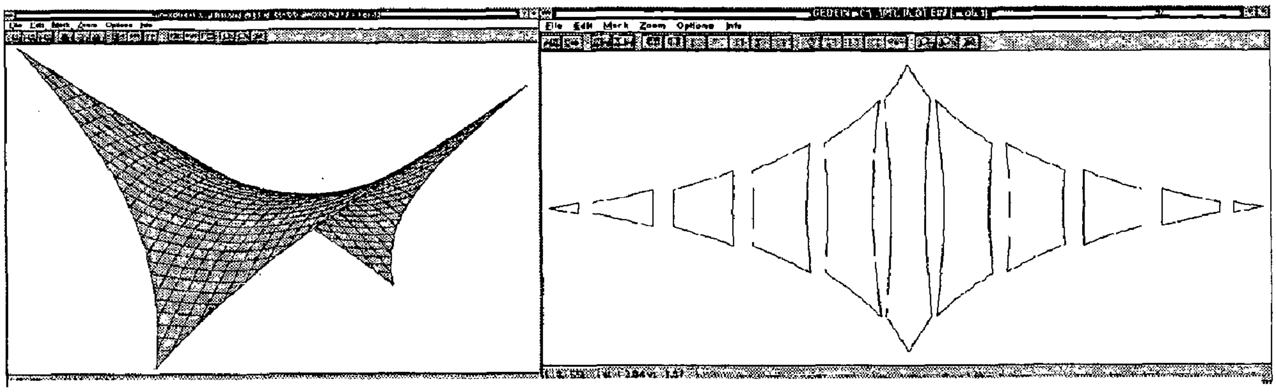


Fig 2.29 (a): Computer modelling (b) Cutting pattern

A geodesic surface is generated for the cutting pattern generation. Geodesic lines across a surface are mathematically defined by differential equations in terms of their direction. At each point they are locally straight relative to the plane tangential to the generation surface. Geodesic lines do not curve in the tangential plane. In addition the shortest path between two points over a surface will be geodesic. It is the fact that a geodesic is straight rather than its length which leads to its excellent suitability for seam generation in textile architectural applications. For an infinitely narrow cloth, the resulting planar pattern from a geodesic generation will have straight sides. As the cloth widths increase, and the corresponding patterning distortion increases, the sides will curve. Consequently, a surface properly patterned on the basis of geodesic lines can have cloths which minimize cloth usage as well as the angles between textile weave and surface principle stresses.

2.4.4.2 Cutting

The actual cutting takes place in a long table around 5m wide and 20m long. A long rod slides along the length of the table and a holder slides along the length of the rod. The movement of the rod and holder is controlled by a computer, the movement of these enables marking and cutting of the fabric in both the directions, facilitating the cutting of the fabric in any shape. The fabric is stretched along the table below the rod and holder, a marker is placed in the holder and the computer is programmed to give the necessary command to mark the required shape on the fabric. After the shape is drawn, the holder has a blade fitted with, which precisely cuts out the drawn shape. The cut fabrics are then welded accordingly.[11]

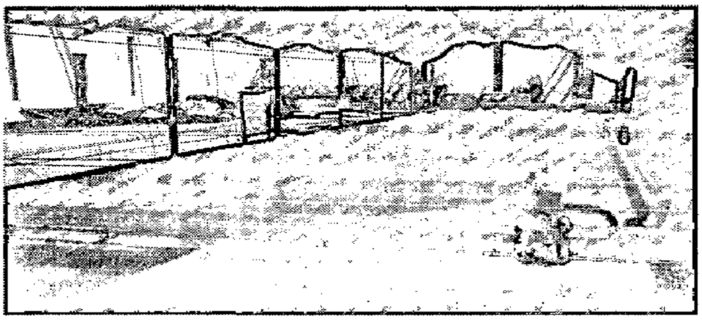
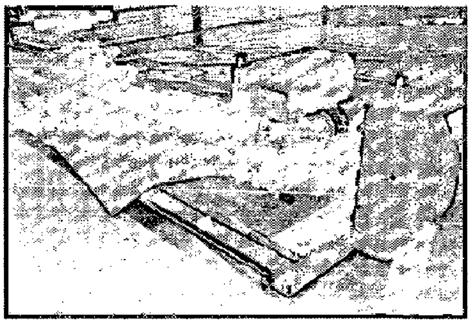
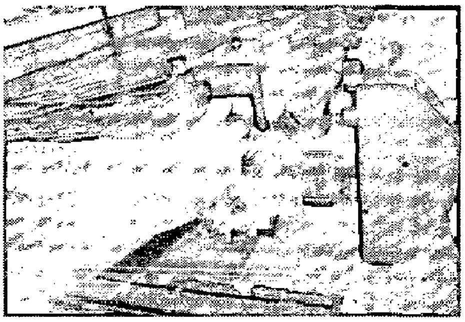
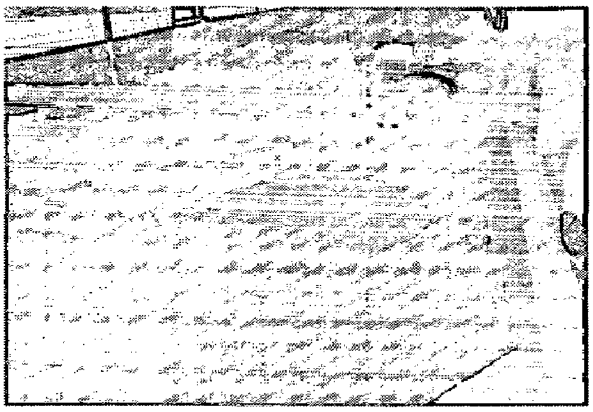
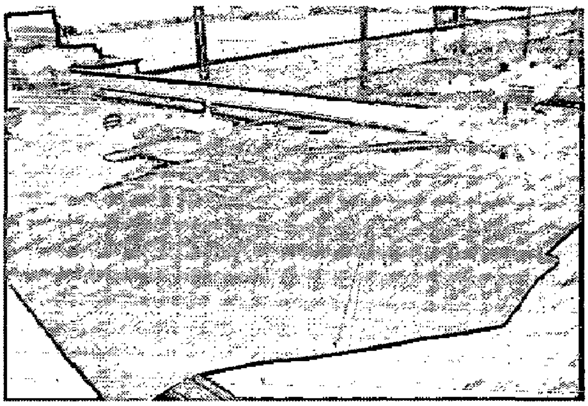



Fig 2.30 Clockwise from top : Cutting

2.5 SUMMARY

Though technology has taken over the process of form finding, physical modeling still helps understanding of the form. The forms and their development in actual projects will be discussed in the following chapter. Three international cases have been studied.

CHAPTER 3

CASE STUDIES

Study of actual cases help us in better understanding of the subject and gives us an insight into the practical issues to be considered. They give us lessons on the problems, solved and unsolved in the development of the project.

3.1 GENERAL

The main criteria for the choice of case studies have been the varied roof shapes and different space usage. Relevant international and Indian case studies have been chosen.

3.2 INTERNATIONAL CASE STUDIES

The three international cases chosen were designed by Horst Berger over the years. Each case is significant in its own way, having a varied form and use. They are studied by their approach towards the form and the methods adopted in achieving the design and construction. [1, 29]

The international cases are:

- **Denver International Airport Fabric Roof.**
- **The Haj Terminal of the Jeddah International Airport.**
- **The Cynthia Woods Mitchell Center For The Performing Arts, Texas.**

3.2.1 : Denver International Airport Fabric Roof

Fig 3.1: Denver International Airport

The fabric roof of this project has a length of 1000 ft. (305 m) and an average width of 240 ft. (73m) the masts reach heights of 120 ft. (36.5m)

A continuous inner fabric liner, independently supported, provides insulation, sound control, and protection against condensation. Separate exterior canopies on both ramps extend the full 1000 ft. of the building.[28]

Cost of tensile structures: $ 35 million.

Completion: May 1994.

Architect: C.W. Fentress J.H.Bradburn and Associates, Denver

Roof Design Consultant and Structural Engineer for the Tensile Structures: Horst Berger as Principal Consultant

- Approach
  - The conceptualized plans of the proposed building design were analyzed to narrow down the various possibilities of the forms and finalize the most feasilble one.
  - The plans showed two rows of internal columns which left a 150ft wide space down the middle of the 900ft long building.
  - The building plan had a rectangular plan form which is composed of repetitive arrangement of rectangular bays, hence the roof unit will preferably be a repetitive module of the radial form (the architect was interested in having a tent shape of the Indian tipîs)
  - A repetition of a single radial unit along the length of the building would require a central compressive support and might result in deeper folds. Instead a twin radial unit, the compressive masts of which are placed 60ft apart would be a more suited solution. This type of arrangement would also coincide with the proposed building column layout.
  - The tent masts would support ridge cables shaped to form the upper boundary of the series of radial forms. They would be anchored to the framing of the low roof surfaces on the long sides of the building.
  - In order to emphasize the entrances, the tent units near the entrances where raised a little higher.
  - This conceptualization was followed by a study model and further digital modelling.

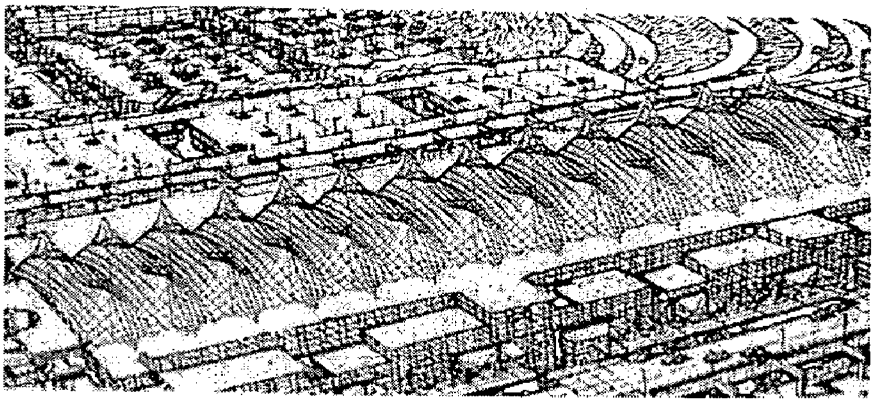


Fig 3.2: Computer Model

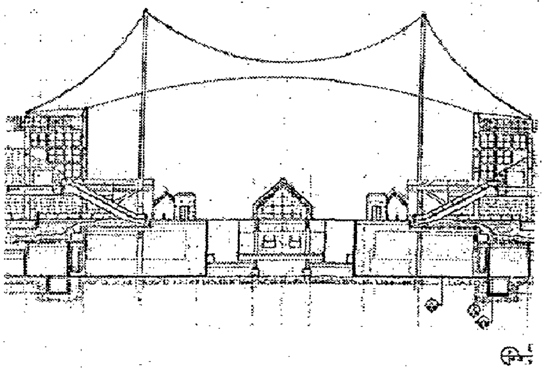


Fig 3.3: Section

- Special Design / Construction Features

  - In case of snow accumulation, dips should be formed in the fabric such that atleast one area of the surface, along the periphery slopes continuously. This would avoid ponding of the snow.

  - A set of 5/8" diameter cables, spaced approximately 40' apart and running the length of the building in sections attached to the ridge cables and valley cables, was placed just under the membrane. They are part of a rip-stop system which would contain any accidental rip within the 40ft length between any two such surface cables. To achieve this, fabric strips which are heat-sealed to the outer fabric contain the cables in a staggered loop pattern.

  - Valley cables, edge catenaries, vertical and lateral anchor cables all come together in the 'octopus' connector, which is in turn pushed down to stress the membranes accordingly.

  - The roof consists of two layers of fabric; an inner liner located approximately 24" below the outer membrane. The inner liner's purpose is to provide thermal insulation and acoustic absorption. It is supported by its own system of ridge and valley cables; around the periphery it is connected to the upper members of the window wall framing system.

- Inflated tubes form closure panels between the window wall frame and the roof membrane.

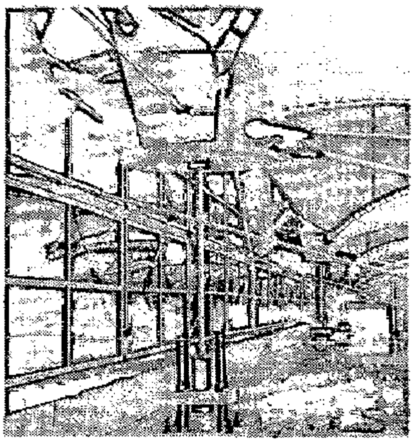


Fig 3.4: Octopus Connector

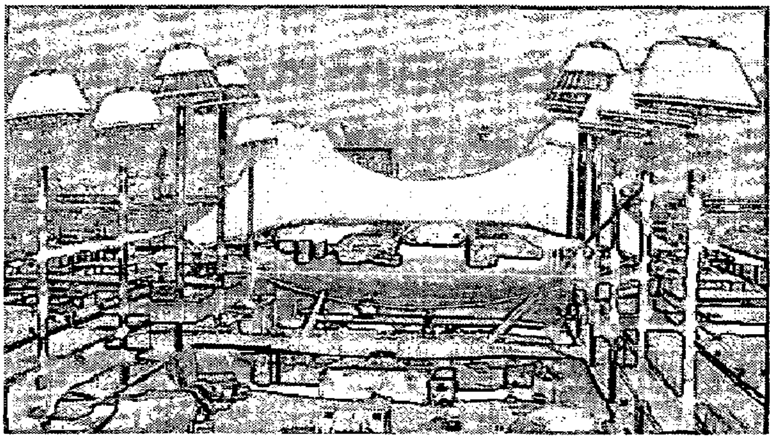


Fig 3.5: Roof during construction

➢ Inferences

- *Fabric:* Woven Fiberglas substrate coated with Teflon
- *Form:* Repetitive twin paneled tent forms.
- *Significant support structures:* Steel masts, steel cables and octopus connectors.
- The roof form gives an identity to the airport; it forms the most significant visual character in the building.
- The fabric roof design offers plenty of day lighting.
- The heightened roof units near the entrances are a commendable visual clue.
- The project has offered plenty of scope to innovate with end and edge connections, like the octopus connector and the inflated tubes.

3.2.2 The Haj Terminal of the Jeddah International Airport

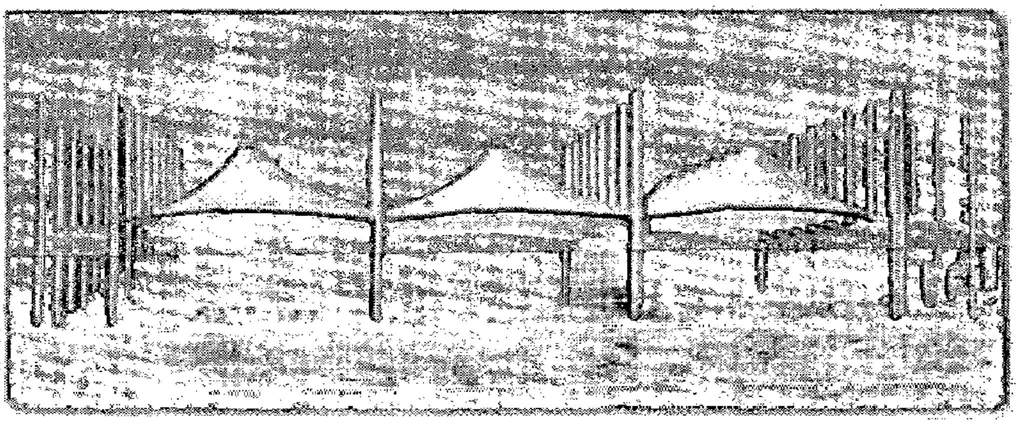


Fig 3.6: Haj Terminal

This Terminal was built to accommodate the pilgrims on their way to Mecca during the holy month. Up to 100,000 people pass through it in one day.

The fabric roof covers 430,000 sq.m. of plan area which is by far one of the the largest roof structure in the world. The roof consists of 10 modules of 320m by 138m, each having 21 tent like units. Their peaks are suspended from steel pylons leaving the space under the units wide open.

Fig 3.7: Inside the Haj Terminal

Completion Date: 1982.
Cost of the roof structure: $ 180 million.
Architect/Engineer for conceptual design: Skidmore Owens & Merril
Roof Design Consultant and Structural Engineer : Geiger Berger Associates. Horst Berger.

- Approach

  - The plan form consists of repetition of square bays of side 45 m (150 ft.).
  - The architects focused on the design to be simple, elegant, powerful and uniform in appearance. Hence repetitive modules of the visually simple radial tent units are adopted.
  - In order to avoid central masts under the peaks of the tents, pylons at the corners of the tent units are made high enough so that the tent peaks could be held by four sets of cables suspended from the mast tops.
  - The edge units needed heavily reinforced double pylons to resist the large anchor forces high above the ground.
  - A typical radial tent unit has 32 radial cables. Its edges are made of edge catenaries or valley cables.
  - The corners are connected the pylons 20 m (65 ft.) above ground. At the upper end of the tent units, fabric and radial cables terminate in a 15 ft. diameter steel ring – the lower part of a matched pair of rings – located 34 m (110 ft.) above ground.
  - In accordance with the geometry defined by these elements and the prescribed uniform prestress in the fabric, a computer program would find the shape of the units, the length of all cables, and the patterning required for the fabrication of each fabric unit.

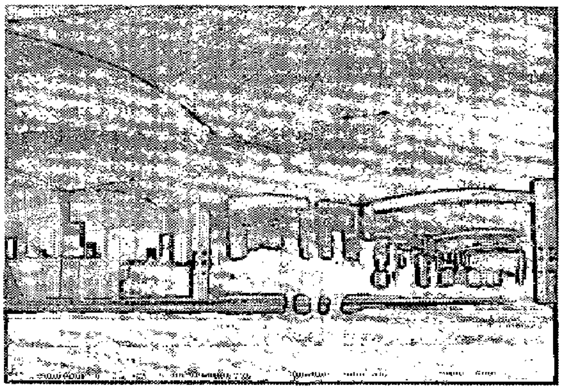


Fig 3.8: Haj Terminal

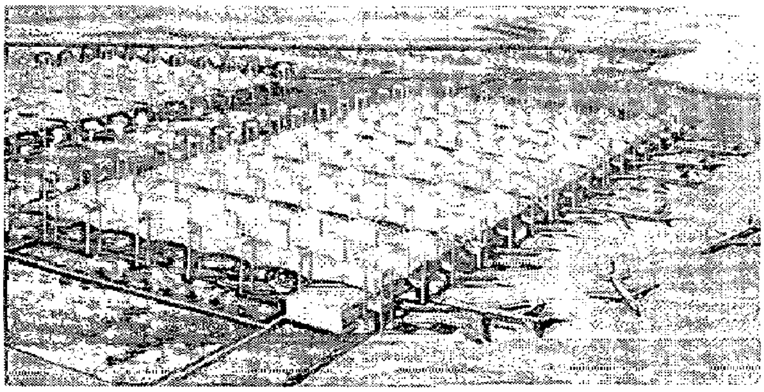


Fig 3.9: Aerial View

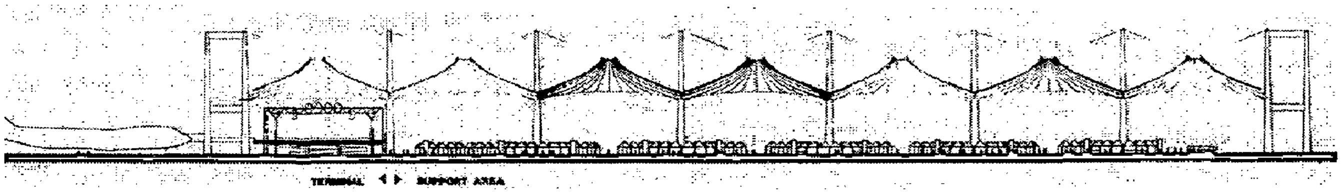


Fig 3.10: Elevation

➢ Special Design / Construction Features

- The cables are high strength galvanized bridge strand of the type used in suspension bridge hanger cables. The large cables where protected from corrosion by enclosing them in a polyurethane sheathing.
- The pylons are made of tubular steel sections which taper from a diameter of 3.66 m (12 ft.) at ground level to a diameter of 1.83 m (6 ft.) diameter at their peak. They collect all the vertical and lateral forces exerted by the cables – suspension cables at the top connection of the tent units, and edge catenaries, ridge cables, and stabilizing cables at the bottom connection – and bring these forces down into the foundations. The exterior pylons required thicker sections to resist unbalanced load in one direction; in the case of corner pylons it was in two directions.
- During the installation of the radial tent units, installation of one tent unit caused the loads on the pylons to change and made them move at their tops, until the adjacent module had been installed and stressed. To overcome this, a double ring arrangement was made. The upper ring was installed and put

under stress, then all the twenty one radial tent units where assembled near the ground. The top of each tent unit was attached to a bottom ring, which was in turn attached to the cables of a winch in the top ring. All the twenty one units where then raised and stressed together as the rings slid into one another.

- Inferences

  - *Fabric:* Fiberglas substrate coated with Teflon
  - *Form:* Repetitive radial tent forms.
  - *Significant support structures:* Tubular steel sections masts pylons, high strength galvanized bridge strand
  - The roof structure gives a uniform yet powerful appearance, no particular portion of the plan is highlighted.
  - Made of Teflon coated fiberglass the roof reflects most of the heat; while translucency allows enough daylight.
  - Reduction in construction time as most of the components are brought on site and just installed.

3.2.3 The Cynthia Woods Mitchell Center For The Performing Arts, Texas

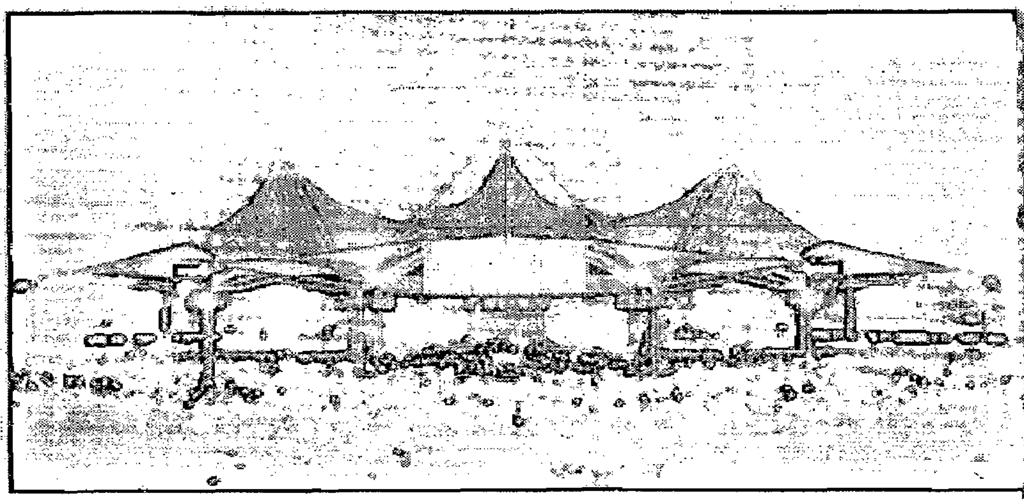


Fig 3.11: Cynthia Woods Mitchell Center For The Performing Arts

The Center serves as the summer home for the Houston Symphony. It also offers a wide variety of performances including musicals, ballet, rock and other programs. The center seats a total of 10,000 people, 3,000 under the fabric roof cover, and 7,000 on the lawn. The fiber roof covers an area of 27,000 sq. ft. Its structure consists of three tent like units suspended from steel A-frames.

Location: Woodlands, Texas

Project Cost: $ 8 million.

Completion Date: April 1990

Architectural Design & Engineering: Horst Berger Partners, Cons. Eng., New York

- Approach

  - The plan form is a circular sector, which is more than a semi-circle. The seating to be covered radiates from the stage area, which is in front of the stage house. Such an arrangement warranted radial aisles and walkways.
  - Columns had to be placed in line with the radial aisles and walkways to facilitate proper sightlines. Such an arrangement formed three bays to be covered by individual roofing units.
  - A tent unit, with its high point is chosen to add character to the structure.
  - Four trussed steel columns hold up three A-frames, and horizontal struts link the top of the columns to the stage house. Other struts reach out from the top of the columns to the periphery. Together, they neutralize the horizontal forces caused by the tensile forces of fabric and cables, so that only vertical loads are transmitted through the columns to the foundations.
  - The fabric membrane is held up at its high points beneath the A-frames, and held down by its low points on top of the main masts.
  - Ridge cables lead from the periphery to the A-frame peaks and back to the stage house. Valley cables scallop from the stage house down to the mast points, and back out to the periphery.

- Special Design / Construction Features

  - Provision is done for water to drain from the roof through the main columns. To avoid the danger of the membrane roof filling with water if a drain clogged, the intakes have been designed as a two-layer funnel with a narrow gap between the layers. In case of clogging, water can escape inside the space, running down the column to a floor drain.
  - The ceiling's curved and folded surface geometry does not necessitate any additional acoustic treatment.

- Inferences

  - *Fabric:* Teflon coated fiberglass
  - *Form:* Repetitive paneled tent forms
  - *Significant Support Structures:* Trussed steel columns, struts and trussed steel A-frames.
  - The roof forms the most visually identifiable and appealing character of the built form.

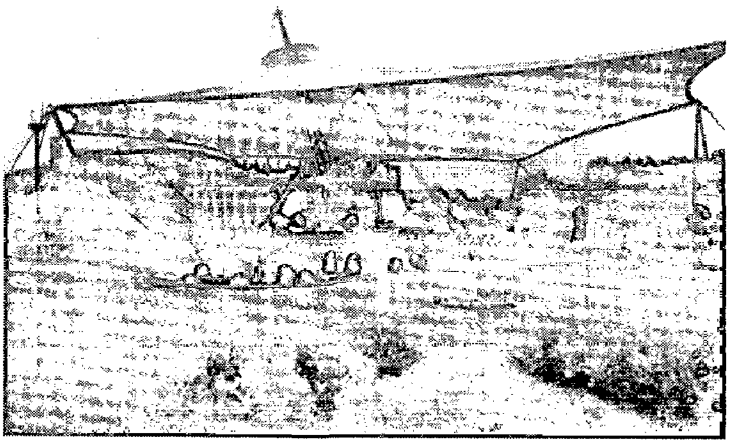
3.3 NATIONAL CASE STUDIES:

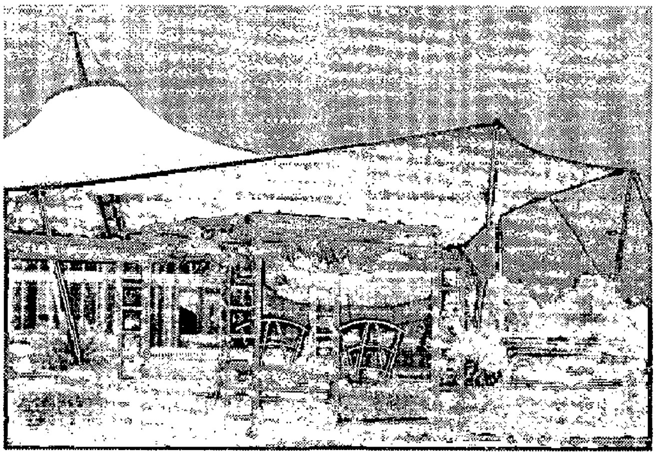
Tensile fabric roofs, though a comparatively recent trend in India, are slowly growing to be a significant number and are unique in their own way. Though the fabric for most of the Indian fabric roofs is imported, considerable interest might pave way for quality national producers. The four cases discussed below have structures designed and constructed by Construction Catalysers, Pune, India. The following studies were developed on the basis of material (incl. figures) provided by Construction Catalysers.[9][10][11][23]

The cases are:

- **Deccan Harnest, Pune**
- **Select City Walk, New Delhi**
- **Archery Stadium, New Delhi**
- **Vasant Square Mall, New Delhi**

3.3.1 Deccan Harvest, Pune.





(a) Fig 3.12 Deccan Harvest (b)

Space: Roof for open air restaurant

Location: Pune, India.

Architectural Design & Engineering: Construction Catalysers, Pune.

Date of Completion: December, 2002

The tensile fabric roof spans 19.87m on one side and 22.5m on the other, the fabric used is Valmex 900 (For specifications refer Table 4.2), which has a polyester base coated with PVC, weighing 900 gr/m^2 . The roof has a radial tent form with point supports composed of steel masts and cables.

- **Approach**

For an outdoor restaurant, a radial tent fabric roof form is chosen to shade. The tensile fabric roof acts like an umbrella over the head, providing a sense of enclosure yet giving a true sense of the outdoors. Ample natural lighting around the perimeters, the central mast also supports a skylight providing for lighting in the centre. Slender supporting masts do not take up much of the dining space, only the central supporting mast occupies any of the usable dining space, the end supporting masts are all located outside the dining area. The roof form is symmetrical along one axis in plan, this symmetry is not much apparent in the human eye view, yet the view of the roof is dominant and dynamic.

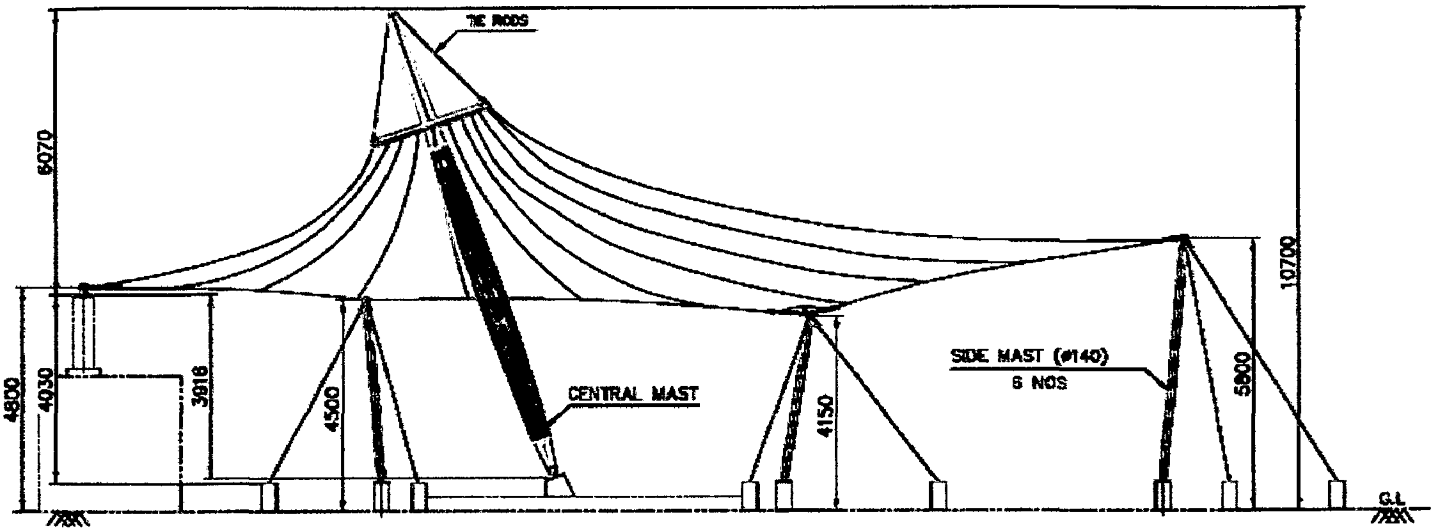
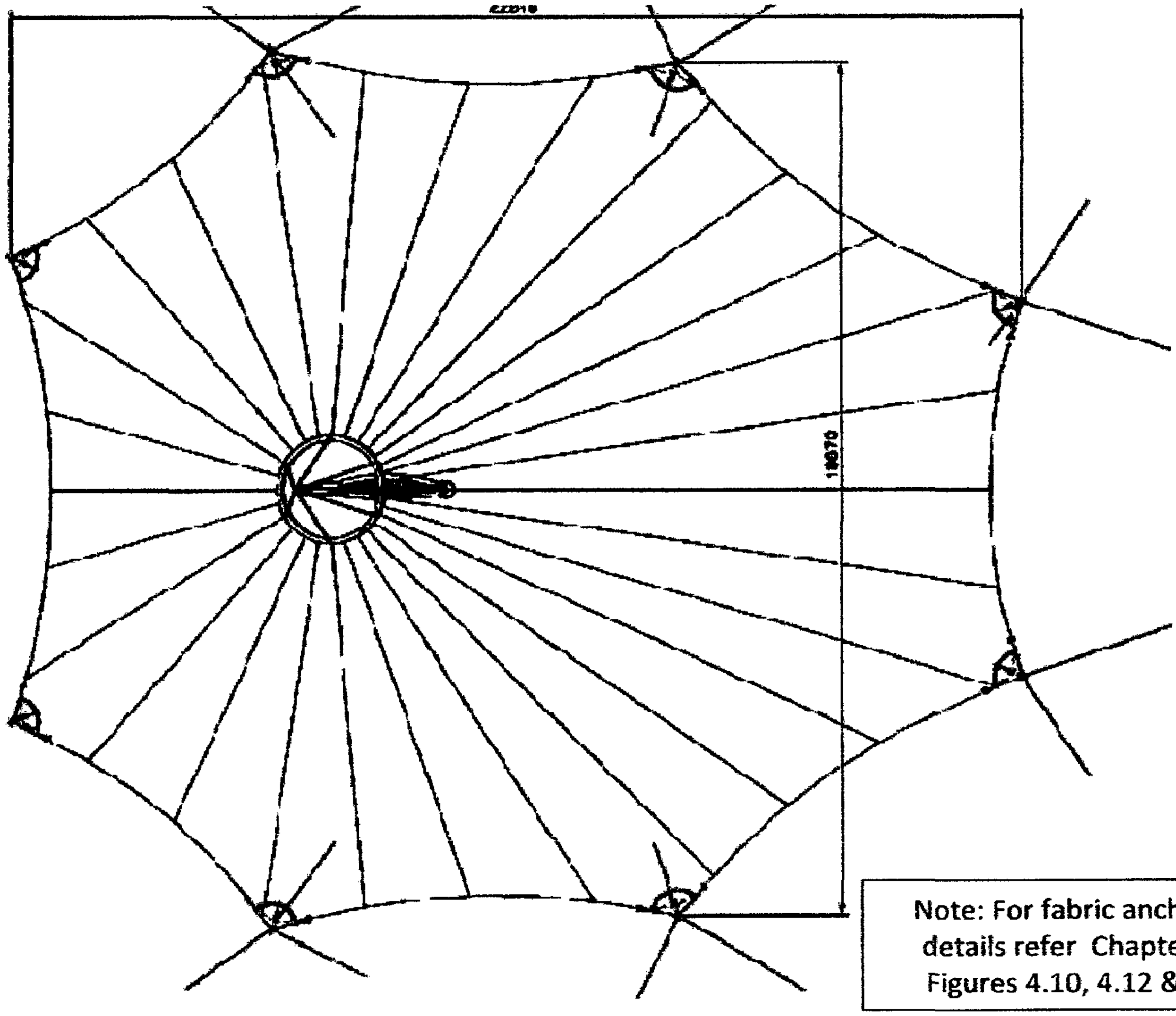


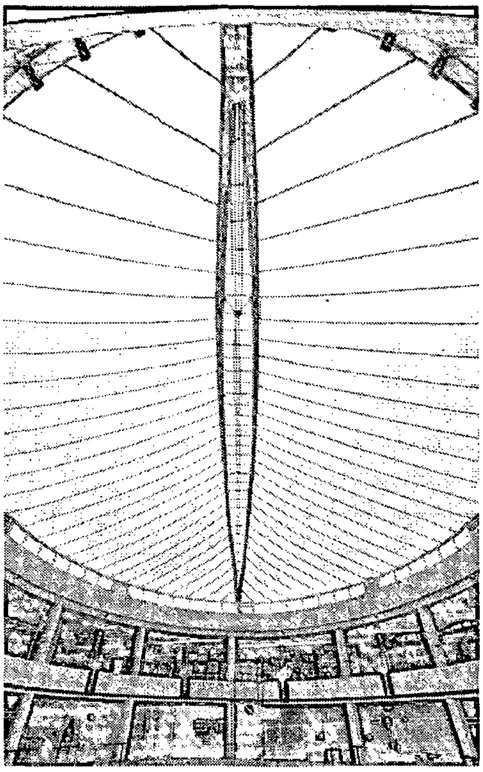
Fig 3.13 Above: Elevation

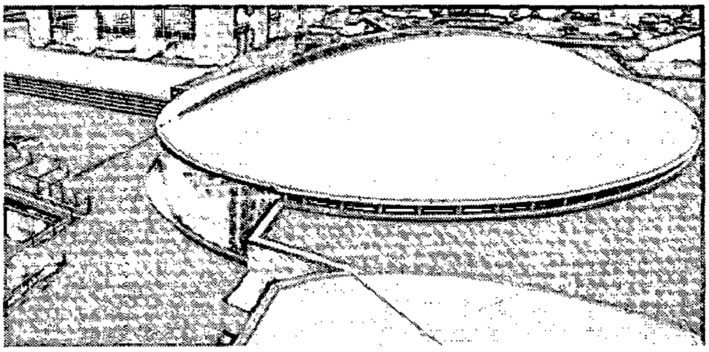
Fig 3.14 Below: Roof Plan



Note: For fabric anchorage details refer Chapter 4.7, Figures 4.10, 4.12 & 4.13

3.3.2 Select City walk, New Delhi.





(b)

(a) Fig 3.15 Select City Walk, New Delhi

Space: Roof for Elliptical Atrium

Location: New Delhi, India.

Architectural Design & Engineering: Construction Catalysers, Pune.

Date of Completion: September, 2007.

The tensile fabric roof was completed in six months; it covers an elliptical atrium, which has a major span of 36.1m and minor span of 26m. It's a twin saddle roof, the fabric used being Ferrari 1002S (For specifications refer Table 4.1), polyester base coated with PVDF. It is supported on the periphery continuously by a steel beam, and centrally by an assembly of triangular girded arch and cables.

- **Approach**

The atrium being a conditioned environment needs to be fully covered with no intermediate support, this is achieved by means of a continuous steel beam and a central triangular girded, cable suspended arch. Ample day lighting is provided by the translucent membrane and the central skylight over the top girders like an eye. Fail safe cables and suspension cables hold the arch in position.

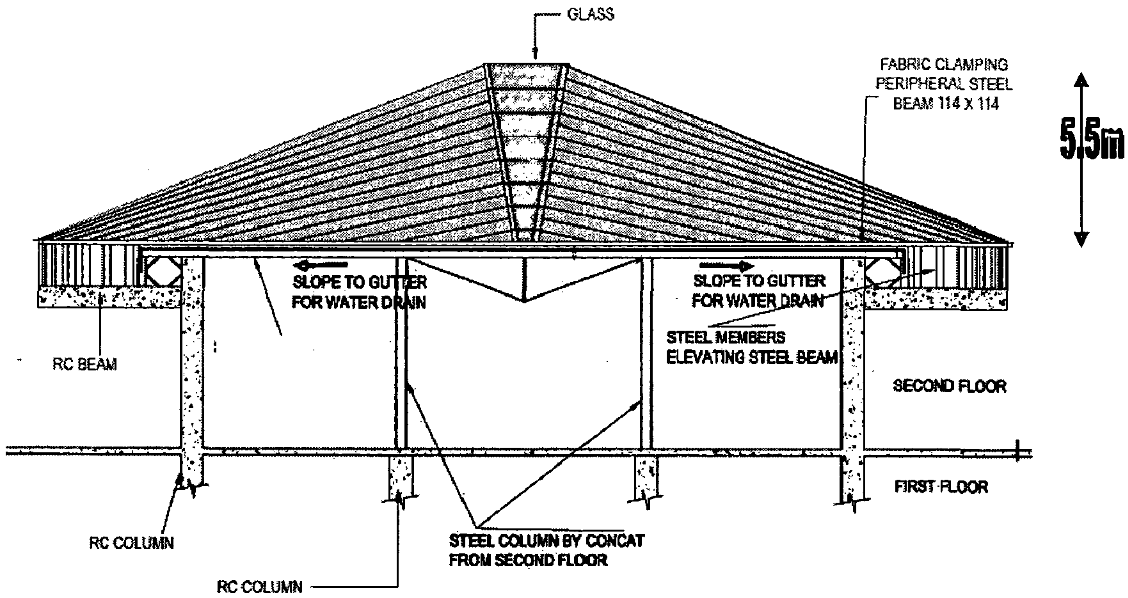


Fig 3.16 Elevation along the minor span

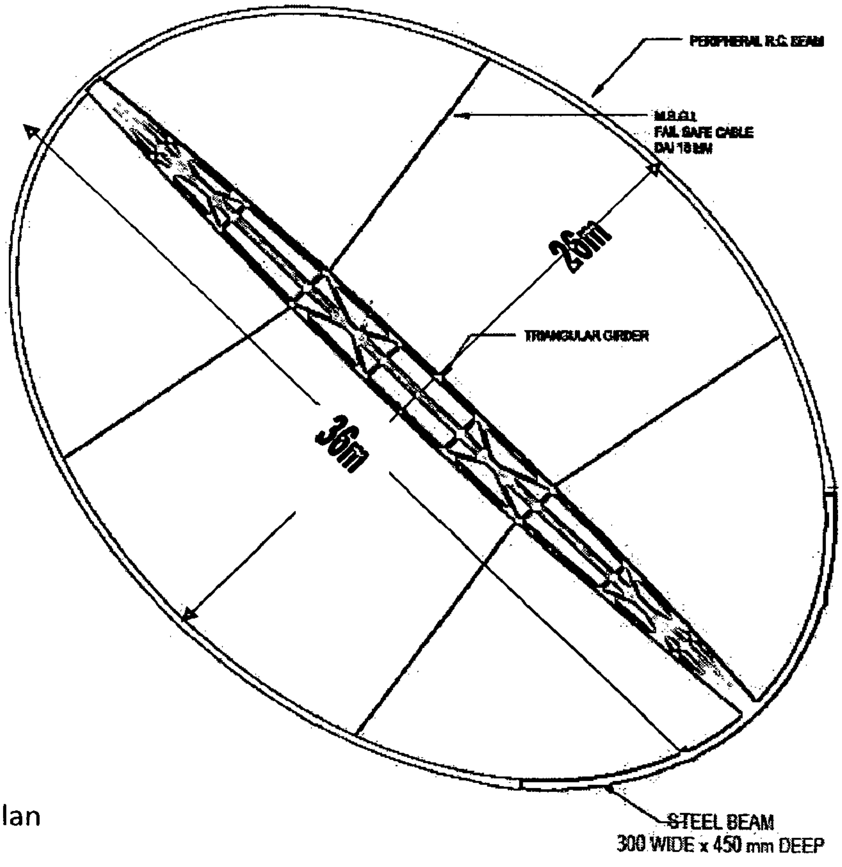


Fig 3.17 Structural Plan

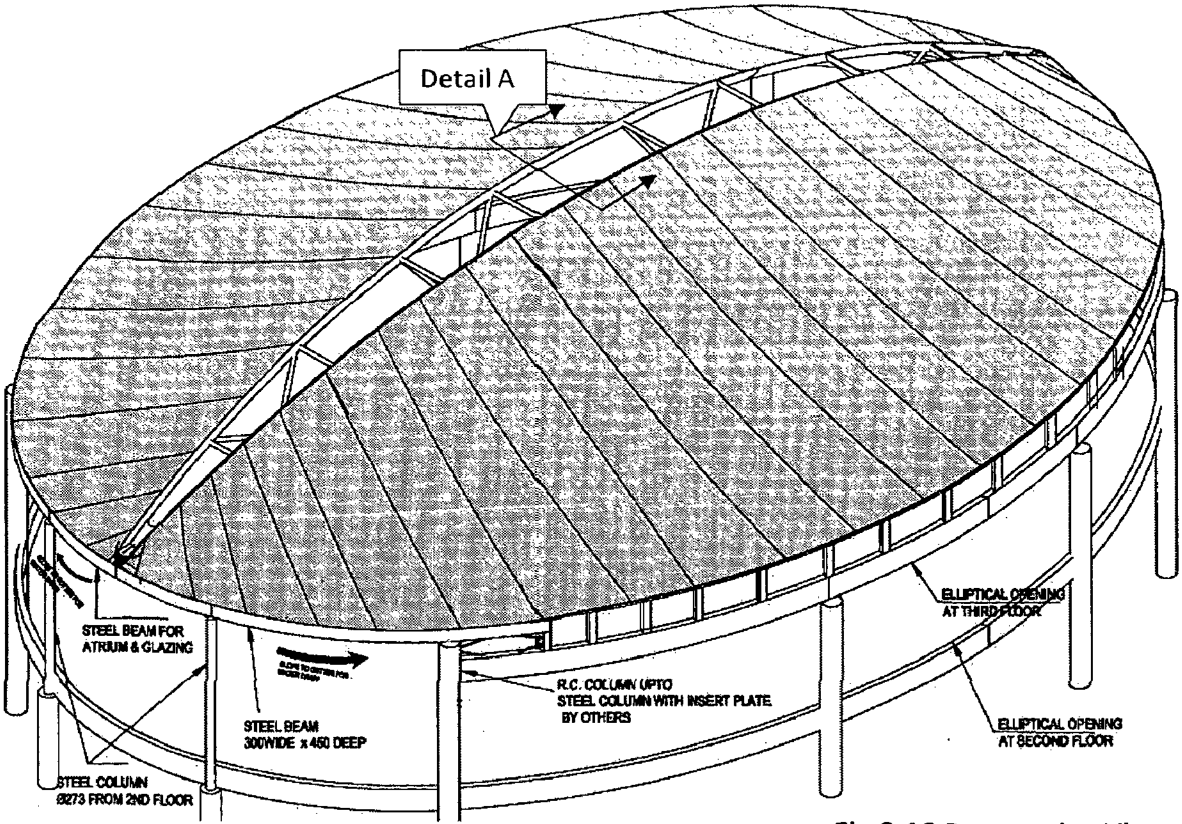


Fig 3.18 Perspective View

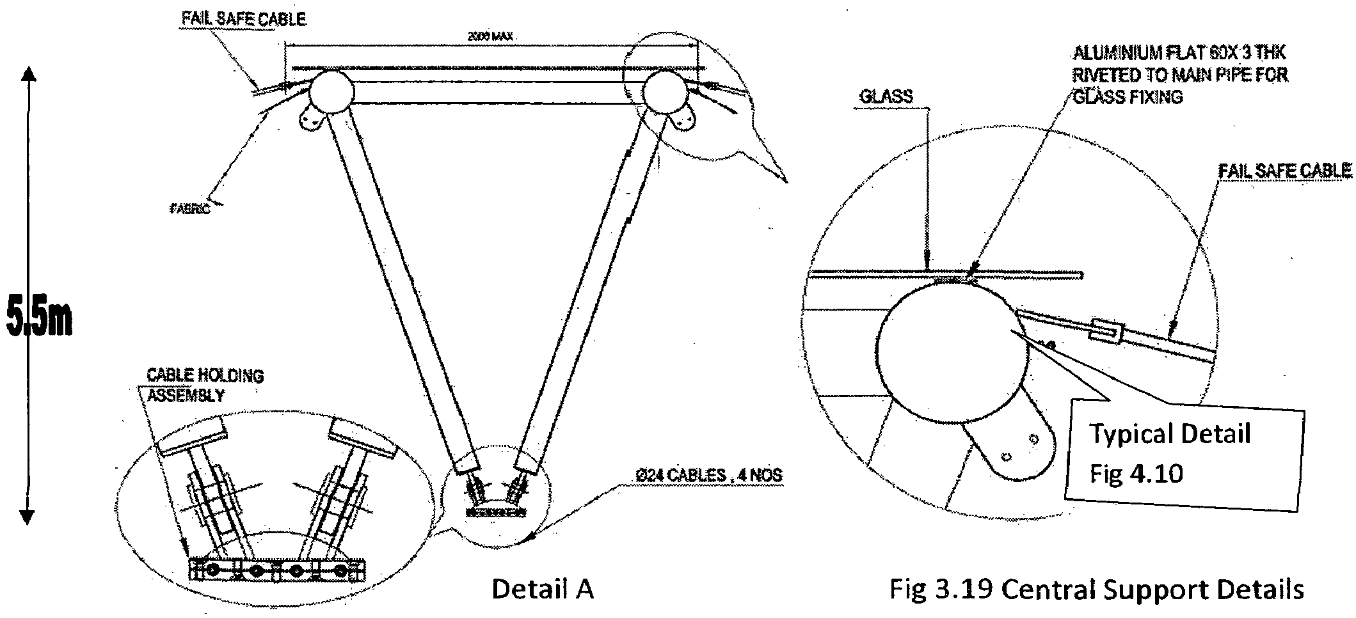
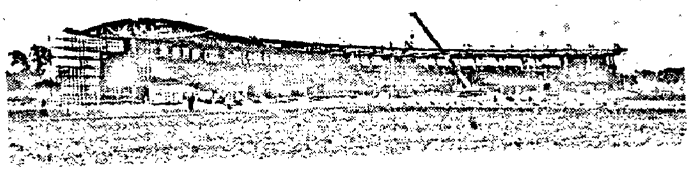


Fig 3.19 Central Support Details

3.3.3 Archery Training Venue, Sports Complex, New Delhi.



(a)

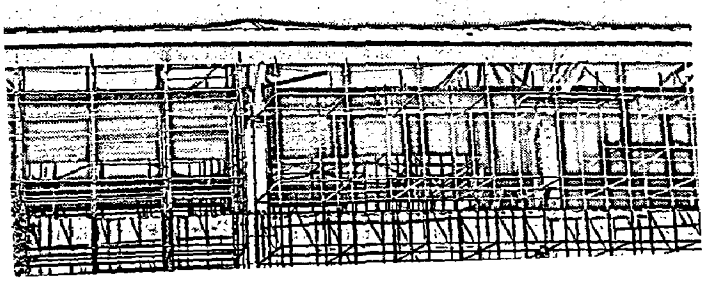


Fig 3.20 Archery Stadium (b)

Space: Stadium Roof

Location: New Delhi, India.

Architectural Design & Engineering: Construction Catalysers, Pune.

Date of Completion: March, 2010

The stadium forms part of a sports complex. It is the venue for archery training and games. The actual action of the game takes place in the outdoors. The built structure serves for the spectators' seating, players' rooms, and other related and essential services. The three storied RCC structure of the building is 11m high; the plan is a continuous inward looking curve with a width of around 21m. A continuous belt of seating forms the inner width of around 13m; other facilities are accommodated behind the seating. It covers an area of 3100sqm.

- **Approach**

The architects decided on a tensile fabric roof for the structure and approached the consultants for the same. They chose a form for the roof that they thought would be more feasible and the consultants were entrusted with the task of fine tuning the form and providing the finer details for construction. It is a curved roof structure made up of tubular steel pipes and PVC polyester fabric. The tensile fabric roof is a single continuous curved form both in plan and section. The fabric forms a saddle between two consecutive trusses and two structural steel sections, hence having a continuous support. The top curve of the cross section is less apparent on entering the building, unless one enters from the sides directly on to the seating, in which case the sectional curves are more apparent; from a distance the curves of the section are more prominent. The architects would have preferred such a form to complement the form of the plan. There might also have been economic considerations considering the material usage.

Once the shape of the form is decided upon, the NISA software is used to feed the co-ordinates of the end profile the form will take. The software will generate a form in triangular meshing. Such meshes are, as discussed earlier non-developable, hence whatever the form location of strategic points would not change. After the form is finalized, the triangular meshing of the form is converted to rectangular meshing, and the form is tested for expected loading conditions. This allows some distortion to take place in the form. Moreover in the case of rectangular meshing, presence of cables can also be considered. This stadium was designed assuming dead load of all the fittings and wind pressure, live load is taken as 75 kg/sq.m in accordance with IS-875 Part-2 as access to the curved roof is not provided except for maintenance. Then cutting pattern is generated with minimal wastage for the fabric. Elegant steel trusses cantilever from the RCC roof of the top most floor. Cross bracings are provided as required and a steel gutter forms the entire periphery of the roof. The fabric is attached to these components.

➢ **Fabric:**

The fabric used is Valmex FR 1400 Premium – Type IV (For specifications refer Table 4.3), it is a translucent white membrane imported from Germany. The fabric base is polyester it is coated with PVC and finished with a top coat of PVDF which gives protection from ultra-violet rays, fungal and microbial attack. Such a fabric will last 15-20 years after which the fabric might have to be replaced. The fabric is cut patterned and stretched between the trusses. The precise cutting facilitates the designed stresses in the fabric to stretch between the supports. Each panel of fabric has a cuff in its periphery through which a twisted strand steel cable runs enclosed in a plastic casing. Holes are punched in the overlapping fabric near the cuff through which the bolt passes. The overlapping fabric is sandwiched between rubber strips and bolted to the support structure with the help of steel flats. A plastic cap covers the bolts for protection. Flashing is provided by means of the fabric itself; a strip of fabric covers the end connections and is held in place by adhesives. (Refer Fig 4.11). Adhesives are used only for the flashing; any other fabric to fabric connection is welded together before being brought to site.

Although it is not functionally necessary the fabric stretches between both the tops and bottoms of the trusses. The relevant people found it more aesthetically appealing. In the periphery the fabric is connected to a steel gutter in the same way as discussed above. For maintenance, the fabric might have to be wiped with a house hold mild cleansing solution once a year if necessary.

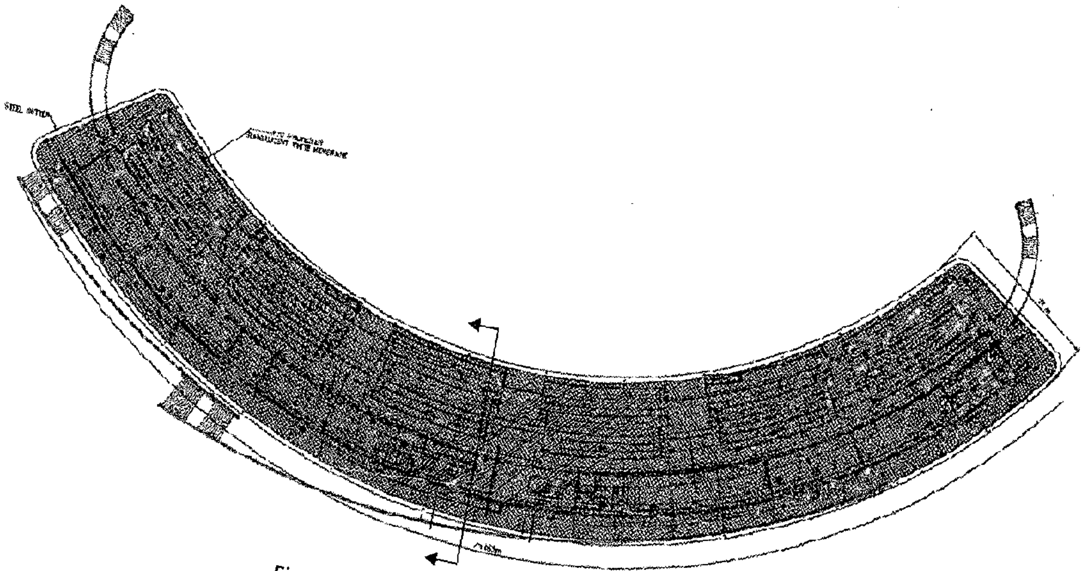


Fig 3.21 Archery Stadium, Roof Plan

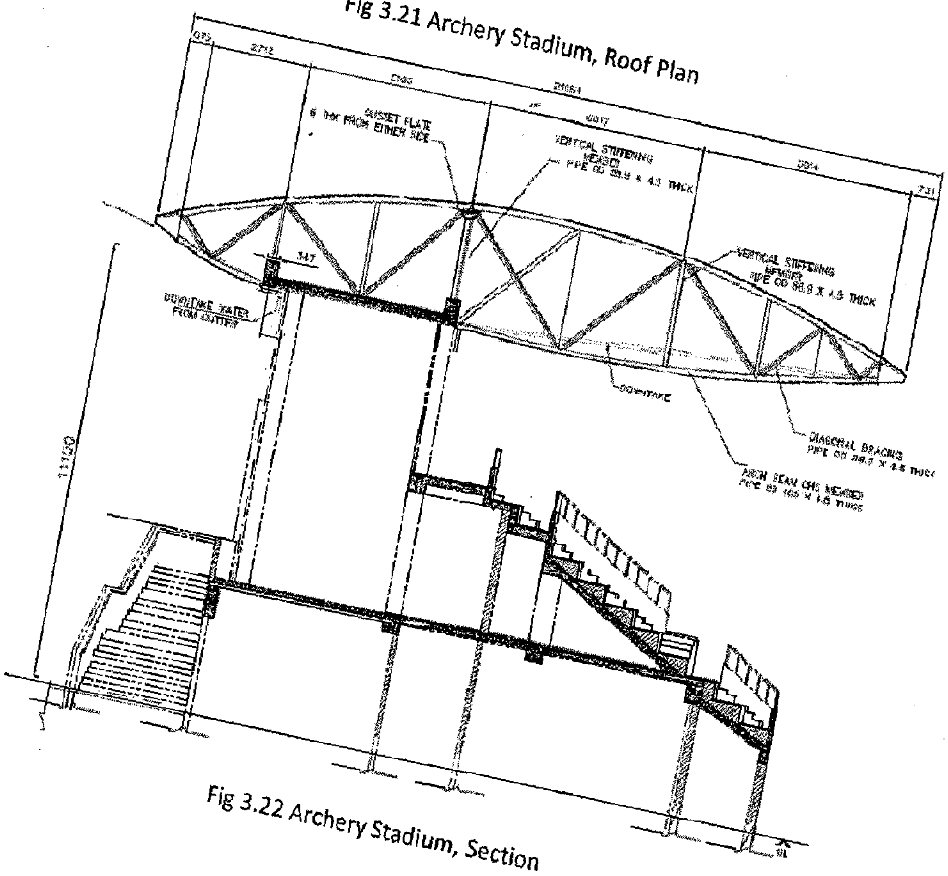


Fig 3.22 Archery Stadium, Section

3.3.4 Vasant Square Mall, New Delhi.

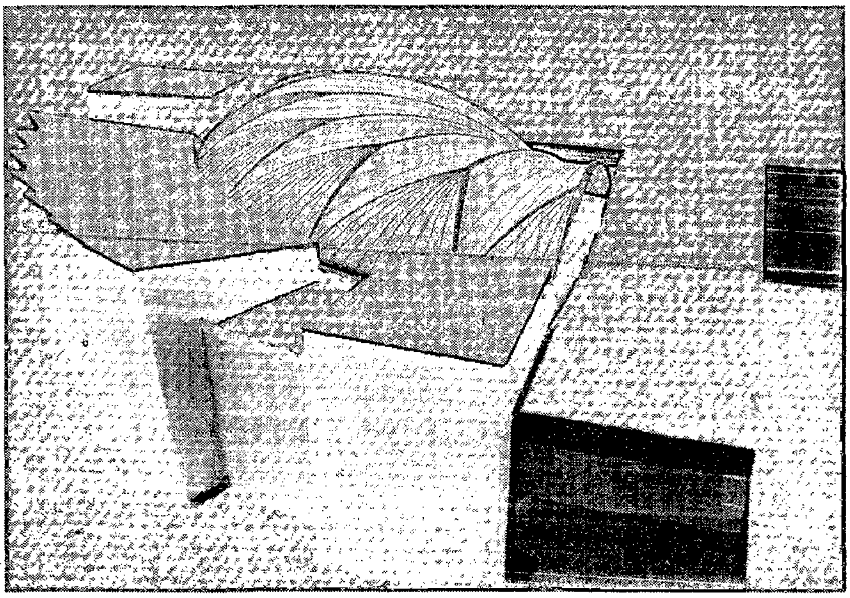


Fig 3.23 Vasant Square Mall, New Delhi.

Space: Roof for Shopping Mall

Location: New Delhi, India.

Architectural Design & Engineering: Construction Catalysers, Pune.

Date of Completion: September, 2008.

The tensile fabric roof covering the atrium space took twelve months to complete. The fabric used is a Mehler type4 FR1400 (For specifications refer Table 4.3) which has a polyester base coated with PVC. It is supported by arches and they form the main supporting structure.

- **Approach:**

The tensile fabric roof is required to cover a space that in plan resembles a quadrant of a circle. Being a conditioned space it is required to be covered completely. Arches radiate from the angular side and bifurcate as they reach the perimeter. The arches are a combination of girders and cables that hold it in place and cables form valleys in between the arches. The whole structure allows the atrium to be naturally lighted during the day as the fabric is translucent.

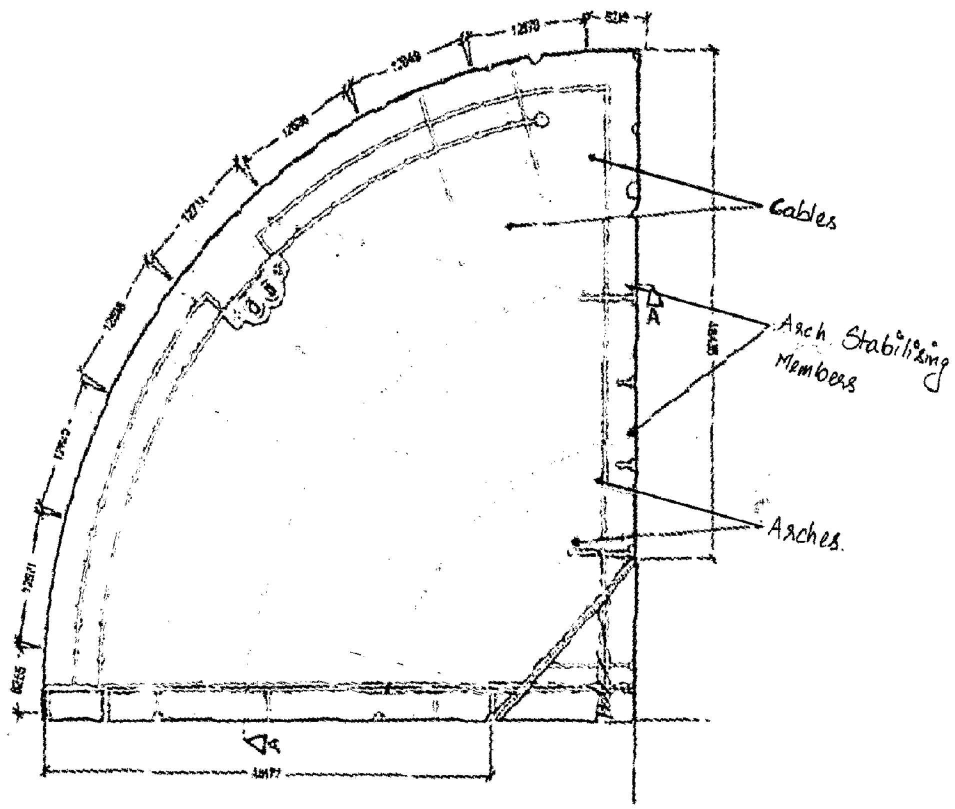
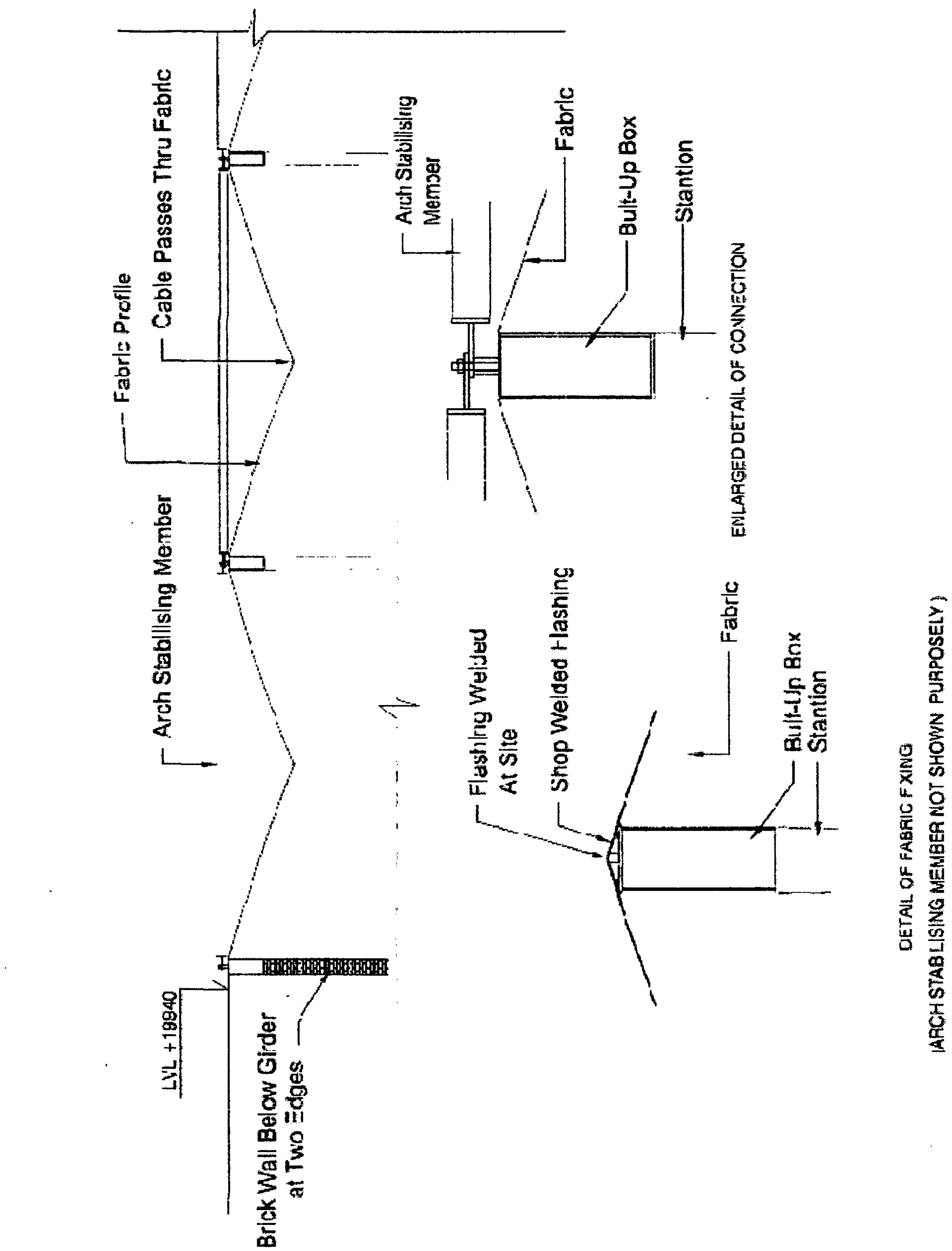


Fig 3.24 Vasant Square Mall, Roof Plan.


Fabric Profile
Cable Passes Thru Fabric
Arch Stabilising Member
LVL +19940
Brick Wall Below Girder at Two Edges
Arch Stabilising Member
Fabric
Built-Up Box
Stantion
ENLARGED DETAIL OF CONNECTION
Flashing Welded At Site
Shop Welded Flashing
Fabric
Built-Up Box Stantion
DETAIL OF FABRIC FIXING
(ARCH STABLISING MEMBER NOT SHOWN PURPOSELY)

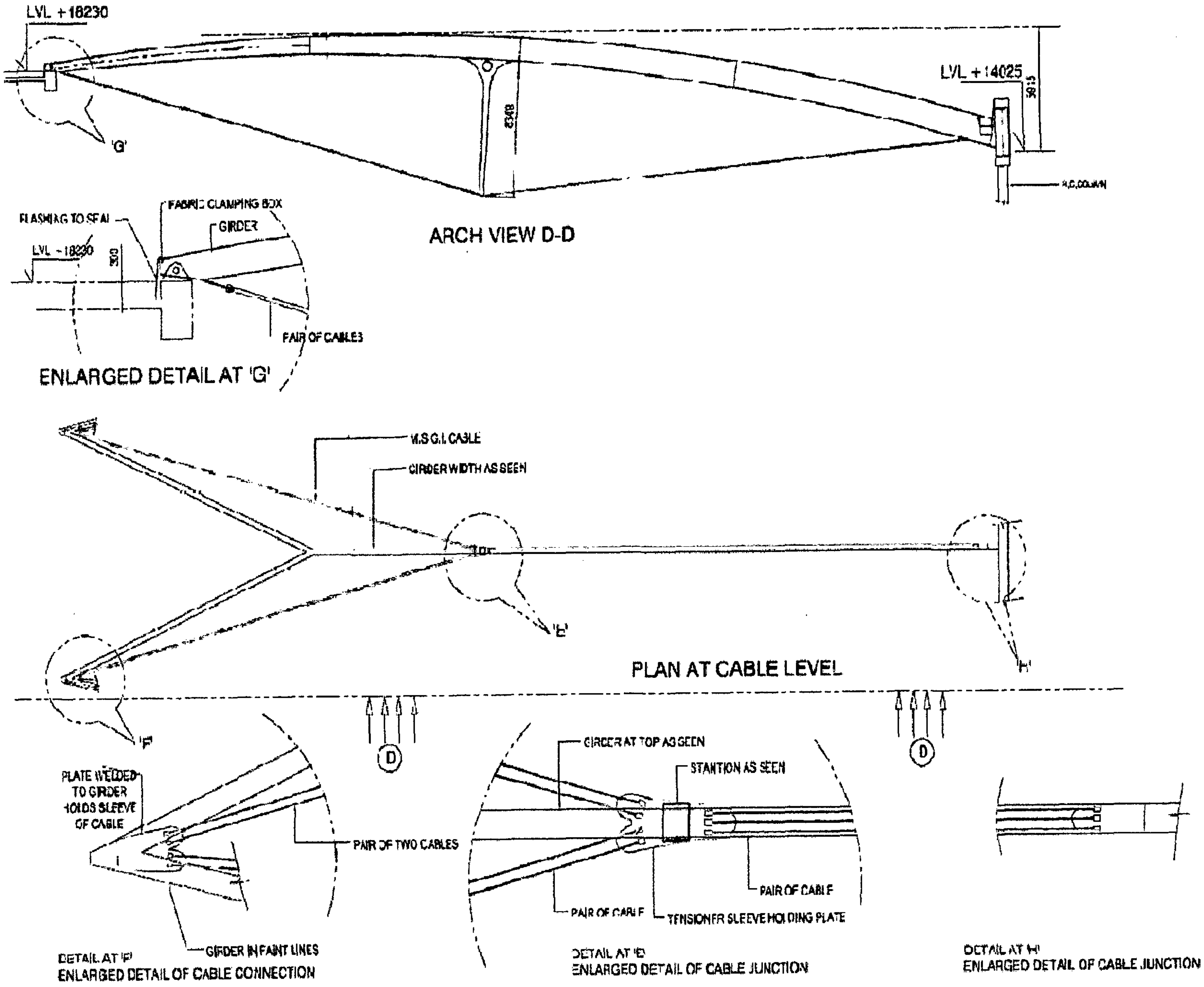
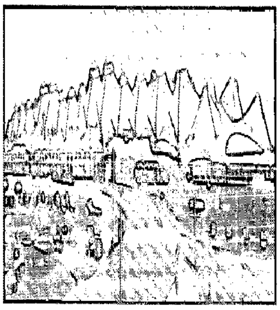
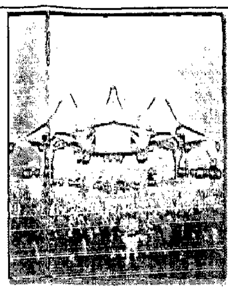
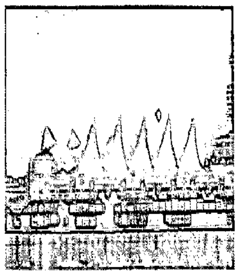
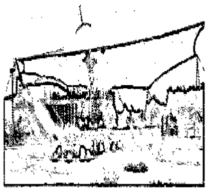
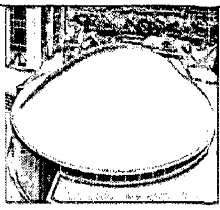
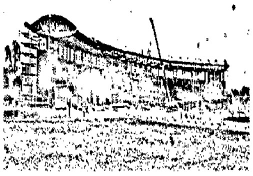
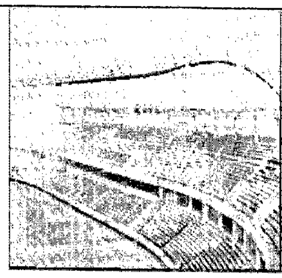


Fig 3.26. Arch Details

3.4 (a) ANALYSIS MATRIX

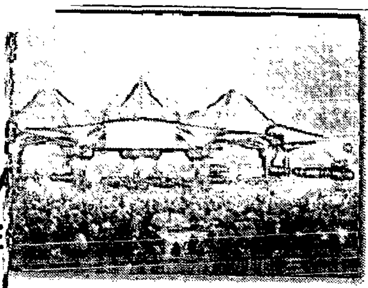
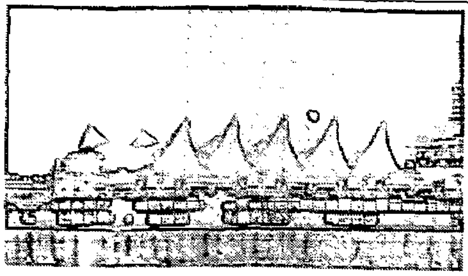
INTERNATIONAL CASE STUDIES	 Denver International Airport	 The Haj Terminal of the Jeddah International Airport	 The Cynthia Woods Mitchell Center For The Performing Arts	 Canada Harbour Place, Vancouver
SPAN (FT.)	150 X 60	150 X 150	~ 160 ft radius, 240°	180 X 240
PLAN FORM	Linear repetition of Rectangular bays	Rectangular array of square bays	Semi-circular array of three sectors	Linear arrangement of rectangular bays
FORM.	Repetitive twin paneled tent forms	Repetitive radial tent forms	Repetitive paneled tent forms	Wave form
FABRIC	Woven Fiberglass substrate coated with Teflon	Fiberglass substrate coated with Teflon	Teflon coated fiberglass	Teflon coated fiberglass
SUPPORT STRUCTURE	Steel masts, steel cables and octopus connectors.	Tubular steel sections masts pylons, high strength steel cables	Trussed steel columns, struts and trussed steel, A-frames.	Steel masts and cables

3.4 (b) ANALYSIS MATRIX

NATIONAL CASE STUDIES	 Deccan Harvest, Pune.	 Select City Walk, New Delhi.	 Archery Training Venue, Sports Complex, New Delhi.	 Vasant Square Mall, New Delhi.	 Cross River Mall, New Delhi.	 Ranchi Stadium, Jharkhand.
SPAN (FT.)	65 x 74	85 x 118	69 x 20	Radius – 158 Arc length - 333	72 x 38	12 x 31
PLAN FORM	Polygon	Circular	69ft wide Arc	Quadrant	Rectilinear	Rectangle
FORM	Radial tent unit	Twin Saddle roof	Continuous saddle	Central arch supported	Central arch supported	Continuous saddle
FABRIC	Polyester coated with PVC	Polyester coated with PVDF	Polyester coated with PVC	Polyester coated with PVC	Polyester coated with PVC	PTFE
SUPPORT STRUCTURE	Steel mast and cables	Steel beam, triangular girded arch and cables.	Steel truss	Gridered arch and cables	Triangular Arches	Steel Trusses

3.6 Summary

The case studies clearly show the visual impact and other structural and functional advantages of tensile fabric roof structures over conventional construction. Though the offer many challenges during the process of design and construction, architect need not be a mere spectator in its development. Further on the various options in the form, material and loading are discussed as an assimilation of the knowledge gained so far.

INTERNATIONA STUDIE	 a Woods Mitchell Center For he Performing Arts	 **Canada Harbour Place, Vancouver**
SPAN (F	160 ft radius, 240 °	180 X 240
PLAN FO	cular array of three sectors	Linear arrangement of rectangular bays
FORM	itive paneled tent forms	Wave form
FABRI	lon coated fiberglass	Teflon coated fiberglass
SUPPORT STR	el columns, struts and trussed steel, A-frames.	Steel masts and cables

CHAPTER 4

DESIGN APPROACH

The various aspects of tensile fabric roof structures concerning the architect are discussed; based on the analysis of information in the earlier chapters. The design of forms that are essentially double curved has been elaborated.

NATIONAL CASE STUDIES	 all,	 Cross River Mall, New Delhi.	 Ranchi Stadium, Jharkhand.
SPAN (FT.)		72 x 38	12 x 31
PLAN FORM		Rectilinear	Rectangle
FORM	rted	Central arch supported	Continuous saddle
FABRIC	vith	Polyester coated with PVC	PTFE
SUPPORT STRUCTURE	d	Triangular Arches	Steel Trusses

4.1 GENERAL

The chapter gives an approach towards designing a tensile fabric roof structure until the structure can be fine tuned by a structural engineer. By following these steps, any architect is supposed to get an idea of the form, support structures and hence the visual, structural and financial implication it might lead to, thus helping the architect in taking vital decisions with regards his tensile fabric roof structure. As part of the approach; basic forms, the various fabric options currently available and support conditions are discussed.

While conceptualizing the project the space that is to be covered by the tensile fabric roof has to be identified in the initial stage. The fabric roof can cover a part of the building (like for eg. Select City Walk) or be the principle roof for a structure (like for eg. Deccan Harvest). In case of the latter, more freedom can be exercised with the support structures; in the former case, deciding on the form and supports earlier will help in synchronizing the support structure of the building with that of the tensile fabric roof structure; else it might result in expensive and unsightly additional supports, further the fabric roof form needs to be in harmony with the rest of the built form.

The form of the tensile fabric roof depends on the plan form and span, from the case studies, the largest unsupported length will be in the range of 40m. Based on the case studies and many examples, the following basic forms are have been identified and developed.

4.2 BASIC FORMS

Technically speaking, the surface form of a tensile structure can best be described as a graphic representation of a complex field of forces in equilibrium. Mathematically, it is represented most conveniently by a net of intersecting force lines. When correctly shaped, the forces in all the lines intersecting at any node are in equilibrium, with the weight of the structure acting on this node. Once the support conditions and the laws governing the force pattern are established, the form of a tensile structure will follow.

Architecturally speaking, depending on the project type and spaces the form can be decided based on the spanning and support conditions. A single form might not work for large spans, as it might require larger prestressing resulting in bulky support structures to prevent a huge sag in the curvature. The forms of the tensile fabric roof structures can be primarily categorized into five; for the sake of convenience, the first four are characterized by their appearance, and the final one by its support.

- Single Saddle Form
- Radial Tent Form
- Paneled Tent Form
- Wave Form
- Central Arch Supported Form

All the forms achieved are combinations and modifications of these basic shapes. They are either designed as a single entity or as repetitive modules depending on the span and support.

The support elements are always a series of compression and tension elements. Now if an architect knows the span a single entity of particular shape can support and the support elements that go with it, he can decide on the form based on the usage and budget allotted. The support elements can be played with to obtain interesting forms. The work of Prof. Dr. Eng. M. Mollaert, Department of

Architecture, Vrije Universiteit Brussel,[28] helped in the understanding and development of the following forms.

Single Saddle Form:

If we consider two lines to be cables in a roof structure, and turn the lower cable by 90degree to run across the upper one, we will achieve a stable point at their intersection. Adding two more tie-down cables parallel to the first will generate two more stable intersection points. The addition of edge cables placed between the upper and lower support points begins to turn this arrangement into a two way cable-net. It is in turn completed using denser set of cables, parallel to the original ones, in each direction.

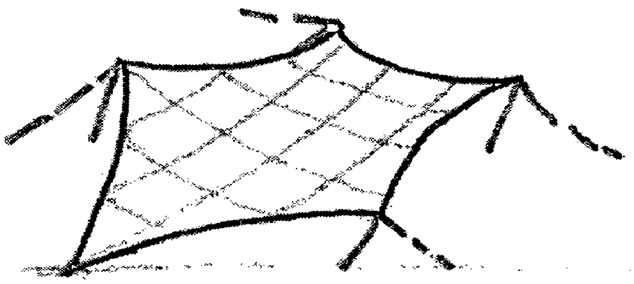


Fig 4.1 Point Supported Saddle Roof

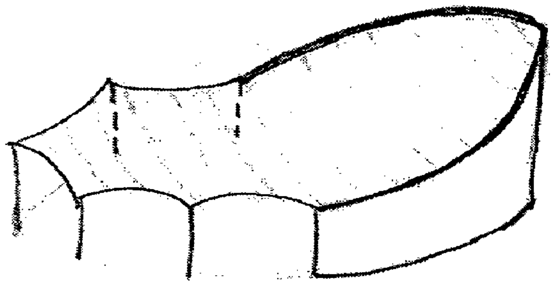


Fig 4.2 Point and continuous supported saddle roof

We have now arrived at a two way cable net structure which has one unique characteristic: any two cables which meet at an intersection point, or node, are bent in opposite directions, one pulling downward, one pulling upward, and thereby exerting pressure against each other. This is a four point structure, which is the simplest form of a saddle shape. [1] If the surface is not a cable net but a continuous fabric membrane, in the structural analysis the net lines shown will represent strips of fabric. Hence a saddle surface can be any fabric element spanning four support elements like arches, cables etc.

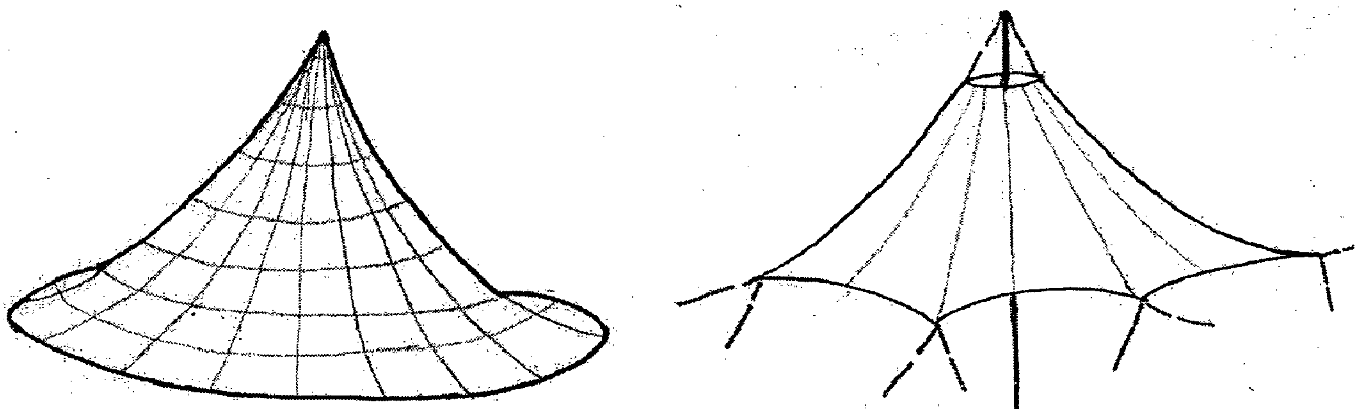
- A saddle roof is always supported along its edges, there are no supports in-between the fabric surface like an arch or a mast etc.

- A saddle roof has a minimum of four support points. These points are in turn a combination of high and low points with at least one high point.
- A saddle can also have a continuous edge support like a compression arch.
- A saddle surface can also have a combination of edge supports like an arch and a point support.

Radial Tent Form:

A spider's web is nature's very own example of a sturdy tensile structure; the spider starts as a line between two supports then the third line starts from the middle of the first line and the other lines radiate closely followed by the spirals. The strands are adequately pretensioned at the supports and the web is ready for the prey. If a small mast pushes the net upward in the third dimension at its center, the radial tent form is obtained i.e. the interior support is a compression member.

The fact that the ring lines are self-contained is a main advantage of the radial tent structure. They require no costly end connections. A great variety of structures can also be composed using the radial tent as principal module.



(a) Fig 4.3 Radial Tent Form (b)

- Radial tent units consist of radiating fabric lines from the high point to the edges.

- One radial tent unit will have only one high point, however two or more radial tent units can be combined to have a number of high points.
- In case of inverted radial tent units, each unit will have only one low point.
- The outer end, or edge point, needs to be connected to another member- a beam, arch or cable – for further transmission of its end forces to fixed supports.

Paneled Tent Form:

- A paneled tent unit will consist of a tent form with a single high point and a minimum of three panels of anticlastic fabric surface joined at the seam.
- The ridge lines formed by the joining of these panels will radiate from the high point to the edges.
- Panel tent forms can be combined to have more than one high point.
- An inverted paneled tent forms will have only one low point while in combination can have more than one low point.

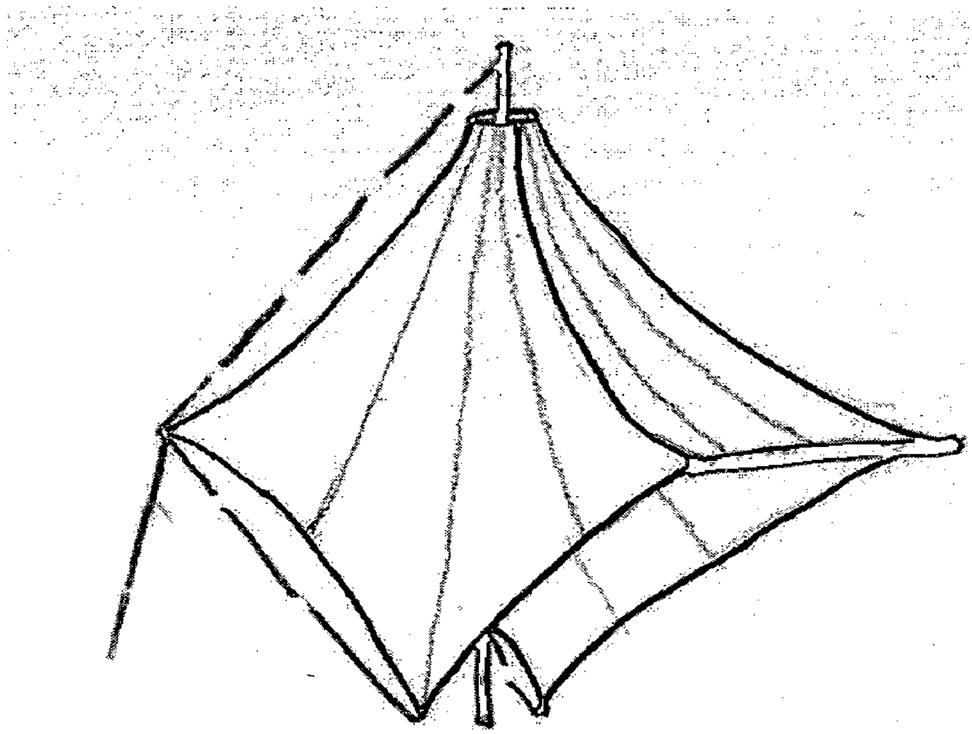


Fig 4.4 Paneled Tent Form

Wave Form:

This form is characterized by the undulating surface of the wave. A form can be categorized as wave if it has,

- Alternating lines of ridge or upward cables and valley or downward cables.
- They have alternating support and anchor points generating a surface that rises and falls i.e. the load bearing and tensioning cables are parallel.
- There are only two sets of high and low points on a side.
- The variation between heights of consecutive high points or consecutive low points does not deviate to a large extent. i.e. the deviation does not affect the profile of the form

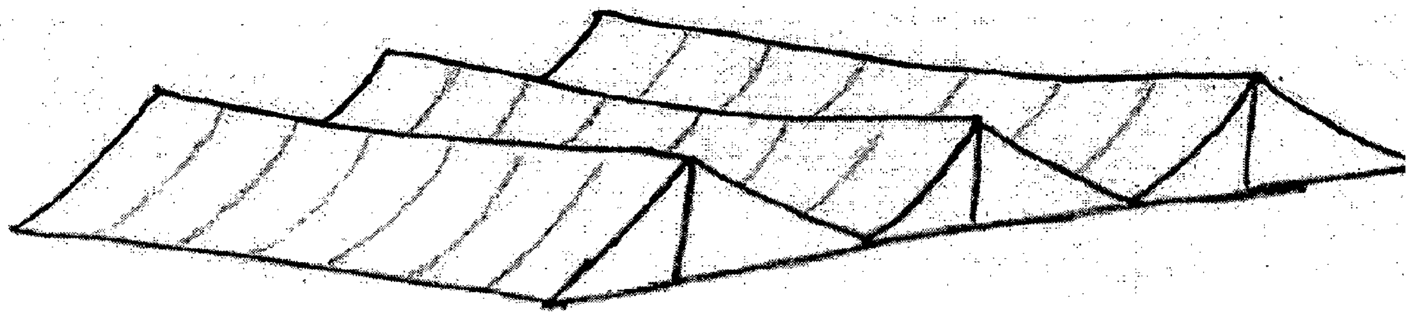


Fig 4.5 Wave Form

Central Arch Supported Forms:

Forms in which arches that are not placed on the edge, but within the form, as a support structure are called central supported arch forms. It may have a single, a series or a combination of arches.

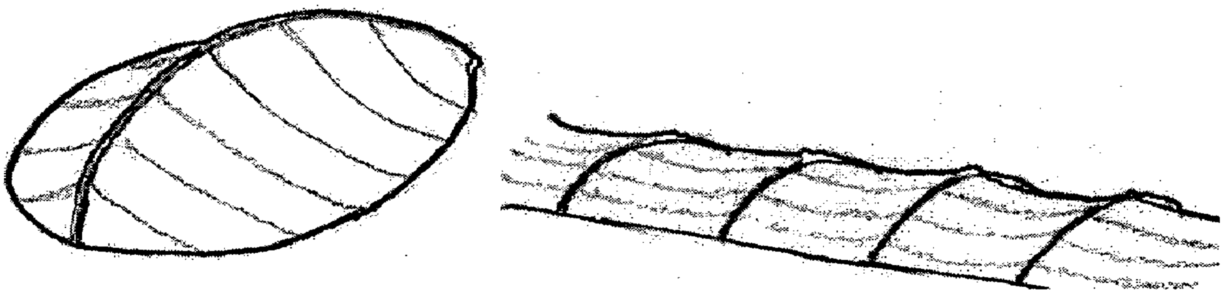


Fig 4.6 Central Arch Supported Form

- A central arch supported form will have an arch as a principal support structure, which is not an edge support.
- The arches can be supporting the fabric structure internally or externally.
- There can be more than one arch supporting the fabric.
- The arches can be parallel or connected.

4.3 CHOICE OF SUPPORT STRUCTURES

Although the fabric forms the primary component of the tensile fabric roofs, the support structures hold it in place and give it the form it takes. The decision on the form and the support structures is not independent of each other; the form is conceived considering the supports that will help take the form. There is no exhaustive list of support components, but there are a few elements that find prominence in many past fabric roof structures and hence have become common options with the fabric roofs.

Cables are a part of almost all tensile fabric roofs; their flexibility compliments that of the fabric and helps in anchoring the fabric in position. It usually forms the link between the fabric and other rigid structural elements, like columns and masts. The role of cables has been discussed in Chapter 2.3.3.

Fabric roofs have a combination of high points and low points, based on the site conditions, these points and edge conditions are achieved with the help of rigid elements. Masts are a common option as point supports, more recently flying masts are used as a compression element, especially in places where a central high point has to be achieved without disturbing the floor space.

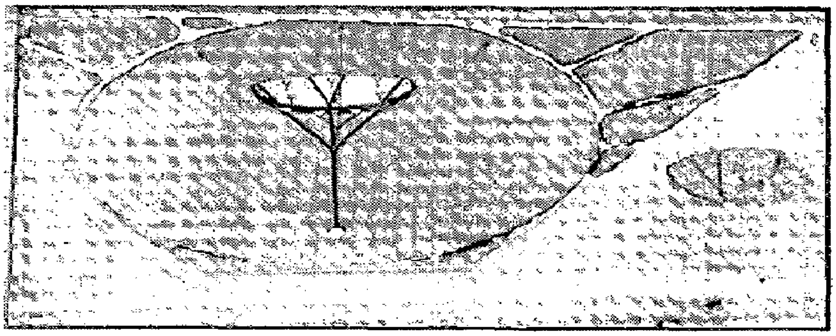


Fig 4.7 Flying Mast

Arches are continuous supports, which provide for two low points and a high point without the need for a central support. They can act as edge supports also. Arches can support the fabric above it or hold them below.

Trusses are a common sight now in fabric roof structures as horizontal and vertical members, and also as 'A-frames'. They give a heavier appearance to the support structure. A-frames also like arches give a combination of high and low points, though they support the fabric only from outside i.e. the fabric hangs below the frames.

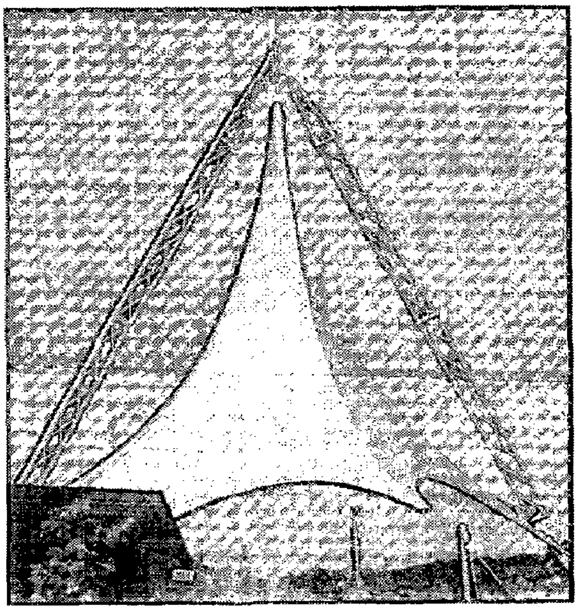


Fig 4.8 A- Frames

The supporting structures can be as innovative as the fabric forms itself. The use of a few of these and other support structures can be seen in Chapter 3 and Chapter 5.2.

4.4 FABRIC OPTIONS:

After the form and supports are frozen, the choice of the fabric is to be made. The choice of fabrics is not very wide. PVC coated fabrics are usually used for temporary structures, Teflon used for permanent buildings in the last two decades, a recent development for permanent structures is the silicone coated fiberglass fabric. [1, 14, 21, 26]

Sample Materials

Polyester fabrics with PVC coatings – by far the least expensive materials available may last 15 to 20 years if special precautions are taken to protect the polyester against ultra-violet rays. Because these materials are combustible, fire safety will depend on the mechanism by which seams will open. Dirt resistance requires special surface finishes.

Teflon-coated fiberglass has become the primary material for tensile architecture now; chemically both Teflon coating and glass fibers are totally inert. To avoid dangerous surface tension, fiberglass requires protection against moisture, and because Teflon is a relatively rigid substance with minute hair cracks, moisture protection is provided by an undercoat of silicone. Teflon coated fiberglass is noncombustible, very easy to keep clean, highly reflective and highly translucent. Teflon coated fiber glass fabrics should have a life span of 25 to 30 years, but suffer disadvantages of high initial cost, difficult handling due to the stiffness of the fabric, low tear strengths, and highly nonlinear behavior at low stress.

Silicone forms the basis of both the fiberglass threads of the fabric, and the silicone rubber of the coating of **silicone-coated fiberglass**. This similarity in chemical structure allows the design of highly translucent fabrics, while the water protection provided by the silicon rubber coating assures long life for the fiber glass. With regard to cost and handling, silicone/fiberglass lies somewhere between Teflon/fiberglass and PVC/polyester.

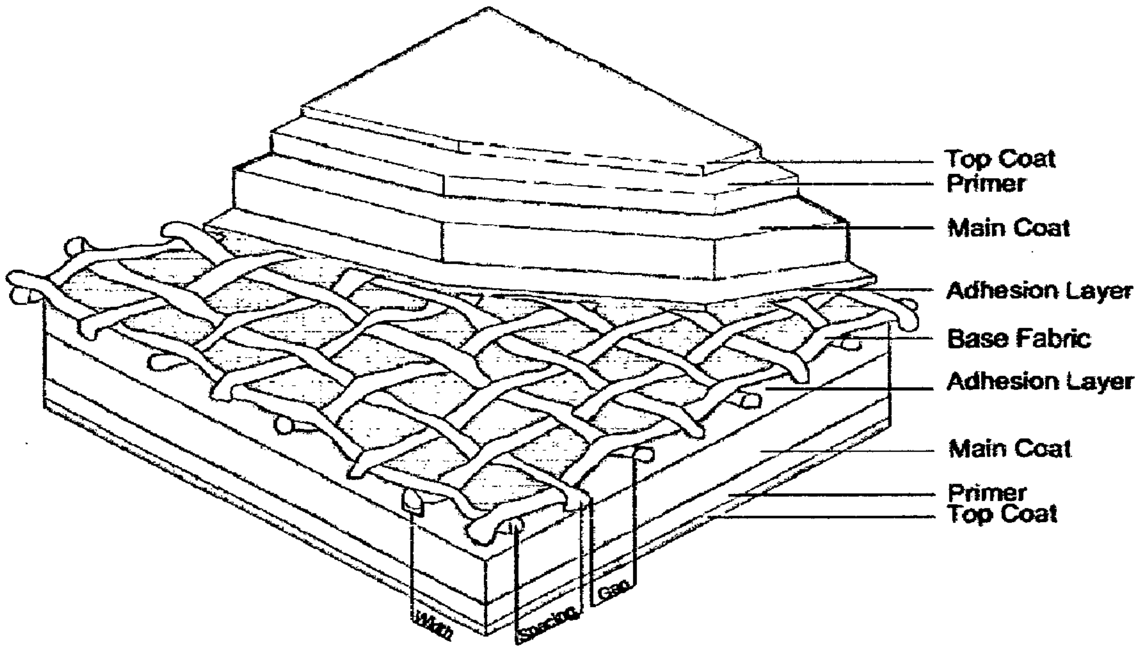


Fig 4.9 Layers of a Fabric

In India, prominent structures have just now begun to come up, and due to the non-availability of dependable fabric manufacturers the fabric is imported. The fabric thus used is mostly sourced from Germany and France. This usually comes in 200m long rolls which are 1.8m to 2.7m wide. So far, no special consideration has been given to the surface coating, the preset coatings of the suppliers are used as such. The specifications of the fabric types often used in India are tabulated below. The last table, listing out the specifications of PTFE-teflon coated fabric architectural membrane is to give an idea of the Teflon coated fabric used extensively abroad. They are preferred for structures requiring longer life span.

Table 4.1: **FERRARI 1002S FABRIC**

Technical Specifications	Precontraint 1002 Formula S
Yarn	Pes HT 1100 Dtex
Total Mass	1050 g/sqm
Width	180 cm
Tensile Strength (warp/weft)	4200/4000 N/5 cm
Tear Strength (warp/weft)	550/500 N 60
Adhesion	120 N/5 cm
Flame retardancy	B1/DIN 4102 NFPA 701 – UNE 232727 90 – SN 1988 98 BS 78 – CSFM – SIS 650082 NFP92.503
Surface Treatment	FORMULE S : Alliage PVDF CALIBRE /CALIBRATED PVDF Alloy
Light Transmission	7.5%
Global Thermal Conductivity	6.0 W /Sq.m./ °C
Coating thickness at the top of the yarns	350 microns
Total Thickness	0.78 mm
White Index	82
Thermal Values	Solar transmission Ts 6% Solar reflection Rs 78% Solar absorption As 16% Solar factor Fs 12%
UV Transmission	T-UV 0%

Note: Information obtained from *Construction Catalysers, Pune.* Some modifications made to bring uniformity.

Table 4.2: **VALMEX FR 900 PREMIUM – TYPE II**

Base fabric Support	Din 6001	PES low - wick
Yarn dtex	DIN 53830	1100
Weave		P 2/2
Type of coating		PVC
Total Weight gr /m^2	DIN 53352	900
Tensile Strength Warp / weft N/ 50 mm	DIN 53354	4200 / 4000
Tensile Elongation Warp / weft	DIN 53354	20 / 26
Tear Strength Warp / weft N	DIN 53363	500 / 450
Adhesion N / c	Complan Richtlinien	> 20
Cold resistance ^{0}C	DIN 53361	- 30
Heat resistance ^{0}C	Complan Richtlinien	70
Light – fastness Note	DIN 54004	> 6
Crack – resistance 100.000	DIN 53359 A	O.K
Flame Retardancy	DIN 4102 B1, CSE – RF –1 / 75 C2, California T 19, BS 7837, NFP 92 507 M2 (only for white colour)	
Finish	PVDF Lacquer top coat – lacquer on the reverse side protected against fungal and microbial attack, UV protected	

Note: Information obtained from *Construction Catalysers, Pune.* Some modifications made to brind uniformity.

Table 4.3: **VALMEX FR 1400 PREMIUM – TYPE IV**

Base fabric Support	Din 6001	PES
Yarn dtex	DIN 53830	1670
Weave		P 3/3
Type of coating		PVC
Total Weight gr/m^2	DIN 53352	1400
Tensile Strength Warp / weft N/ 50 mm	DIN 53354	7500 / 6500
Tensile Elongation Warp / weft	DIN 53354	20 / 30
Tear Strength Warp / weft N	DIN 53363	1200 / 1200
Adhesion N / c	Complan Richtlinien	25
Cold resistance ^{0}C	DIN 53361	- 30
Heat resistance ^{0} C	Complan Richtlinien	70
Light – fastness Note	DIN 54004	> 6
Crack – resistance 100.000	DIN 53359 A	O.K
Flame Retardancy	DIN 4102 B1	
Finish	PVDF Lacquer top coat – lacquer on the reverse side protected against fungal and microbial attack, UV protected	

Note: Information obtained from *Construction Catalysers, Pune.* Some modifications made to bring uniformity.

Table 4.4: **PTFE-TEFLON COATED FABRIC ARCHITECTURAL MEMBRANE.**
HEAVY WEIGHT TYPICAL PROPERTIES OUTER MEMBRANE

Typical Properties	HCH-AR 100	HCH-AR 080	HCH-AR 075	HCH-AR 060	HCH-AR E100
Thickness Fabric (mm)	1.10±0.10	0.82±0.08	0.75±0.08	0.60±0.08	1.20±0.15
Coated Fabric Weight (g/m 2)	1590±150	1330±125	1300±125	1030±98	1250±125
Density (25mm/pc)	20x19±1	26x19±1	22 x 19±1	34 x 22±1	20 x 20±1
Tensile Strength (N/cm)	1672x1600	1372x1098	1285 x 1160	930x910	1150x1150
Elongation (%) below	12x17	7x10	9x14	13x15	6x8
Tearing off Intensity (N)	363 x 463	272 x 263	226 x 226	138 x 136	325x325
Scale off intensity (N/cm)	27	25	24	24	24
Solar Transmission, %	11±2	14±3	17±3	18±3	26±3
Solar Reflectance, %	70±10	75±10	75±10	75±10	70±10
Burning Characteristics Flame Spread Smoke Generation	5 max. 5 max.	5 max. 10 max	5 max. 20 max	5 max. 20 max	5 max. 10 max
Incombustibility of Substrates	Pass	Pass	Pass	Pass	Pass
Fire Resistance of Roof Coverings Burning Brand	Class A	Class A	Class A	Class A	Class A

Note: Information obtained from *http://www.teflon-tapes.com/pdf/02_hch_ar.pdf.* Some modifications made to bring uniformity.

4.5 LOADS:

After all the above mentioned aspects have been taken care of, the following loading issues have to be considered while designing the tensile fabric roof structures. They will help in the approximate sizing of the structures, and hence give an idea of the costs and quantity to be incurred. The application of the appropriate loads in design will be seen in the following chapter.

- Dead loads:

  The self weight of the fabric is insignificant when compared to the bulky conventional construction. However the support structures might have significant dead load.

- Imposed Load

  The tensile fabric roof is not designed for occupancy, however the weight of a man should be considered for maintenance purposes.

- Wind load

  Wind load is a very important consideration in the stressing of the fabric in the design of tensile fabric roof structures. The fabric is considered to be subject mainly to this loading after erection. Bracing is to be provided appropriately.

- Seismic load

  The fabric being very light weight is not directly affected by seismic loading, but the support structures like columns, masts, arches etc will have to be designed for seismic safety.

- Precipitation load

  Precipitation load is a significant loading criteria in the stressing of fabrics when located in places subject to heavy rain and snowfall. Care should be taken that the rain and snow does not accumulate and weaken the fabric.

- Temperature Effects

  Expansion and contraction due to changes in temperature is an important issue in the cutting pattern generation of the fabric. Compensation is applied in the cutting pattern process considering elongation of the fabric during stressing. Similarly compensation relative to temperature changes might also be necessary depending on the physical properties of the fabric.

After deciding on the loading that the fabric will be subjected to, which in the case of India will mainly be wind load, (the self weight of the fabric is negligible) design pressure and the pressure co-efficients have to be figured out first from the National Building Code. A minimum live load of 40 kg/m^2 may be considered, in case a person has to access the roof for cleaning or repair purposes. Following this step the force analysis of the fabric panel is done and the pretension is determined. Now for the forces in the fabric, the supporting structures are analysed and designed. The building codes can be used for all these issues.

4.6 END & EDGE CONNECTIONS

The end and edge connections discussed here are typical for fabrics.Fabrics can have only point end connections or continuous edge connections to the support structures, the details corresponding to these connections are given below. Apart from this, a fabric panel connects to another fabric panel through seams; the welding process is discussed in Chapter 2.3.1.

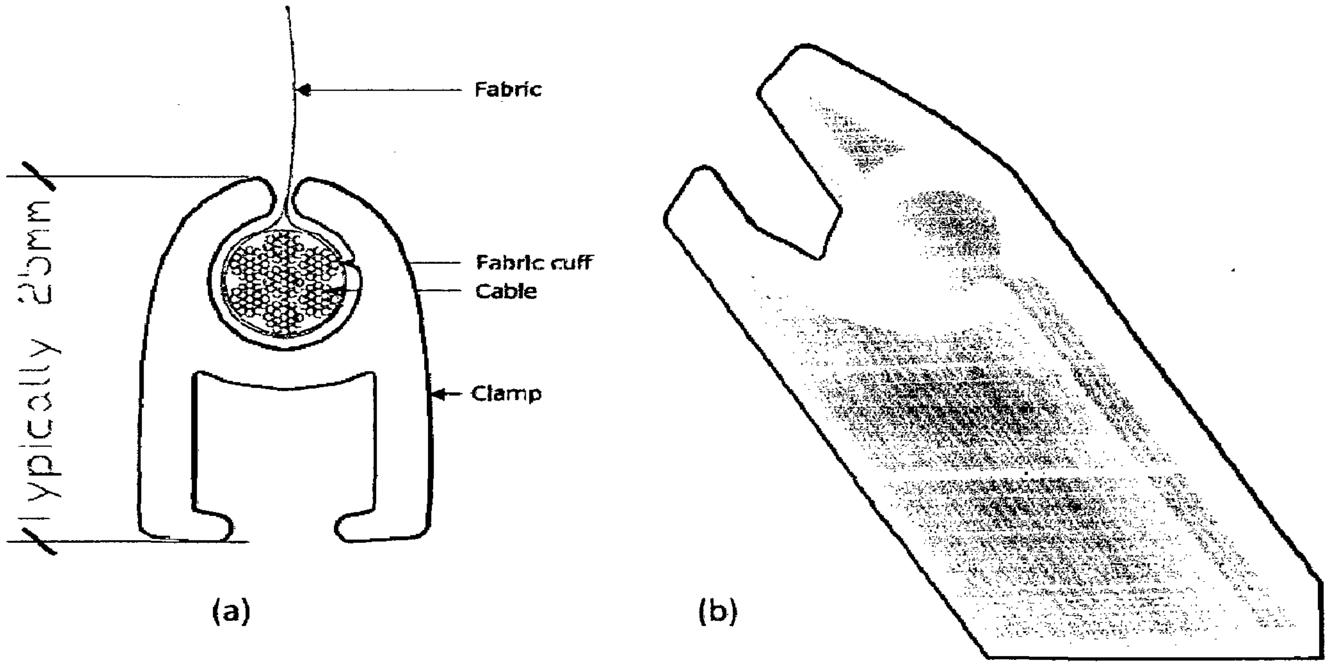
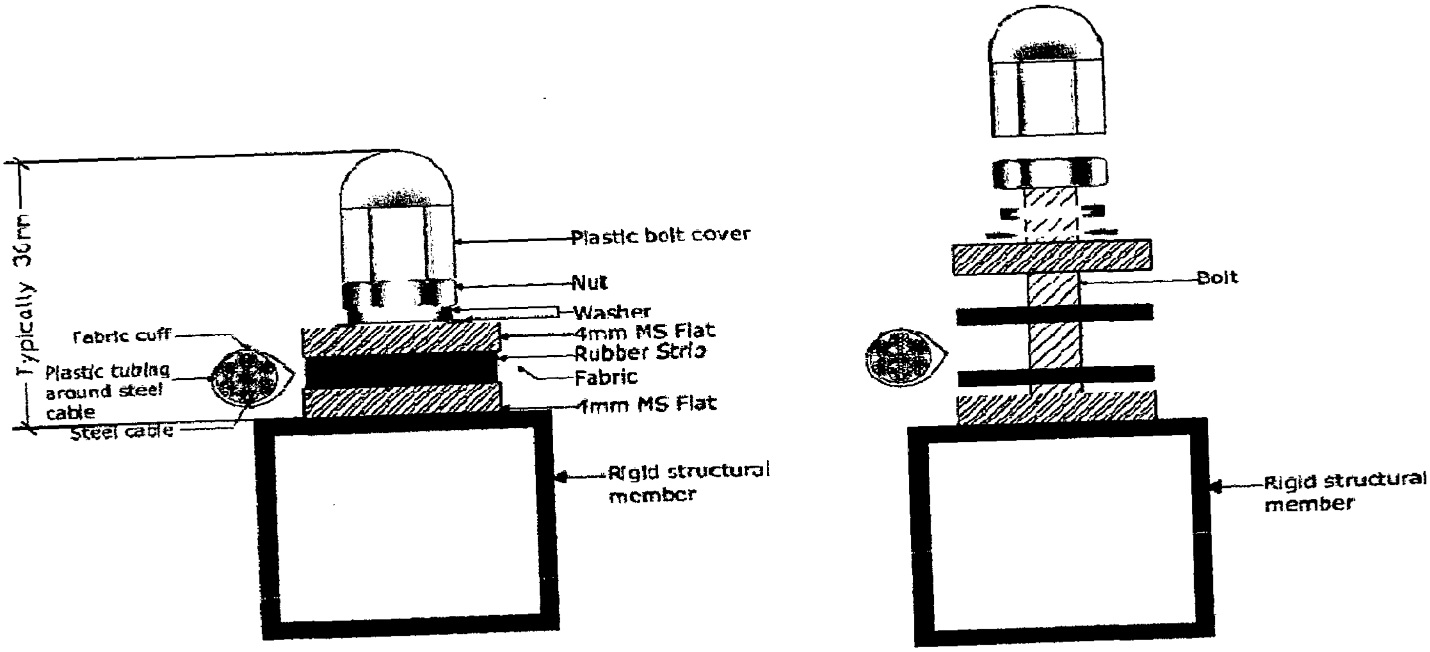


Fig 4.10 Edge Connection – Continuous Clamp



(a) Fig 4.11 Edge Connection – Fabric to Cable (b)

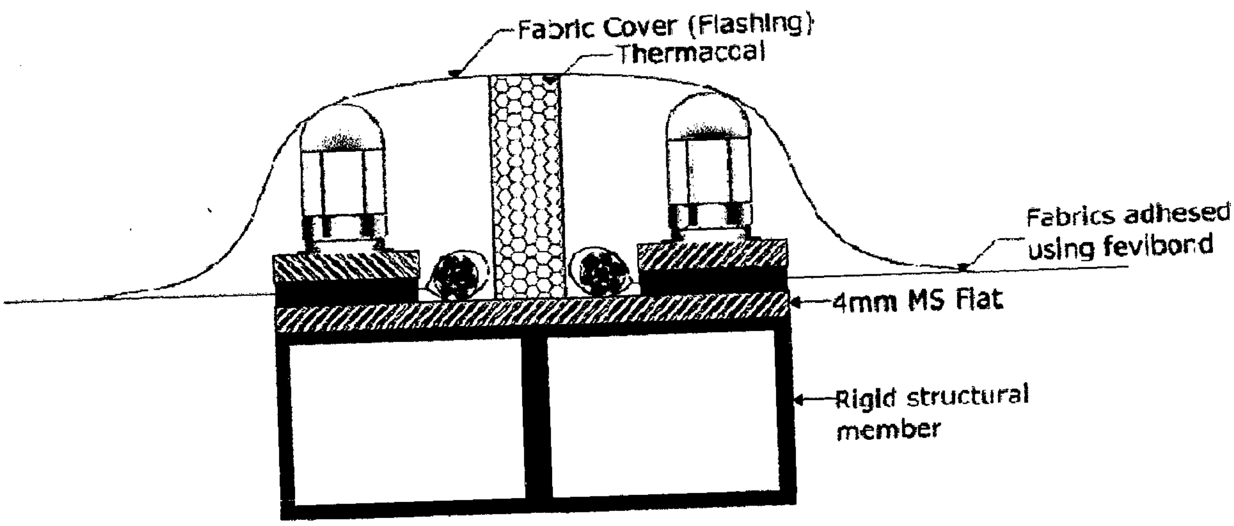


Fig 4.12 Flashing

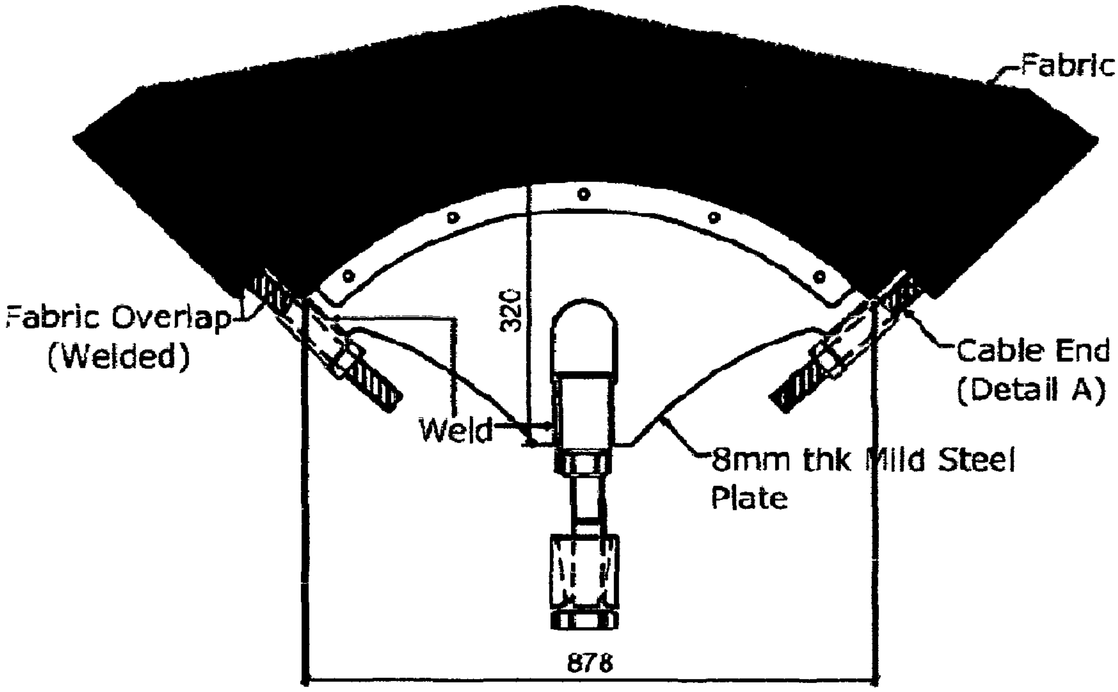


Fig 4.13 Fabric Clamping – End Point Anchorage
(Deccan Harvest, Pune. Refer:Chapter 3.3.1)

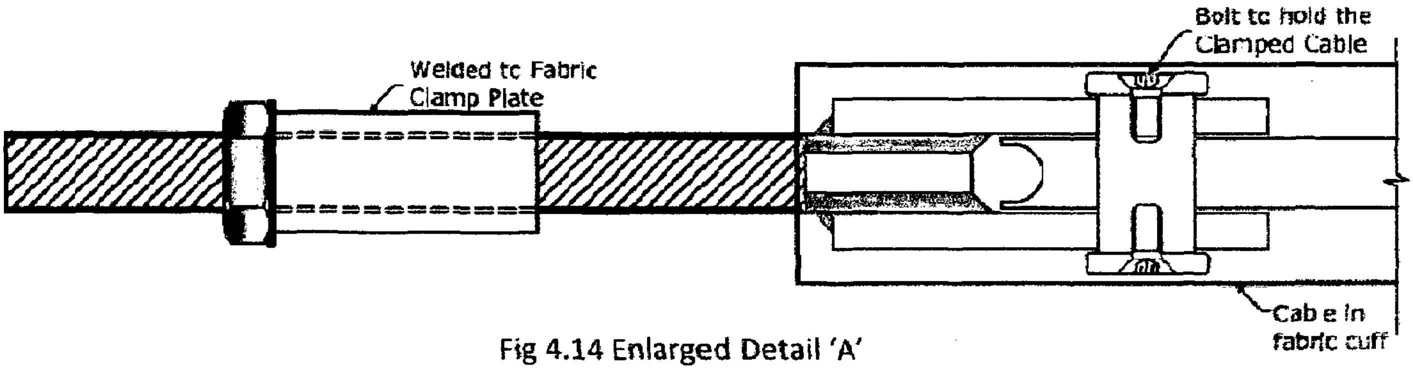


Fig 4.14 Enlarged Detail 'A'

Chapter 5

Application of the Approach

With the understanding of the forms, materials and the construction assembly techniques that go with it, alternative tensile fabric roof forms for an existing structure is attempted.

5.1 GENERAL

The different forms, materials, supports, end and edge connections have been discussed in the earlier chapter. A study case has been taken to study the validity of the above mentioned aspects. Tensile fabric roofs are now being considered in India as prospective solutions for prominent structures like pavilions, airports and stadiums. The study case will be one such structure and tensile fabric roof forms will be designed for the same structure. The existing conventional roof will be compared on different issues to understand the benefits of each over the other.

5.2 BASE CASE

The base case is the pavilion in Major Dhyanchand stadium at IIT Roorkee. The pavilion is 32m x 11m, it is a covered seating space with toilets for spectators. It was constructed in 2007 and the roof took eight months in erection. The plan is symmetrical, a set of six steps on either side lead to the 1m high plinth from where the seating starts. The spectator seating is in the form of 450mm high steps and face east- west. Five such steps lead to a central aisle, on which, seven pairs of circular RCC columns, each measuring 450mm diameter carry a steel trussed roof. The central aisle leads to a bay on either side; the bays form the roofs of toilets below. The toilets have a separate plinth of 450mm, each toilet (one each for male and female) have two doors, one leading to the toilet from outside and the other leading from the toilet to another central aisle below, steel railings on the periphery provide safety. The nine Howe trusses stretch 10.8m across the width and are composed of channel sections, they are covered by aluminium corrugated sheets painted red on the outside. The total height of the structure is 8.6m. Without hampering the basic functions of the pavilion, two alternatives of tensile fabric roof are proposed.

The tensile fabric roof will form the principle roof of the pavilion, with all the sides open. Considering the existing design, the range of visibility in the seating and the location of toilets are quite convenient, hence no change has been attempted in these aspects.

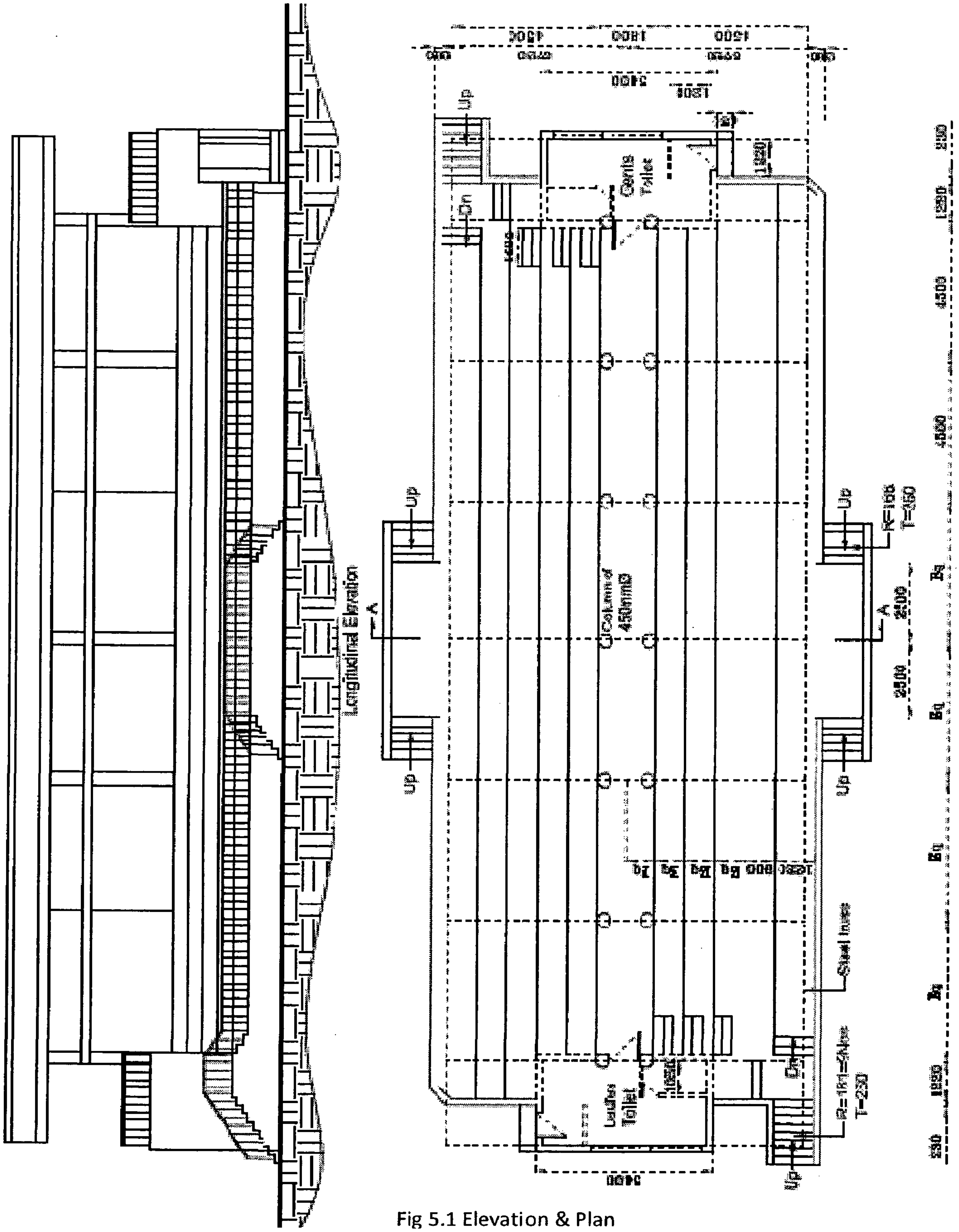


Fig 5.1 Elevation & Plan

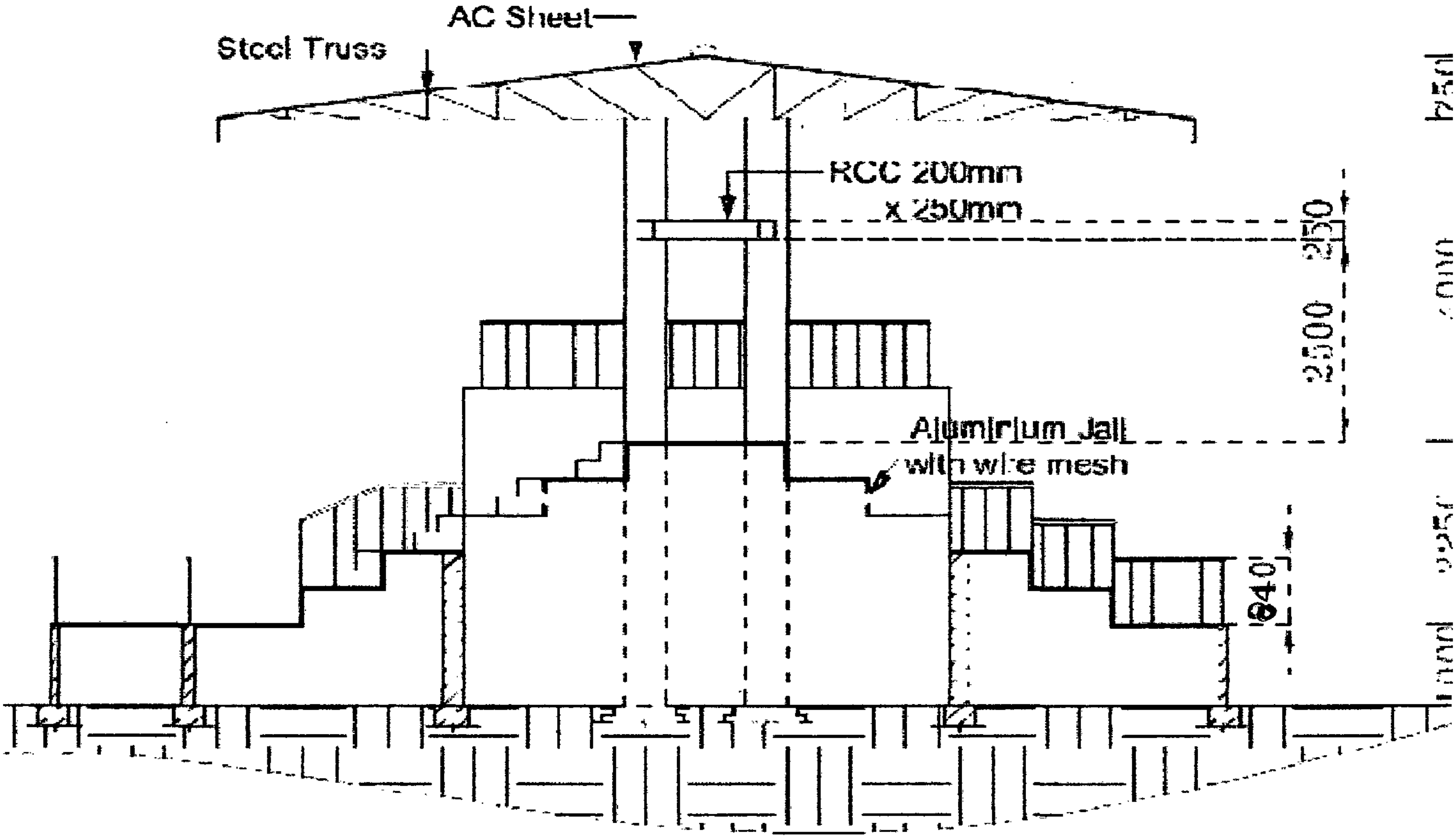


Fig 5.2 Section A-A

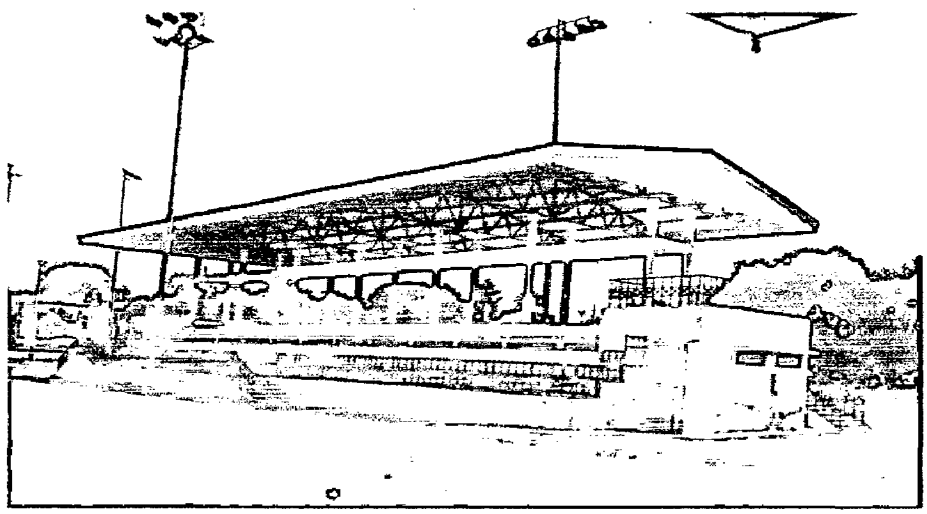


Fig 5.3 Major Dyanchand Stadium

5.3 DESIGN CASE - I

5.3.1 Form and Fabric:

The principal supporting element in this design is a central arch in the longitudinal direction. The existing columns supporting the roof are located in the central aisle. If we consider freeing this space and placing all the structural elements of the roof outside the pavilion, the central arch supported form can be an option. A single arch can be made to span the length of the pavilion in the centre as the main support. As the pavilion is meant to have all its sides open, poles placed near the corners can be used to support the edge catenaries.

Considering the use of the space i.e. the pavilion, PVC coated polyester fabric can be used for the double curved roof.

5.3.2 High points & Low points:

Now the approximate form and dimensions have to be frozen. The high points and low points have to be decided on.

In the present design, points A and B are the end points of the arch at ground level, C, D, E and F are the top of the poles at 4m. Points I and G indicate the points in the arch at 6m height from the ground and in line with the top of the poles. The fabric is not connected along the whole length of the arch; the fabric can be taken to start after 4m from both the ends i.e. the fabric stretches for 1m outside from the bay on either side. H is the top most point of the arch.

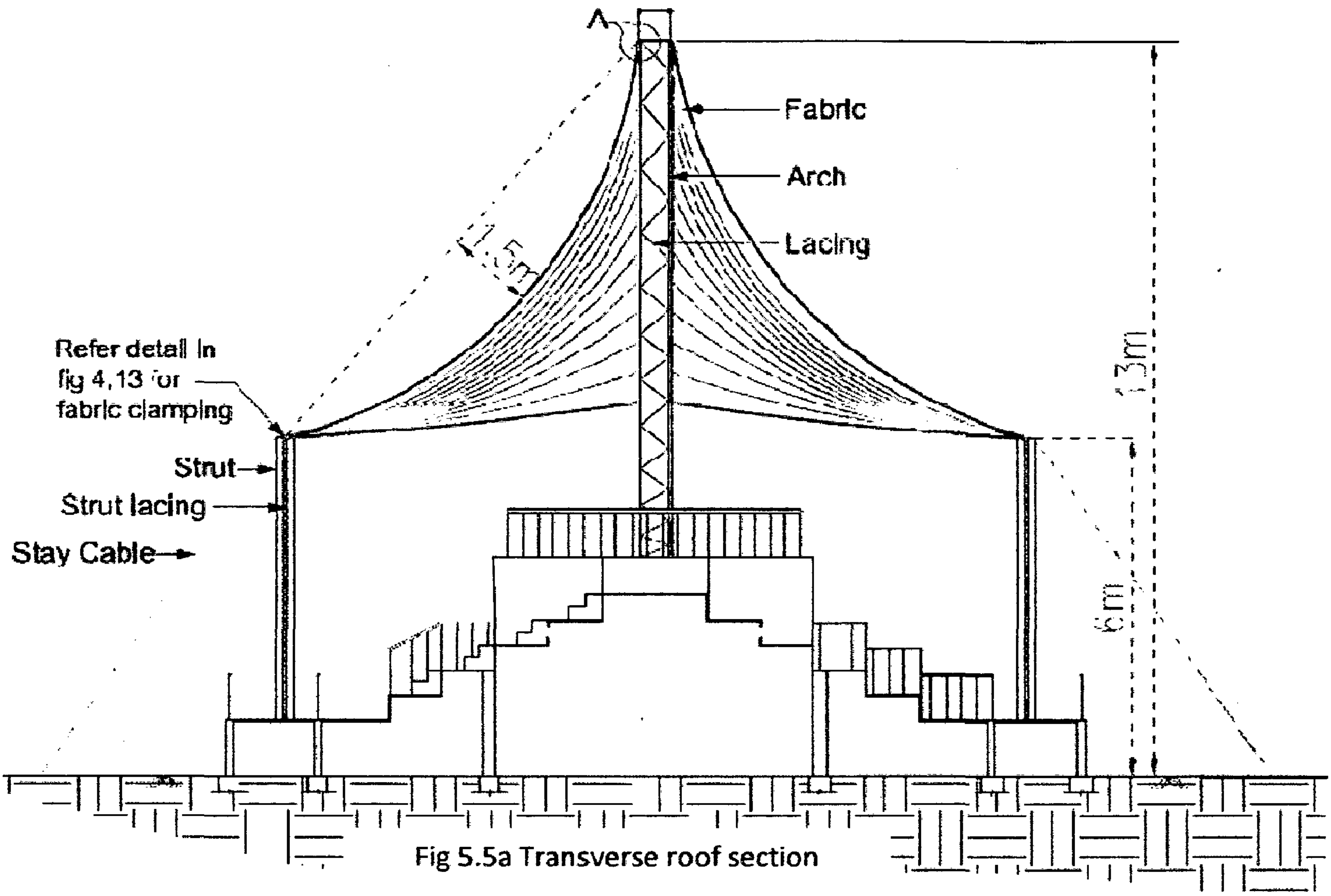


Fig 5.5a Transverse roof section

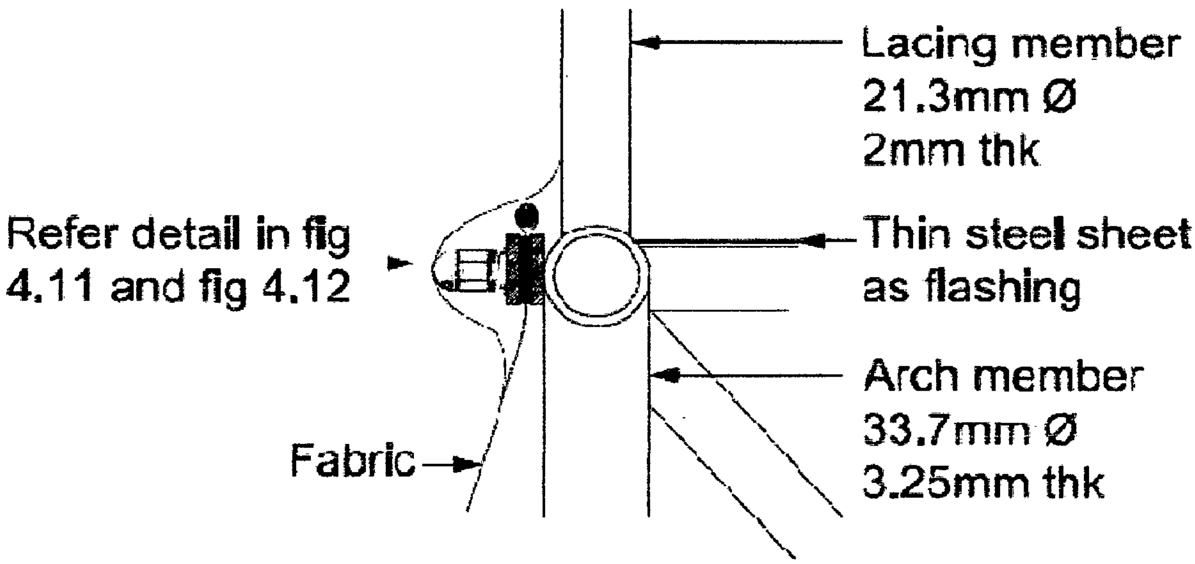


Fig 5.5b Detail A

Note: The sizing of the members is disused below

In order to determine the height H, a minimum clearance at G is taken as 6m.

If we take a section at DGE, and using the equation of the parabola,

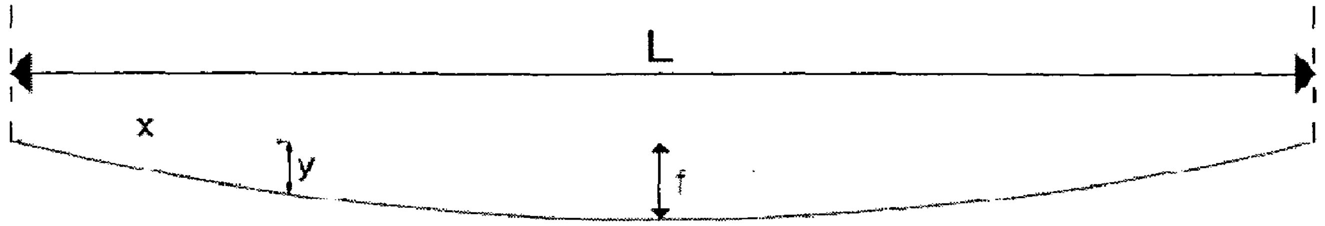


Fig 5.6 Equation of parabola

$$y = 4fx\,(L-x)/L^2 \quad \text{, at G, } x = 6m,\ y = 6m$$

$6 = 4 \times f \times 6\ (45 - 6) / 45^2$

$f = (6 \times 45^2) / (24 \times 39) = 12.98 \sim 13$

H = 13m

5.3.3 Load calculation:

Design Wind Speed is V_z

$$V_z = V_b\, k_1\, k_2\, k_3$$

(Source: Section 4.4.3, Part 6,National Building code of India (NBC) 2005)

Where **V_b = basic wind speed in m/s = 47m/s** (For Roorkee) *(Source : Fig. 1 of NBC 2005)*

k_1 = probability factor (risk coefficient) = 1 *(Source: Table 4 – All general buildings and structures NBC 2005)*

k_2 = terrain, height and structure size factor = 1.02 *(Source : Category 2 terrain, Class B and Height = 15m – Table 5 of NBC 2005)*

k_3 = topography factor = 1 *(Source: Section 4.4.3.3 of NBC 2005)*

Hence $V_z = 47 \times 1 \times 1.02 \times 1 \sim 48$ m/s

Design Wind Pressure (p_z) = 0.6 V_z^2

$p_z = 0.6 \times 48^2 = 1382$ N/m^2

External Pressure Coefficients (C_{pe}) for a canopy like the one for the pavilion, from Table 11 of NBC 2005, for a roof of angle of 45° and solidity ratio $\varphi = 0$, an extrapolation gives a value of -1.0

Note: C_{pe} can be figured out from Table 8 of NBC 2005, if the sides are enclosed.

Hence Design **Wind Load (p) = C_{pe} X p_z = -1382 N/m^2 ~ -1400 N/m^2**

5.3.4 Force analysis of the fabric:

After the heights and dimensions of the fabric roof have been decided upon, the force analysis of the fabric panel has been carried out for the above load. For this a point in the fabric panel approximately in the middle is taken and fabric strips of 1m width in both the directions are considered, to represent the roof membrane.

The fabric should have adequate tension, so as not to become slack under the above mentioned wind suction. The pretension in the fabric is therefore estimated for an equivalent load of 1400 N/m^2. This load will be shared amongst the transverse and the longitudinal strips of the fabric. Following the mathematical expressions of *Sec 3.5 of Prem Krishna: "Cable Suspended Roofs"(1978) (refer Appendix (iii))*, the **tension in the transverse strip is worked out as 4200 N/m** and that in the **longitudinal one is -12850 N/m.** The minimum tension therefore has to be 12850N/m in the longitudinal section.. Choosing Ferrari 1002s fabric.

5.3.5 Design of supports:

Now the **arch** has to be designed considering the tension in the transverse fabric strips as a load on the arch.

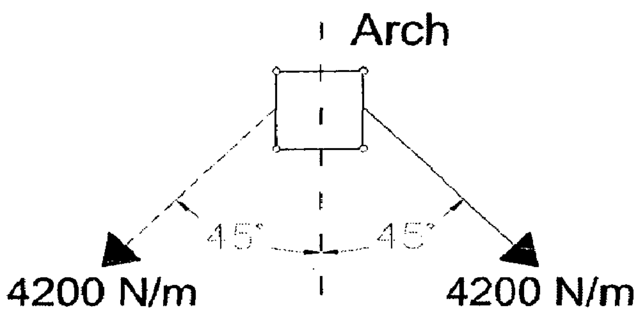


Fig 5.7 Arch section

Thus, the total load on the arch = 2 x 4200 x sin 45 = 5939 N/m ~ 6000 N/m

Hence force exerted = (6000 x 45^2) / (8x13) = 116826.9 N ~ 117 kN

Assume that the, **arch member is made up of four hollow circular steel sections connected by slacing.** The effective length (l_a) will be 22.5m and the force exerted on each hollow circular steel section will be 117000/4 = 29250 N ~ 30 kN

Slenderness ratio (λ), l_a/r = 22500/r

where r is radius of gyration = √ (I/A)

I = Moment of inertia

A = Area of cross section

Assuming the cross **section of the arch is 600mm x 600mm** with the hollow steel sections in the corners,

$\sqrt{(I/A)} = \sqrt{((4A \times 300^2)/4A)} = 300mm$

Therefore, $\lambda = l_a/r = 22500/300 = 75$

From the steel tables, the permissible stress (f_c) in axial compression for mild steel with $\lambda = 75$ is 107 N/mm^2.

Now to find the hollow circular steel section member size, $A \times f_c = 30000N$,

$$A = 30000/107 = 280.37mm2$$

Four hollow structural steel members of outside diameter = 33.7mm and t = 3.25mm can be used.

Now for the **lacing**

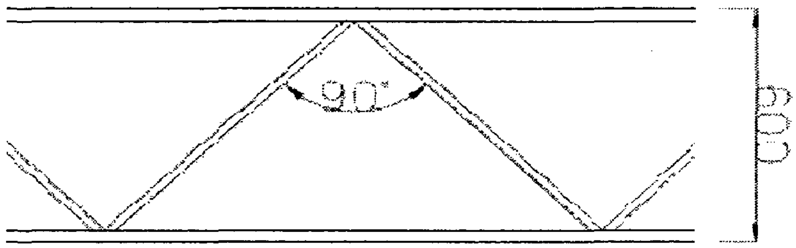


Fig 5.8 Arch lacing

Lacing is provided at an angle of 45° between the outer tubes will have a length of 566.3√2

$$l = 566.3\sqrt{2}$$

l/r should not be greater than 120

$$r = 556.3\ \sqrt{2}/120 = 6mm$$

Choose 21.3mm light structural tube.

Now considering the **base of the arch**, the four tubes should be fixed to a **steel base plate anchored by bolts.**

Resolving the force on the arch, 117kN, into horizontal and vertical components,

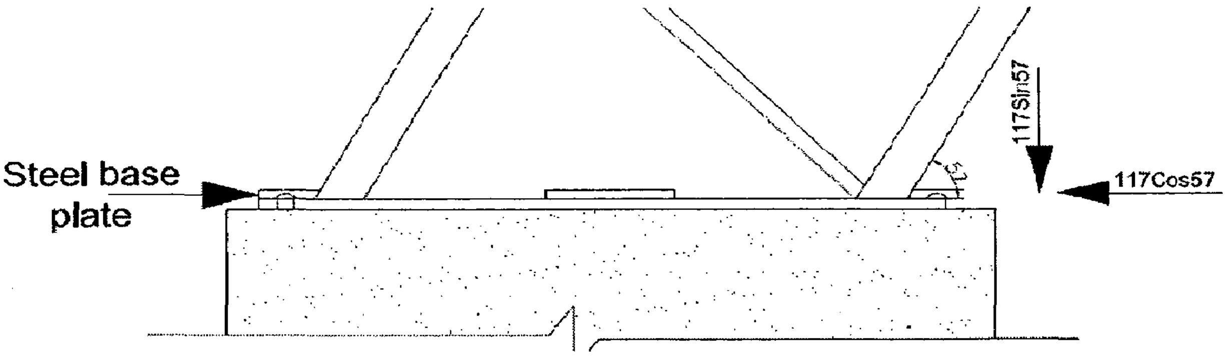


Fig 5.9 Arch base

Horizontal component = 117cos57 = 63.7kN

Vertical component = 117sin57 = 98kN

Now the shear force of 63.7kN will be taken by the anchoring bolts

Considering 4 bolts,

Shear/bolt = 63.7/4 ~ 16kN

Steel can take a shear stress = 100N/m2

Hence net area required = 16000/100 = 160mm^2

4 nos. of 20mm dia bolts are adequate.

A steel **base plate of 820mm x 820mm** with **12mm thick is provided.** Two ribs of 150mm x 6mm perpendicularly bisecting each other on the plate surface are welded.

Considering a foundation of M25 concrete, which takes 0.8 N/mm^2; For the struts, the load on the strut = 877kN

Hence area of the base = 877000 / (0.8 x 10^6) = 1.09 m^2

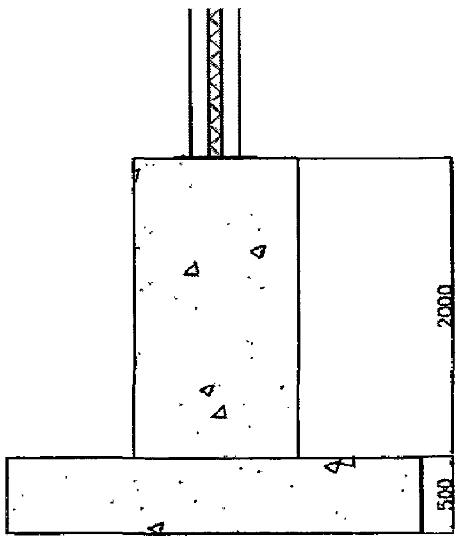


Fig 5.10 Arch Foundation

Consider the strut fixed at the base to a steel plate of 500mm x 500mm and 12mm thick, fixed to a foundation of 1m x 1m x 2m with a base of 2.5m x 2.5m x 0.5mm.

Catenary cable between points D and C,

Tension in the cable is = $(6000 \times 33^2) / (8 \times 1)$ = 816750 N ~ 816.75 kN

Minimum breaking strength required for the cable = 816.75 x 2.2 = 1796.85 kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 53.98mm can be used between DC and EF

Catenary cable between points C and I_e,

Tension in the cable is = $(12850 \times 6.1^2) / (8 \times 1)$ = 59768.56N ~ 60kN

Minimum breaking strength required for the cable = 60 x 2.2 = 132kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 11.11mm can be used between CI_e, I_eF, DG_e and G_eE

The **strut at C**, whose height is 6m, effective length (l_s) = 6000 mm

The load on the strut due to the two cables DC and CI_e is 816.75kN + 60kN = 876.75kN ~ 877kN

Assuming the **strut member to be made up of four hollow circular steel sections, placed at 300mm square plan connected by lacing**, the effective length (l_a) 6m,

$$\text{Slenderness ratio } (\lambda)\ l_a/r = 6000/r$$

$$\sqrt{(I/A)} = \sqrt{((4A \times 150^2)/4A)} = 150\text{mm}$$

$$\text{Therefore, } \lambda = l_a/r = 6000/150 = 40$$

From the steel tables, the permissible stress (f_c) in axial compression for mild steel tubes with $\lambda = 40$ is 139 N/mm^2. Force on each tube = 877/4 = 220kN

Now to find the hollow circular steel section member size, A x f_c = 220000N,

$$A = 220000/139 = 1582.7\text{mm}^2$$

Four hollow structural steel tubes of outside diameter = 114.3mm and t = 4.5mm can be used.

Now for the lacing,

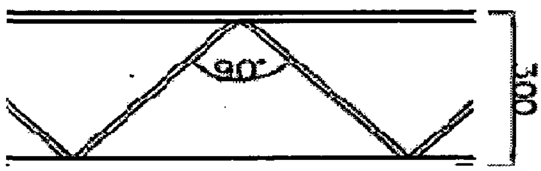


Fig 5.11 Strut lacing

Lacing at an angle of 45° between the rods will have a length of 185.7√2.

l = 185.7√2

l/r should not be greater than 145

$$r = 185.7\sqrt{2}/145 = 1.1\text{mm}$$

Choose a minimum of 12mm dia mild steel bar.

Now considering the stay cables to hold the strut at C in place,

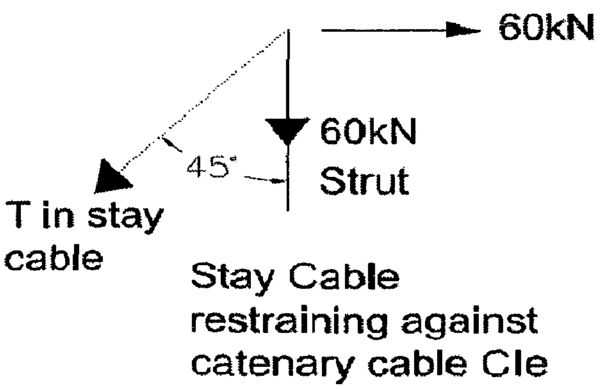


Fig 5.12a Stay cable

$$T \sin 45^0 = 60\text{kN}$$

$$T = 84.9\text{kN} \sim 85\text{kN}$$

Minimum breaking strength required for the cable = 85 x 2.2 = 187kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 17.46mm can be used at struts C, D, E & F to restrain them against cables CI_e, DG_e, G_eE and I_eF.

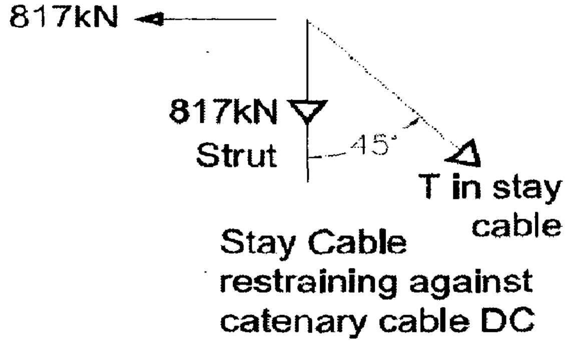


Fig 5.12b Stay cable

In the perpendicular direction, T $\sin 45^0$ = 817kN

T ~ 1155kN

Minimum breaking strength required for the cable = 1155 x 2.2 = 2541kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 63.5mm can be used at struts C, D, E & F to restrain them against cables DC and EF.

5.3.6 ESTIMATION:

The approximate estimation of the quantity of materials in the roof will help in having an idea of the cost component of the design.

5.3.6.1 Fabric:

In order to quantify the fabric, the dimensions of the fabric have to be calculated, the length can be calculated as below,

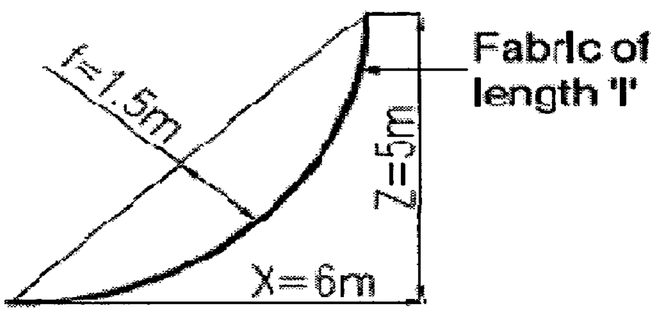


Fig 5.12 Fabric length

$$\textbf{Length, } l = X\,[\,1 + (8f^2/3X^2) + (Z^2/2X^2)]$$

(Source:P 33, of "Cable Suspended Roofs", Prem Krishna, 1978)

The value of Z reduces from a maximum of 7m at the middle of the arch to a minimum of 3m at the end; hence an average of 5m is taken as the value of Z.

$$= 6\,[\,1 + ((8 \times 1.5^2)/(3 \times 6^2)) + (5^2/(2 \times 6^2))]$$

$$= 6\,[\,1.16 + 0.35\,]$$

$$= 9\text{m}$$

Area of fabric on both sides = 9 x 33 x 2 = 594 sqm

5.3.6.2 Cables:

- **Longitudinal cables:**

These are the cables that run between DC and EF

In the same equation above, which is used to calculate the length of the fabric, the value of Z becomes zero.

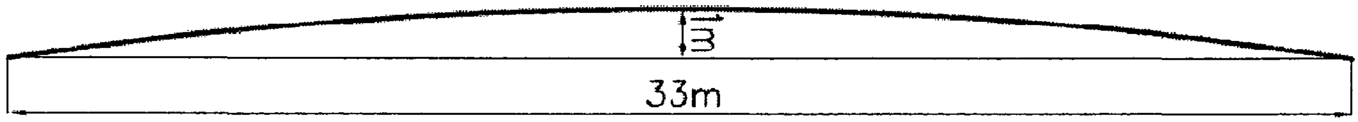


Fig 5.14a Cable length

$$\textbf{Length, } l = X\,[\,1 + (8f^2/3X^2)]$$

$$l = 33\,[\,1 + (8 \times 1^2)/(3 \times 33^2)]$$

$$\sim 33.1 \text{ m}$$

53.98mm diameter cable has a weight of 112.7N/m

Weight of the two longitudinal cables = 33.1 x 112.7 x 2 = 7460N

- **Transverse cables:**

These are the cables that run between CI_e, I_eF, DG_e and G_eE

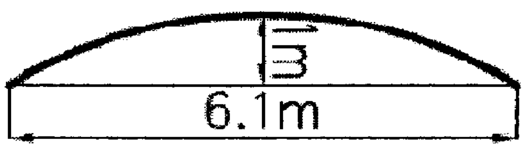


Fig 5.14b Cable length

$$l = 6.1\,[\,1 + (8 \times 1^2)/(3 \times 6.1^2)]$$

$$\sim 6.5 \text{ m}$$

11.11mm diameter cable has a weight of 4.7N/m

Weight of the four transverse cables = 6.5 x 4.7 x 4 = 122N

- **Back stays of strut:**

These cables are the ones that hold the struts in place. The struts are of 4m height, hence the length of cables which are inclined at 45^0 will be;

$$l = 4\sqrt{2} \sim 5.66m$$

17.46mm diameter cable stay has a weight of 11.56N/m is

Weight of cable = 11.56 x 5.66 x 4 = **262N**

Cable weight of 63.5mm diameter cable stay having a weight of 154.5N/m is

154.5 x 5.66 x 4 = **3496N**

Total weight of the cables = 7460 + 122 + 262 + 3496 = 11340N

5.3.6.3 Arch:

Similar to the cables, length of the parabolic arch, $l = X [1 + (8f^2/3X^2)]$

$$l = 45 [1 + (8 \times 13^2) / (3 \times 45^2)] \sim 55m$$

Four tubes of 33.7mm outer diameter and 3.25mm thick having a weight of 24.4N/m

Weight of four hollow steel sections = 24.4 x 55 x 4 = 5358N

Number of bracings on all four sides = 55 x 1000 x 4 / 565 ~ 388

Bracing of tube size 21.3mm diameter and 2mm thick having a weight of 9.5 N/m, has a **weight = 388 x 800 x 9.5 / 1000 = 2948 N**

5.3.6.4 Struts:

Length of a strut, l = 6m

Four tubes of 114.3mm outer diameter and 4.5mm thick having a weight of 121 N/m

Have a weight = 6 x 121 x 4 = **2904N**

Number of bracings on all four sides = 6000 x 4 / 265 ~ 92

Bracing on all four sides of tube having length 262.6mm, 21.3mm diameter and 2mm thick having a weight of 9.5 N/m

Bracing weight = 92 x 262.6 x 9.5/1000 = 224 N

Total weight of steel = 5358 + 2948 + 2904 +224 = 11434N

5.3.6.5 Foundation:

The total volume of concrete for a strut = (2 x 1 x 1) + (2.5 x 2.5 x 0.5) = 5.12 m^2. Considering a foundation of 1m x 1m x 2.5m = 2.5m^3at the base of the arch.

The total volume of foundation at the two ends of the arch and four struts, (5.12 x 4) + (2.5 x 2) ~ 25.5 m^3

5.4 DESIGN CASE – II

5.4.1 Form & Fabric:

In this design two columns form the principle support of the tensile fabric roof; located in the same aisle as the existing columns. The fabric radiates from these two columns to the edge catenaries forming double curves; these in turn will be supported by poles placed near the corners of the pavilion.

5.4.2 High Points and Low Points

Points A and B are the center of the hollow steel columns at the top, at a distance of 16.5m from each other and at a height of 12m from ground. C, D, E and F are the top of the poles at 6m height.

5.4.3 Load Calculation:

As the site is the same, the design wind pressure (p_z) is the same as the previous option 1382 N/m^2.

External Pressure Coefficients (C_{pe}) for a canopy like the one for the pavilion,

C_{pe} = -1.6 *(Source: Table 18 of IS875)*

Hence Design **Wind Load (p) = C_{pe} X p_z = -1.6 x 1382 N/m^2 ~ 2200 N/m^2**

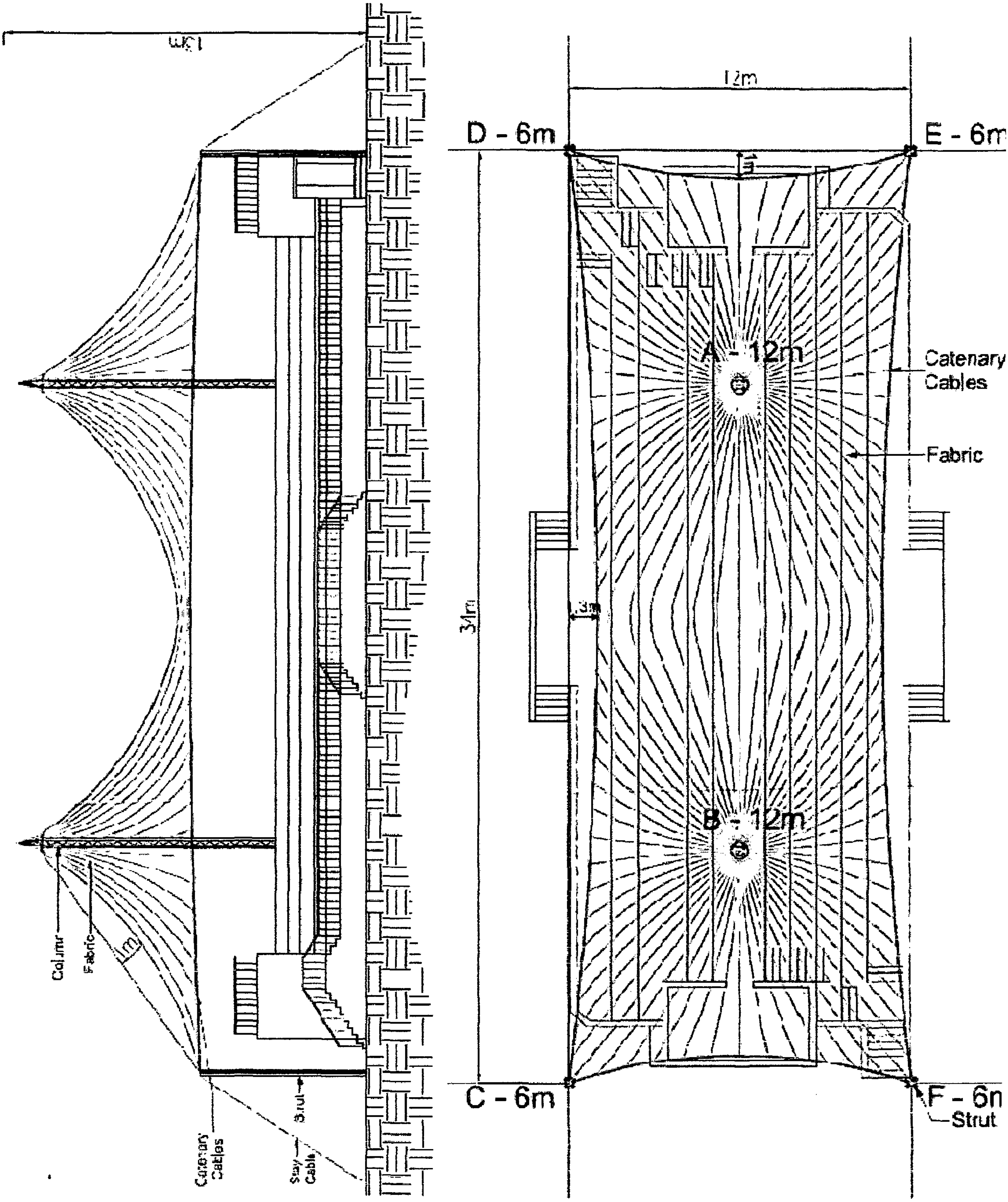


Fig 5.15 Elevation & Plan

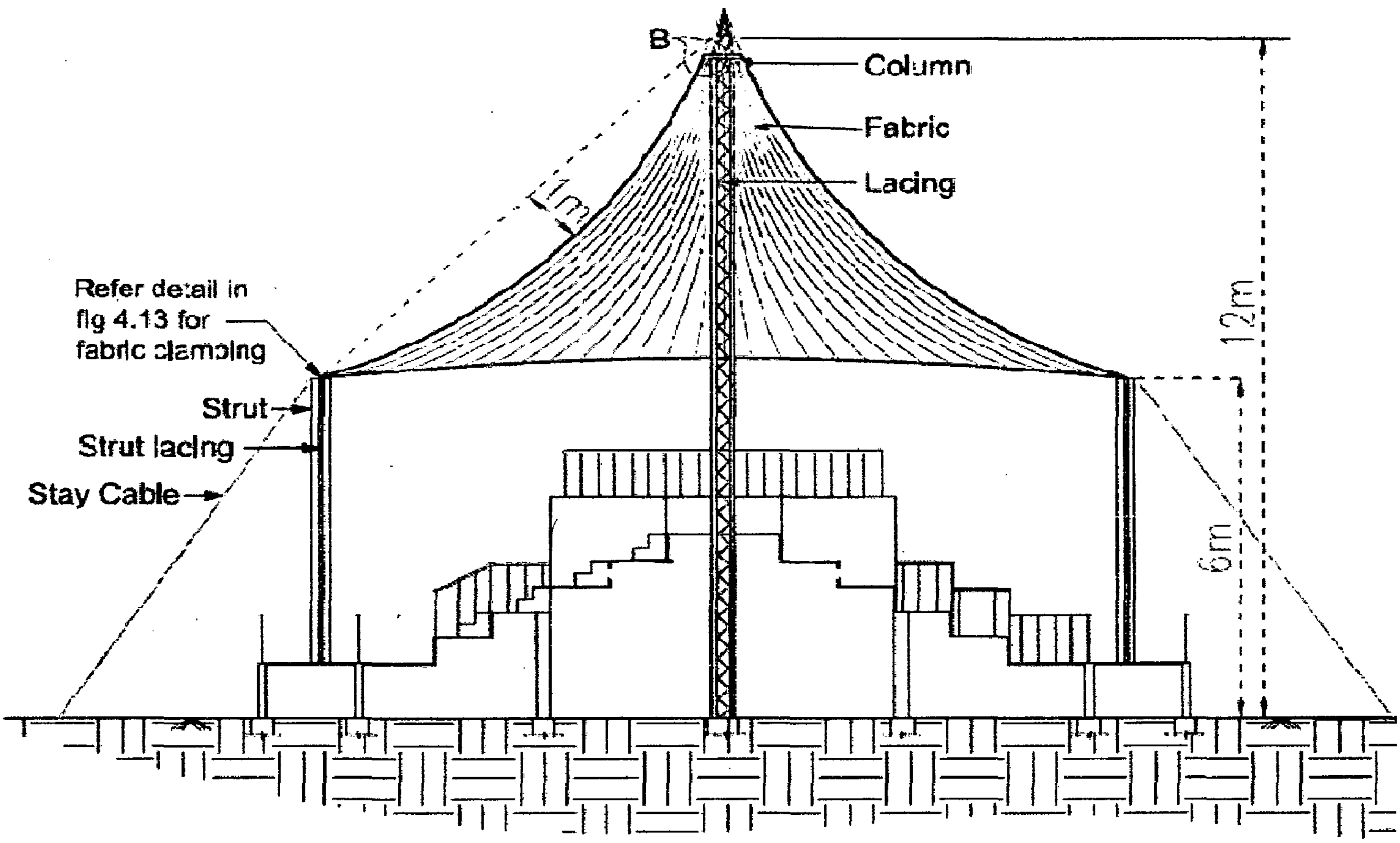


Fig 5.16a Transverse roof section

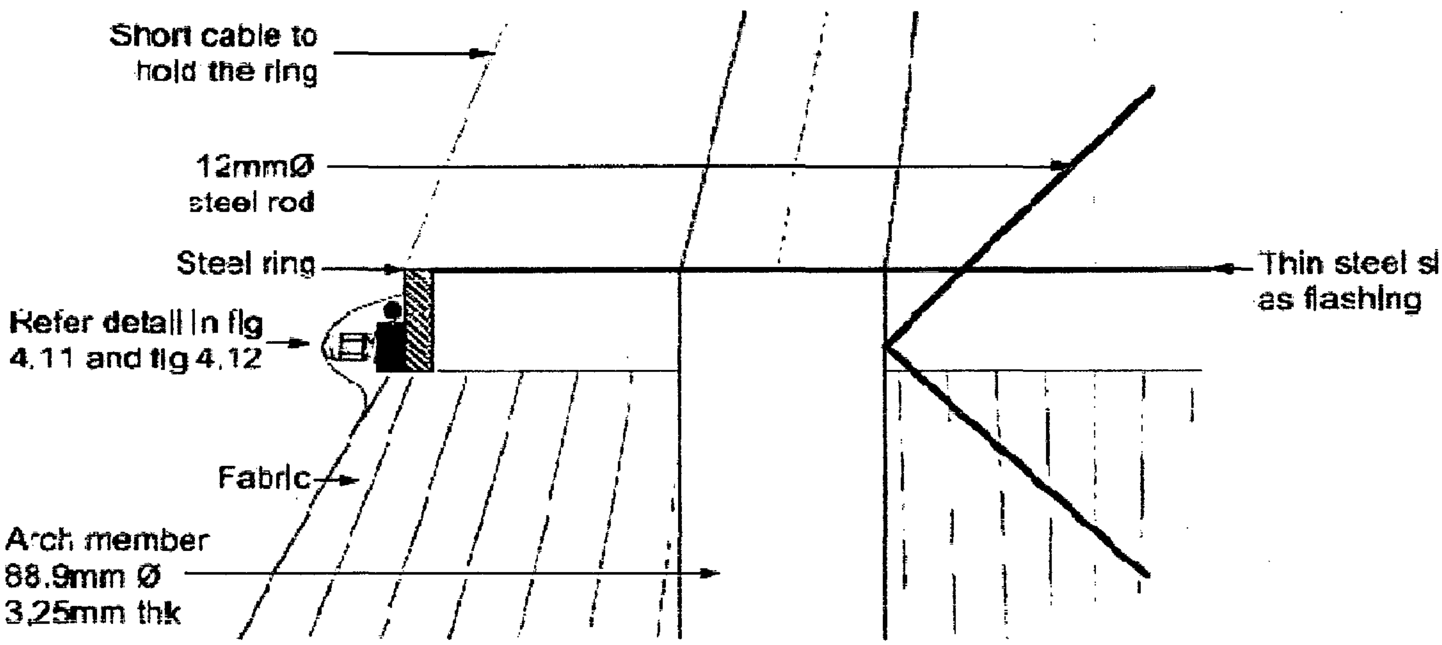


Fig 5.16b Detail B

5.4.4 Force Analysis of the Fabric

Considering the roof as two tents joined in the center, one tent unit will cover 12mx17m in plan. The tent unit is further divided into meridional strips; that radiate from the centre near the pole to the ends and circumferential strips that are concentric strips of fabric 1m in width around the poles. Considering strips of fabric 1m width at the base for the meridional strips, the perimeter will consist of 58 strips that radiate from around 10cms near the pole to a meter at the perimeter. The average width of this strip will be taken as 55cms. The maximum length of the fabric from the pole to the edges will be around 10.5m; hence approximately a tent unit can be divided into nine circumferential strips of width 1m.

In order to approximately asses the forces in the fabric consider two intersecting strips of average dimensions; meridional strips 0.55m wide and 9.5m long and circumferential strips 1m wide and diameter 10m. Sag in either direction can be taken as 1m.

Assuming 50% of load taken by meridional strips and 50% by circumferential strips, these being of like dimensions.

Tension in the meridional strip will be;

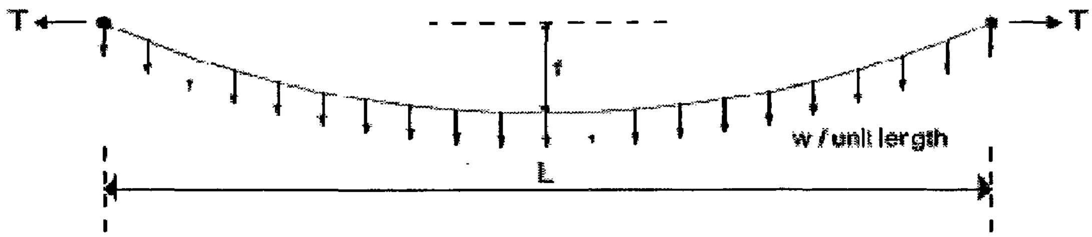


Fig 5.17 Tension Schematic

$$T_m = wl^2 / 8f$$

$$T_m = (1100 \times 9.5^2 \times 0.55) / (8 \times 1) \sim 6825 \text{ N/m at the base}$$

Tension in the circumferential direction; $T_c = w\, r = 1100 \times 5 = 5500$ **N/m**

Choosing Ferrari 1002s fabric.

5.4.5 Design of supports:

Now considering a **column member made of four hollow circular steel sections connected by spiral bracing,** the effective length (l_a) will be 12m and the load on the column due to the fabric can be calculated by considering the meridional strips attached at a 45^0 inclination to the pole, and resolving the force in the strip into its vertical component,

6825 sin45 = 4826 N for a single strip;

For 58 strips, 4826 x 58 = 279908 N ~ 280 kN

The force exerted on each hollow circular steel section will be

280000/4 = 70000N ~ 70 kN

Slenderness ratio (λ) l_a/r = 12000/r

Assuming the cross **section of the column to be 300mm x 300mm** with the hollow steel sections in the corners,

$$\sqrt{(I/A)} = \sqrt{((4A \times 150^2)/4A)} = 150\text{mm}$$

$$\text{Therefore, } \lambda = l_a/r = 12000/150 = 80$$

From the steel tables, the permissible stress (f_c) in axial compression for mild steel with λ = 80 is 101 N/mm^2.

Now to find the hollow circular steel section member size, A x f_c = 70000N,

A = 70000/101 = 693mm^2

Four hollow structural steel members of outside diameter = 88.9mm and t = 3.25mm can be used.

Now for the lacing

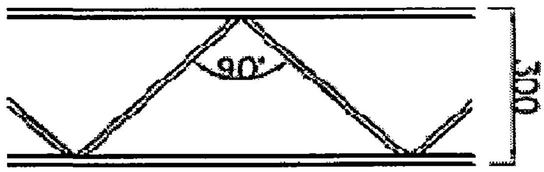


Fig 5.18 Column Lacing

Lacing at an angle of 45° between the rods will have a length of 211.1√2

$l = 211.1\sqrt{2}$

l/r should not be greater than 145

$r = 211.1\sqrt{2} / 145 = 2.0$mm

Choose a minimum of 12mm dia mild steel bar.

Now considering the **catenary cable between points D and C,**

Tension in the cable is = $(6825 \times 34^2) / (8 \times 1.3) = 758625$N ~ 758.6kN

Minimum breaking strength required for the cable = 758.6 x 2.2 = 1668.92kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 50.80mm can be used between DC and EF

Now considering the **catenary cable between points C and F,**

Tension in the cable is = $(6825 \times 12^2) / (8 \times 1) = 122850$N ~ 122.85kN

Minimum breaking strength required for the cable = 122.85 x 2.2 = 270.27kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 20.64mm can be used between CF and DE.

The **strut at C**, whose length is 6m, effective length (l_s) = 6000 mm

The load on the strut due to the two cables DC and CF is;

758.6kN + 122.85kN = 881.45kN

Assume the **strut member to consist of four hollow circular steel sections, at 300mm square plan, connected by lacing**. The effective length (l_a) will be 6m and the force exerted on each hollow circular steel section will be 881450/4 = 220363 N ~ 220 kN

Slenderness ratio (λ) l_s/r = 6000/r

$\sqrt{(I/A)} = \sqrt{((4A \times 150^2)/4A)}$ = 150mm

Therefore, $\lambda = l_a/r$ = 6000/150 = 40

From the steel tables, the permissible stress (f_c) in axial compression for mild steel with λ = 40 is 139 N/mm^2.

To find the hollow circular steel section member size, A x f_c = 220000N,

A = 220000/139 = 1583mm^2

Four hollow structural steel members of outside diameter = 114.3mm and t = 4.5mm can be used.

Now for the **lacing**

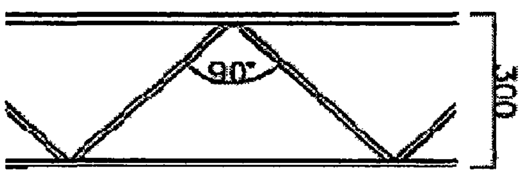


Fig 5.19 Strut bracing

Lacing at an angle of 45° between the rods will have a length of 185.7√2

l = 185.7√2

l/r should not be greater than 145

r = 185.7√2/145 = 1.1mm

Choose a minimum of 12mm dia mild steel bar.

Now considering the stay cables to hold the strut at C in place,

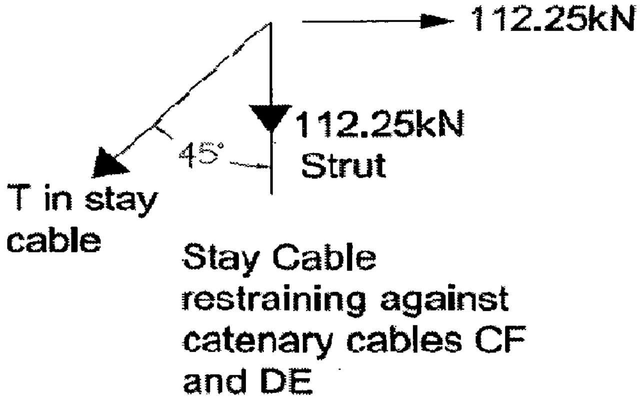


Fig 5.20a Stay cable

$T \sin 45^0 = 122.25kN$

T = 172.88kN ~ 173kN

Minimum breaking strength required for the cable = 173 x 2.2 = 380kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 25.4mm can be used at struts C, D, E & F to restrain them against cables CF and DE.

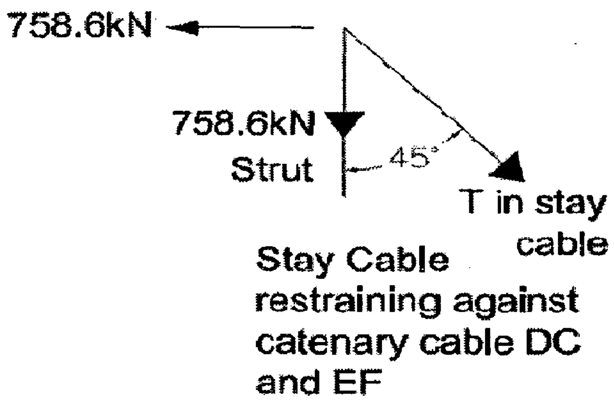


Fig 5.20b Stay cable

$T \sin 45^0 = 758.6kN$

T ~ 1073N

Minimum breaking strength required for the cable = 1073 x 2.2 = 2360.6kN

(Source:Table 7.3 of "Cable Suspended Roofs", Prem Krishna, 1978)

Zinc coated steel structural wire rope of nominal diameter 60.33mm can be used at struts C, D, E & F to restrain them against cables DC and EF.

5.4.6 ESTIMATION:

The second design case involves a different geometry than the first, the estimation will help in concluding if covering the same plan form will consume similar quantity of materials irrespective of design.

5.4.6.1 Fabric:

In order to quantify the fabric, the dimensions of the fabric have to be calculated, the length can be calculated as below,

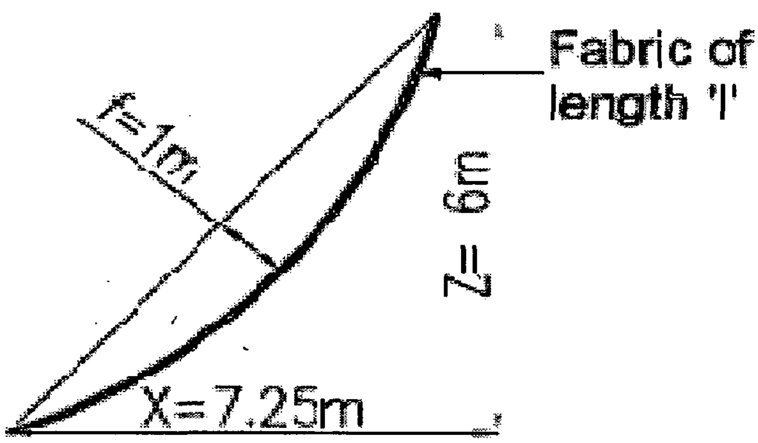


Fig 5.21 Fabric length

$$\textbf{Length, } l = X\left[1 + (8f^2/3X^2) + (Z^2/2X^2)\right]$$

(Source:P 33, of "Cable Suspended Roofs", Prem Krishna, 1978)

The value of X varies between 6m and 8.5m around the pole, hence an average of 7.25m is taken as the value of X.

$$= 7.25\ [\ 1 + ((8 \times 1^2)/(3 \times 7.25^2)) + (6^2/(2 \times 7.25^2))]$$

$$= 7.25\ [\ 1.05 + 0.34\ ]$$

~ 10m

Considering the four sides of the tent as four triangles having a base, of 7.25 x 2 = 14.5 and height 10m;

Area of fabric on both tents = 14.5 x 10 x 4 x 2/2 = 580 sqm

5.4.6.2 Cables:

- **Longitudinal cables:**

These are the cables that run between DC and EF

In the same equation used to calculate the length of the fabric, the value of Z becomes zero.

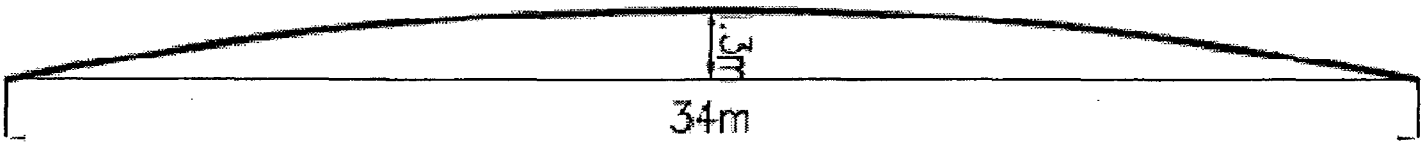


Fig 5.22a Cable length

Length of the cable, l = X [1 + (8f²/3X²)]

$$l = 34\ [\ 1 + (8 \times 1.3^2)/(3 \times 34^2)]$$

$$\sim 34.1\ m$$

50.80mm diameter cable has a weight of 99.86N/m

Weight of the two longitudinal cables = 34.1 x 99.86 x 2 = 6810N

- **Transverse cables:**

These are the cables that run between **CF and DE**

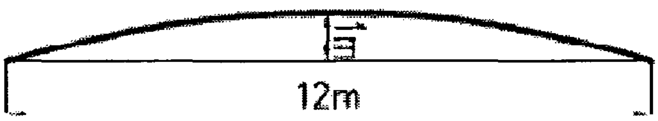


Fig 5.22b Cable length

$$l = 12 [1 + (8 \times 1^2)/(3 \times 12^2)]$$

$$\sim 12.2 \text{ m}$$

20.64mm diameter cable has a weight of 16.07N/m

Weight of the four transverse cables = 12.2 x 16.07 x 2 = 392N

- **Back stays of strut:**

These cables are the ones that hold the struts in place. The struts are of 6m height, hence the length of cables which are inclined at 45^0 will be;

$$l = 6\sqrt{2} \sim 8.5\text{m}$$

25.4mm diameter cable stay has a weight of 23.52N/m

Cable weight = 8.5 x 23.52 x 4 = **800N**

60.33mm diameter cable stay has a weight of 140.14N/m

Cable weight = 8.5 x 140.14 x 4 = **4765N**

Total weight of the cables = 6810 + 392 + 800 + 4765 = 12767N

5.4.6.3 Column :

Length of the column, l = 12

Tube of 88.9mm outer diameter and 3.25mm thick has a weight of 68.1 N/m

Weight of four hollow steel sections = 12 x 68.1 x 4 = 3268N

Number of bracings on all four sides = 54.9 x 1000 x 4 / 565 ~ 388

Bracing of tube size 21.3mm diameter and 2mm thick having a weight of 9.5 N/m

Bracing weight = 388 x 800 x 9.5 / 1000 = 2948 N

5.4.6.4 Struts:

Length of a strut, l = 6m

Four tubes of 114.3mm outer diameter and 4.5mm thick having a weight of 121 N/m

Weight of four hollow steel sections = 6 x 121 x 4 = 2904N

Number of bracings on all four sides = 6000 x 4 / 211 ~ 112

Bracing on all four sides of tube having length 298.5mm, 12mm diameter and having a weight of 8.8 N/m

Bracing weight = 112 x 298.5 x 8.8 / 1000 = 297 N

Total weight of steel = 3268 + 2948 + 2904 +297 = 9417N

5.4.6.5 Foundation:

Considering the forces on the strut and column, we assume the same volume of foundation as in Design Case –I, a total volume of **25.5 m^3.**

5.5 COMPARATIVE COST ANALYSIS

Materials	Rate(Rs.)/ Unit	Base Case*		Design Case - 1		Design Case – 2	
		Qty	Amount (Rs.)	Qty	Amount (Rs.)	Qty	Amount (Rs.)
Fabric	2000/m^2	N/A	N/A	594m^2	1188000	580m^2	1160000
Cables	70/kg ~ 7/N	N/A	N/A	11343 N	79401	12767.45	89372
Steel	4.3/N	185346N	788754	11445.24N	49215	9428.2N	40541
Aluminium Roofing Sheet	660/ m^2	485m^2	320100	N/A	N/A	N/A	N/A
RCC	3733/m^3	72 m^3	268776	N/A	N/A	N/A	N/A
Foundation	2900/m^3	25m^3	72500	25.5 m^3	73950	25.5 m^3	73950
Total Cost (Rs)		1450130		1390566		1363863	

* Obtained from the contractors of the structure.

5.6 SUMMARY

The base case has the advantage of being conventional, hence the materials and expertise in construction is easily available. This gives the appearance of a regular structure, put up in place within a given time frame. Given its conventional type, the design does not involve any new understanding and hence the time required for design and construction can be preconceived.

The two fabric roof options consume a similar quantity of material, and the fabric forms the single largest cost component. The cost of fabric used in the estimation includes the cost of cutting, handling and erection. But the quantity of steel used is comparatively less than the base case. The cost of the fabric can come down if the manufacturing of the fabric is done locally. Even so the cost of, the fabric options is lower and these are land mark structures that stand out in the vicinity, the visual dynamics alone forming an additional strong point in their favour.

Chapter 6

Conclusions and Recommendations

Propositions drawn after careful consideration of the various issues dealt with in the earlier chapters. This chapter also suggests possible future areas of study in this sphere of architecture.

6.1 CONCLUSION

Any form of construction can be exploited to the maximum extent only with the strong knowledge of the basic underlying principles by the architects and engineers. With the growth of technology and the endless innovations that has crept into the construction field, keeping up with the new advancements all over the world is a task in itself. Though constant updation on all the developments need not always be necessary, being enlightened on promising trends that might hold sway in the coming decades is essential. This dissertation is instrumental in familiarizing architects in dealing with the various facets of tensile fabric roof structures. Following the systematic discussions on the different aspects of tensile fabric roof in the earlier chapters, the following conclusions are drawn.

- Tensile fabric roofs are tent structures that have appeared throughout history, the modern technology and materials have enabled them to become more sophisticated as they are now.

  The principle of design and working of cable net structures is very similar to that of fabric roof structures, the main difference being only the material. With the manufacture of the fabric of desired strength and other properties in the recent decades the problem of cladding cable net structures has ceased to exist.

  It is mainly due to the progress in manufacturing industry and computation technology that led civil engineers like Horst Berger to develop mathematical models for them and popularize tensile fabric roof structures.

  All tensile fabric roof structures are essentially double curved. This anticlastic curvature gives strength to the roof and restrains it against flopping in the wind.

  Fabric forms the chief roofing material, and the performance of the roof depends mainly on the properties and form of the fabric.

  Soap films and physical models where important to study and analyze roof forms earlier, but since the recent past computer programs play all the major roles of design, modeling and cutting pattern generation. Though physical models are still done in many cases, they usually don't form part of a detail analysis.

- Design of tensile fabric roofs are unique and might require innovative supports and handling at site for successful erection. Every project is a new experience.
- Familiarity in handling and inherent properties may mean that Teflon will be the material of choice for longer life structures and silicon coated fiber glass may take some time for acceptance even though it might have better properties.
- The forms are dependant to an extent on the plan form, and it's possible to resolve all the forms into the basic forms, their combination or repetition.
- Given the same plan, the quantity of fabric used for different design options is similar.
- It will be possible for an architect with the basic understanding of the concept of tensile fabric roofs to decide on the form, support structures and fabric until it can be fine tuned by a structural engineer. By doing this the architect will be able to have an idea of the feasibility of his structure, in the initial conceptualization stage itself.
- Though an architect can evolve the design to a significant level, the tensile fabric roof can be erected on site only after the finer details have been worked out by a structural engineer.
- As mentioned earlier each design of tensile fabric roofs are unique, hence drawing generalizations is difficult.
- Unlike most other forms of construction, the dynamic visual appeal of this roof is the most important factor that has contributed to its growth over the years.
- Comparatively speedy construction means that the space can be used sooner. Hence in case of a commercial space covered with tensile fabric roof, it will generate revenue faster when compared to covering it with a conventional roof.

- The geometry of the structure decides the quantity of material used, by changing the geometry of the structure; the material quantity can be optimized. For e.g. change in the sag of a catenary cable will affect the dimensions of the cable used and hence its weight.
- Cost of fabric in the fabric in India is high it because there are no reliable manufacturers of fabric within the country and has to be imported. Local manufacturers can lead to reduction in transportation and other related costs.
- The design approach discussed here will help an architect in conceptualizing and fine tuning the design of tensile fabric roofs to a great extent.
- In a few years, tensile fabric roofs should be considered as a valid option in construction by most people.

6.2 RECOMMENDATION

Though this dissertation is an effective compilation of the theories and concepts of tensile fabric roofs, practical experience and constant updation of knowledge is always invaluable; as a follow up to this dissertation, the following points are recommended.

- Since tensile fabric roofs require the use of modern machinery and computing, architects ought to become familiar with these. This will help in handling the project better.

- Architects should keep themselves updated on the fabric materials arriving in the market; this will help them choose an appropriate material for a given project with required specification. With the interest in fabric roofs on the rise, a number of fabric options might be expected in the near future.

- Although initial work of conceptualization is the domain of architects in general, for these newly evolving structures, the involvement of a structural engineer will be invaluable.

- More studies in this field involving a large number of these structures might help in drawing generalizations and developing thumb rules in the design of tensile fabric roofs.

6.3 FUTURE AREAS OF RESEARCH

In depth studies of different aspects of tensile fabric roofs will help in their further understanding. In this respect, attention can be drawn to the following areas.

- An in depth study that brings out the economic implications of tensile fabric roof in comparison with conventional roofs.
- Life cycle costing of tensile fabric roofs.
- Potential applications of fabric in other building elements, apart from roof.
- Effect of tensile fabric roof on the thermal comfort of different spaces.
- Effect of tensile fabric roof on the acoustics of different spaces.

FIGURE CREDITS

FIGURES	CREDITS
Fig 2.1:Reconstructed Tent. Moldovia, Russia. Made of Animal bones and Tusks.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.2: American Tipî	http://redskyshelters.com
Fig 2.3: Black Tents	http://redskyshelters.com
Fig 2.4: Circus Tents	http://redskyshelters.com
Fig 2.5 Top: Roman 'VELA'	http://redskyshelters.com
Fig 2.6 Right: Ship Sails	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.7 Developable Mesh	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.8a Cable Net	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.8b Cable Net.	http://www.architectureweek.com
Fig 2.9: Munich stadium roof for the 1972 Olympic Games	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.10 Left: Tokyo Dome	http://redskyshelters.com
Fig 2.11 Bottom: Principle	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.12: Shukhov's Structure	http://wikipedia.com
Fig 2.13: Shukhov's Structure	http://wikipedia.com
Fig 2.14: Haj Terminal Building Jeddah	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.15: Denver International Airport	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag

FIGURES	CREDITS
Fig 2.16 Top(a): Single four point structure. Three points share the ground as a common plane. The fourth is created by the pole.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.16 Right(b): Anticlastic Surface	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.17: Force diagram of a typical node in a tensile saddle surface, and part of a typical anticlastic surface net.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.18: Force flow as a result of pulling down with prestress force P at one of the struts.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.19: Warp and Fill configuration before stressing.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.20: Warp and Fill configuration after stressing.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.21(a&b): Rip Fabric failure of a roof unit in the Haj terminal, Jeddah due to faulty compensation. Before and After respectively.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.23: High-Strength Bridge Strand Steel Wire Cables	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.24: Soap Buble	http://redskyshelters.com
Fig 2.25: Soap Film	http://www. fountainmagazine.com
Fig 2.26 (a.b&c): Soap Film Technique	Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.
Fig 2.27: Physical Models	(a): Drew Philip: Frei Otto Form and Structure(1976) Granada Publishing Ltd, Staples.

FIGURES	CREDITS
Fig 2.27: Physical Models	(b&c): Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.28 Physical Model.	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 2.29 (a): Computer modelling (b) Cutting pattern	http://technet-gmbh.com
Fig 3.1: Denver International Airport	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.2: Computer Model, Denver International Airport	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.3: Section, Denver International Airport	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.4: Octopus Connector	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.5: Roof during construction	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.6: Haj Terminal	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.7: Inside the Haj Terminal	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.8: Haj Terminal	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag

FIGURES	CREDITS
Fig 3.9: Aerial View, Haj Terminal	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.10: Elevation, Haj Terminal	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 3.11: Cynthia Woods Mitchell Center For The Performing Arts	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 4.8 Flying Mast	www.concat.in
Fig 4.9 A- Frames	Berger, Horst: "Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture". (1996) Basel; Boston; Berlin: Birkhauser Verlag
Fig 4.15 Stitch joints in membrane material	Prem Krishna: "Cable Suspended Roofs"(1978), McGraw-Hill, New York.

REFERENCES

[1] Berger, H. (1996), *Light Structures-Structures of Light: the Art and Engineering of Tensile Architecture,* Boston: Basel; Berlin: Birkhauser Verlag

[2] Drew, P. (1976), *Frei Otto Form and Structure,* Staples: Granada Publishing Ltd.

[3] Drew, P. (1979), *Tensile Architecture,* Staples: Granada Publishing Ltd.

[4] Engel, H. (1968), *Structure Systems,* London: Iliffe Books Ltd.

[5] IS-875 – Indian Wind Code (1987), Bureau of Indian Standards

[6] National Building Code of India (2005), Bureau of Indian Standards

[7] Otto, F. (1962), *Tensile Structures,* : Cambridge and London: The MIT Press.

[8] Krishna, P. (1978), *Cable Suspended Roofs*, New York: McGraw-Hill.

[9] Pushplata; Mittal, K. (March, 2008), *Digital Design Process in Context of Modern Tent Structures,* The Journal of the Indian institute of Architects, Maharashtra, pp. 7-9.

[10] Discussion with Dr. Prem Krishna (Sept, Oct, Nov & Dec 2009, January – June 2010.)

[11] E-mail Conversation with Mr. Vikran Taare, Concat, Pune

[12] Visit to Construction Catalysers workshop, Pune. (March 3-5, 2010)

[13] http://architecture.mit.edu/house_n/web/resources/tutorials/House_N%20Tutorial%20Tensile%20Structures.htm, assessed on 05th Sept, 09

[14] http://livedesignonline.com/theatre/designing_fabric_structures_0109/, assessed on 02nd Dec, 09.

[15] http://nopr.niscair.res.in/bitstream/123456789/1623/1/IJFTR%2033(2)%20146-150.pdf, assessed on 02nd Dec, 09.

[16] http://redskyshelters.com/index.php?page=tensilehistory (as on 05th Sept, 09).

[17] http://technetgmbh.com/fileadmin/Leichte_Flaechentragwerke/Publikationen/Cutpat2.pdf, assessed on 02nd Dec, 09.

[18] http://theconstructor.org/2009/10/cable-and-tension-structures/, assessed on 02nd Dec, 09.

[19] http://www.archiexpo.com/architecture-design-manufacturer/tensile-structure-3504.html, assessed on 05th Sept, 09.

[20] http://www.arkitekturnet.dk/anmeldelser/0012rl.htm, assessed on 02nd Dec, 09.

[21] http://www.arch.mcgill.ca/prof/sijpkes/arch374/winter2002/psyisun/tensilematerials.htm, assessed on 05th Sept, 09.

[22] http://www.arch.mcgill.ca/prof/sijpkes/Philo-2007/form_finding.html, assessed on 02nd Dec, 09.

[23] http://www.bruno.postle.nret/links/tents/software/, assessed on 02nd Dec, 09.

[24] http://www.concat.in/flash/player.html, assessed on 05th Sept, 09.

[25] http://www.designbuild-network.com/contractors/construct_machinery/fabric-architecture/, assessed on 05th Sept, 09.

[26] http://www-ec.njit.edu/civil/fabric/tension.html, assessed on 05th Sept, 09.

[27] http://www.fountainmagazine.com/article.php?ARTICLEID=967, assessed on 02nd Dec, 09.

[28] www.hawisystemer.no/tms_ifo/understanding_tensile_forms.pdf, assessed on 02nd Dec, 09.

[29] http://www.allbusiness.com/business-planning-structures/starting-a-business/391124-1.html, assessed on 05th Sept, 09.

[30] http://www.horstberger.com/web.me.com_horstberger2/Welcome.html, assessed on 05th Sept, 09.

[31] http://www.ifai.com/Awning/FabricArchitecturemagazine.cfm, assessed on 05th Sept, 09.

[32] http://www.meliar.com/related_links.htm, assessed on 02nd Dec, 09.

[33] http://www.membranes24.com/, assessed on 02nd Dec, 09.

[34] http://www.oasys-software.com/information/case_studies/dalton_park.shtml, assessed on 05th Sept, 09.

[35] http://www.plastomertech.com/ptfeproperties.htm, assessed on 02nd Dec, 09.

[36] http://www.teflon-tapes.com/pdf/02_hch_ar.pdf, assessed on 02nd Dec, 09.

[37] http://www.tensileindia.com/about-us.html, assessed on 05th Sept, 09.
[38] http://www.tensionstructures.com/specification.htm, assessed on 05th Sept, 09.
[39] http://www.tensionstructures.com/terminology.htm, assessed on 05th Sept, 09.
[40] http://www.urbanshade.com.au/tensile-structures.htm, assessed on 05th Sept, 09.

APPENDIX (i) Terminology

(http://www.tensionstructures.com/terminology.htm)

Anchor Bolts - Threaded bolts used to fasten structural members to masonry. Anchor bolts can be in the form of "J" bolts or simply a threaded rod. If a threaded rod is used, there will typically be a nut and a washer secured to the imbed section of the bolt to help resist the possibilities of the bolt being pulled from the concrete.

Anisotropy – The feature of fabric wherein the physical properties and behavior are not the same in all directions.

Anticlastic – A surface with positive (Gaussian) curvature in one principal direction and negative (Gaussian) curvature in the other. A saddle shaped surface (potato chip).

Base Fabric – The uncoated fabric, also known as greige goods.

Bias – Oriented at 45-degrees to the warp and fill directions of the fabric.

Biaxial – Taken along two concurrent orthogonal directions, usually principal directions.

Boss Plate – Doughnut-shaped plate attached to a cable ear plate to reinforce the pinhole and allow a thinner plate.

Butt Seam – Seam created when the two pieces being joined are butted together and joined with a strip twice the width of the seam.

Cable Cuff – Edge treatment in which the fabric is folded over on itself to form a pocket in which a catenary cable can be installed.

Cable Fitting – Device attached to the end of a cable to allow a connection to another member. Fittings can be swaged, speltered or compression type.

Catenary – The curve theoretically formed by a perfectly flexible, uniformly dense, inextensible "cable" suspended from each of two end points. In fabric structures experience, this shape is probably not ever truly developed, but is commonly used to describe the shape developed at the boundary of a uniformly stressed fabric structure attached to a cable which is restrained only at its end points.

Catenary Cable - Steel cables that run through the pockets on the perimeter of a tension structure fabric. The shape of the cable follows that of the pocket, which is typically curved with a ratio of 1:10. The length of the cable is to be determined from by the engineer supplying the fabric patterning. The thickness of the cable is to be determined by the engineer who is calculating the reaction loads at the cable ends.

Catenary Edge – Method of securing the edge of a panel with a cable tensioned between two fixed points.

Catenary Pocket - This is the pocket that is placed at the perimeter of the fabric cover to secure the catenary cable. The pocket has a curve with a ratio that is defined by the fabric patterning, but is typically close to a 1:10 ratio. This means for every 10 feet of length, there will be about a foot of bend to it. Due to the curvature of the shape, the pocket is typically fabricated by sealing together two halves of the pocket together with an overlap of 1" to 2" at the outside edge of the pocket.

Clevis – Device used with a cable stud end or a threaded rod to form a pinned connection that is somewhat adjustable.

Coating – A material applied to a fabric for waterproofing and protection of the fabric yarns.

Coating Adhesion – Strength of the bond between the substrate of a fabric and the coating.

Compensation – The operation of shop fabricating a fabric structure or pieces of the structure smaller in the unstressed condition than the actual installed size, to account for the stretch at pre-stress level.

Crimp – The extent of deformation normal to the plane of the fabric that the fill and warp yarns undergo as they are woven together.

Detension – Relieve the tension or stress in a membrane.

Elongation – The change in lengths of a material sample; normally this is associated with some load or force acting on the sample. In fabric, this elongation does not normally refer to true strain of the fiber elements as in the classical sense; but, rather, normally refers to the "apparent" strain resulting from a straightening out of the crimped yarns in the fabric matrix.

Equilibrium Shape – The configuration that a tensioned fabric surface assumes when boundary conditions, pre-stress level, and pre-stress distribution are defined.

Fabric – A woven or laid cloth made of yarns.

Fabric Clamp – Device for clamping the edge of a fabric panel, usually a bar or channel shape and made of aluminum or steel.

Fiber – The basic thread of the material from which the yarns and fabrics are made.

Fill Yarns – The shorter yarns of a fabric, which usually run at right angles to the warp yarns. Also known as weft yarns.

Flutter – Excessive, uncontrolled movement, usually caused by the interaction between the structure and wind. This occurs when the fabric lacks sufficient pre-stress.

Footing - The large concrete anchoring structure that holds the tension structure securely to the ground. The top of the footing is typically flush with the ground level. The footing is comprised of a matrix of steel rebar that is referred to as a cage. The concrete is poured into the hole in the ground that holds the cage. The anchor bolts get placed into the top of the footing at their precise location as indicated in the shop drawings. A certified engineer must calculate the size of the footings. The size of the footing must contain enough weight to hold down the tension structure for the wind loads in the area.

Form Finding– The process of determining the equilibrium shape of a fabric structure.

Greige Goods – Uncoated fabric. Also known as the base fabric.

Guy Cable - This steel cable is used to support the structural integrity of the steel frame. *It may be attached at the ends of the steel struts (or "arms") to hold them together and* resist them from movement relative to each other. Unlike catenary cables, the lengths are calculated by a straight point-to-point dimension. The engineer will need to determine the thickness by calculating the maximum stress on the cable.

Hysteresis – The failure of fabric to return to its original geometry after the strain-inducing force has been removed.

Keder – Brand name for the solid PVC cord used at a "rope edge". Rope edges provide strength and a surface to evenly distribute fabric tension forces.

Lap Seam – Seam created when the two pieces being joined are overlapped by the width of the seam.

Light Transmission – A measure of the portion of light striking a fabric surface that passes through the fabric and into the space to provide daylighting.

Mast – The principal upright in a tension structure.

Membrane – The fabric panels used in tension structures.

Membrane Plate – Metal plates attached to the membrane corners used for securing the membrane to the frame.

Modulus of Elasticity – The ratio of the change in stress to the change in strain. Usually defined as a force per unit width of a membrane material.

Node Points – Intersection points of the elements used to define the fabric shape in the structural analysis; these are normally given in terms of a three-dimensional coordinate system.

Patterning – The process of defining two-dimensional pieces of fabric, which can be spiced together to form a desired three-dimensional shape. M-Panel is an add on tool for AutoCAD that has the ability to assist in the process of patterning.

Poisson's Ratio – The ratio of lateral strain to longitudinal strain; may take a wide range of values due to the deformation characteristics of a woven material.

Pre-stress – The stress state that exists in a fabric structure when it is not acted upon by service loads; usually induced by the boundary conditions of the fabric membrane.

PTFE - "Polytetrafluoroethylene", commonly known by its trademark name Teflon™. This coating is applied to a fiberglass scrim to produce a high strength tension structure fabric membrane with a life expectancy of thirty plus years. PTFE may also be expanded and woven into a fabric that can be coated with a fluoropolymer to create a high strength architectural fabric.

PVC - "Polyvinyl chloride", properly mixed with plasticizers for flexibility and applied to a polyester scrim makes for a high strength and popular tension structure fabric membrane. The life expectancy and cost are proportionally lower than PTFE.

Radius of Curvature – The inverse of the magnitude of (Gaussian) curvature at a location on a membrane surface. The magnitude is typically considered in two principal directions. The orientation of the principal directions and their magnitude may vary continuously over the surface.

Rebar Cage – A reinforcing matrix of steel rods used to strengthen concrete.

Reinforcement – An additional layer of fabric placed in an area of high stress to protect the main fabric.

Roll Goods – Edge treatment in which the edge of the fabric is folded over on itself and a rope or cord is incorporated in the fold to increase the strength of the clamped fabric.

Sectionalizing – Method of field joining large fabric panels utilizing clamping hardware.

Sleeve – A tube of fabric, which loosely contains a structural element such as a cable, rod, etc.

Spelter – Type of cable fitting in which the strands of the cable are opened inside the fitting and molten lead is poured into the fitting to secure the cable.

Stay Cable – A steel cable that is used to stabilize the mast in response to the forces created by wind loads. The stay cables are used to resist movement of the structure relative to the earth. One end of the cable will typically connect to the end of the steel frame near the fabric connection. The other end will terminate to a sturdy section of the mast or a footing in the ground.

Swage – Type of cable fitting in which a sleeve fits over the outside of the cable and the sleeve is compressed around the cable to form a tight fit.

Synclastic – A surface with positive (Gaussian) curvature in both principal directions. A bubble shaped surface.

Thimble – Device used in a simple cable loop end to secure the cable and bear against the pin. Thimbles are usually used with shackles.

Top Finish– An additional coating sometimes used on fabric for greater protection against UV degradation or for ease of cleaning purposes (i.e. Ferrari's PVDF named "T2®"; or Dupont's PVF named "Tedlar®").

Turnbuckle – Threaded device used with cables or rods to allow adjustment.

Ultraviolet (UV) Degradation – The deterioration of a fabric under long-term exposure to sunlight. Using a top finish on the fabric will help prevent the UV degradation.

Uniaxial – Taken along one direction, usually a principal direction.

Warp Yarn – The long straight yarns in the long direction of a piece of fabric.

Weaving – The process of making a fabric from yarns passing alternately over and under each other.

Weft Yarn – The shorter yarns of a fabric, which usually run at right angles to the warp yarns. Also called the fill yarns.

Weldment – Connection component, usually steel, for the attachment of cables and/or fabric. If may be free-floating or connected to other membranes.

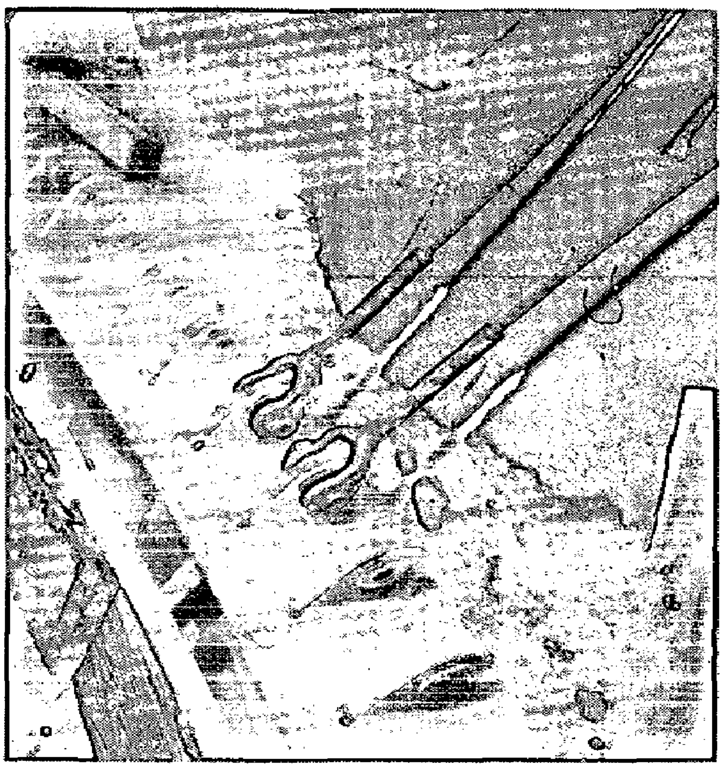
Wicking – The conveying of liquid by capillary action along and through the yarns of the base fabric.

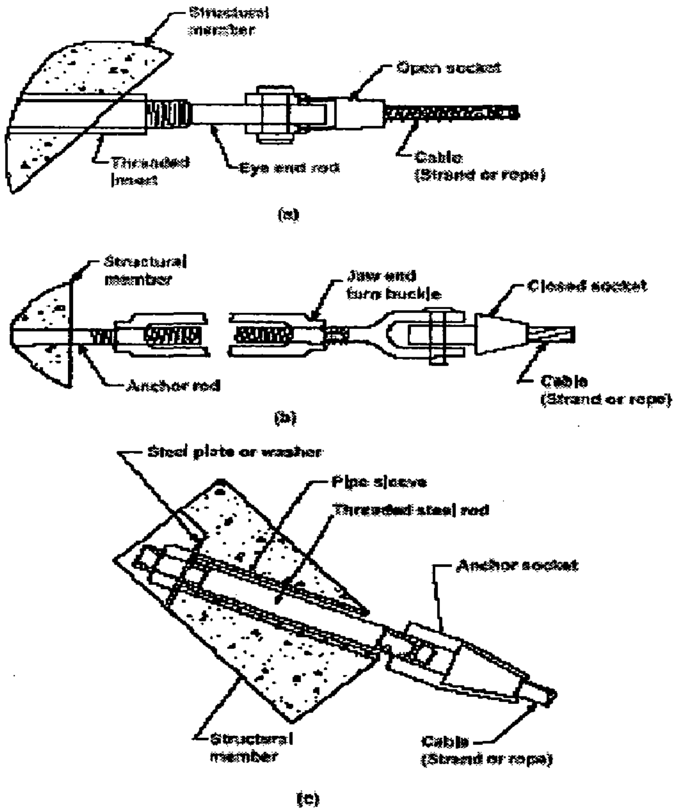
Wire Rope Clip – U-shaped bolt with a special insert, specifically designed to clamp a wire rope to itself when forming a loop end for temporary cables.

Wrinkles – Furrows or ridges on the normally smooth surface of a fabric structure, which are indicative of extreme differences between the principal stresses typically resulting from a lower stress perpendicular to the furrow.

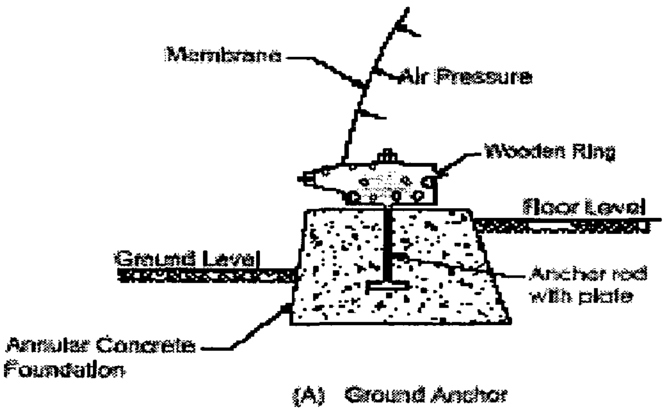
Yarn – A number of fibers grouped together to make a thicker strand for weaving. They may be twisted together or parallel to each other.

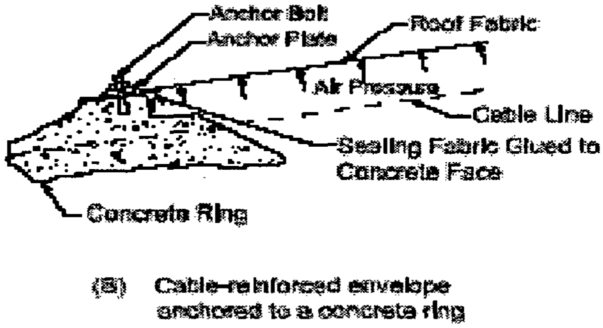
APPENDIX (ii) Connection Details *(Source: Cable Suspended Roofs, Prem Krishna, 1978)*





Figures Left: Swaged Strand Eye – A typical application (Bethlehem Steel)
Right: (a) Open socket application, (b) closed socket application,
(c) anchor socket application

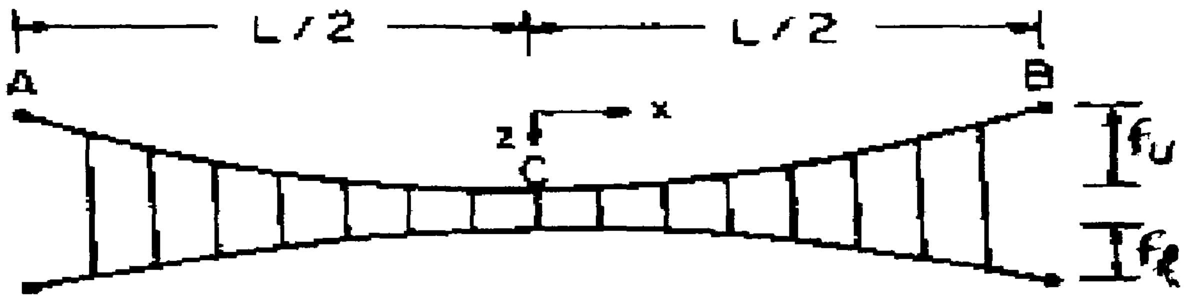




Typical details for anchoring membrane fabric

APPENDIX (iii) Approximate Analysis of the forces of Fabric

(Source:Chapter 3.5, Cable Suspended Roofs, Prem Krishna, 1978)



Tension in the upward strip, $h_u = p_0 L_u^2 / 8f_u (1+\propto\gamma^2)$

$\propto = k_l / k_u = L_u (1 + (8f_u^2/L_u^2)) / L_l (1 + (8f_l^2/L_l^2))$

$\gamma = \theta_l / \theta_u = (8f_l/L_l^2) / (8f_u/L_u^2)$

Tension in the downward strip, $h_l = - f_l h_u (1 + 8(f_u/L_u)^2) / f_u (1 + 8(f_l/L_l)^2)$