A STUDY ON FIBER REINFORCED POLYMER (FRP) ROOF FORMS

A DISSERTATION

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

MASTER OF ARCHITECTURE

By

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JUNE, 2012

CANDIDATE'S DECLARATION

I hereby declare that this report entitled **"A STUDY ON FIBER REINFORCED POLYMER (FRP) ROOF FORMS"** which has been submitted in partial fulfillment of the requirement for the award of the degree of **Master of Architecture**, in 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 2011 to June 2012, under supervision and guidance of **Prof. Rita Ahuja**, Assistant Professor, Department of Architecture and Planning, and **Dr. Anupam Chakrabarti** ,Assistant Professor, Department of Civil engineering, Indian Institute of Technology, Roorkee, India.

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

Date: 14/06/2012

Place: Roorkee

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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Certified that report entitled **"A STUDY ON FIBER REINFORCED POLYMER (FRP) ROOF FORMS"** which has been submitted by **Ms. RUCHIRA SRIVASTAVA**, for partial fulfillment of the requirement for the award of the degree of **Master of Architecture**, in Department of Architecture and Planning, Indian Institute of Technology- Roorkee, is the student's own work under our supervision and guidance. The matter embodied in this dissertation has not been submitted by her for the award of any other degree of this or any other institute.

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ACKNOWLEDGEMENT

I deem it to be my privilege to express my deep sense of gratitude and profound personal regards to Prof. Rita Ahuja, Assistant Professor, Department of Architecture and planning, and Dr. Anupam Chakrabarti, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Roorkee, for their supervision.

I would like to thank Prof. Pushplata, Head of the Department of Architecture and Planning, and Prof. S.Y. Kulkarni, Professor, Department of Architecture and Planning, Indian Institute of Technology, Roorkee for their support.

I am thankful to all the professionals I contacted throughout the year for practical knowledge and data collection, especially Mr. Mark Hobbs (Senior Engineer, Gurit International, U.K.), Dr. David Kendall (MD- Optima Projects,U.K.), and Mr. Gaurav Aggrawal , BLS International Pvt. Ltd, Roorkee for their support and help. I would also like to thank my fellow classmates for their moral support.

I would like to express my gratitude to my parents; their blessings, motivation and inspiration has always provided me with high moral support and contributed in all possible ways, in completion of this work.

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ABSTRACT

In recent times the use of composite materials for construction is gaining popularity specially Fiber Reinforced Polymer composites as a building material. Buildings have been made from the same small selection of materials for the last 100 years – most commonly masonry, timber, steel and concrete. However composites are emerging with an increasing role in building materials. In both new construction projects and renovation work, design professionals are continuing to discover the advantages of plastic composite building products, including durability, light weight, corrosion resistance, high strength, and low maintenance requirements.

This dissertation work presents the basic concepts of the Fiber Reinforced Polymers (FRP) as a building material and then in later sections various roof forms (Dome, Vault, Hyperbolic Paraboloid, Flat) with varying span and rise configurations are analyzed w.r.t. structural strength and cost.

The constituents and properties of FRP have been described in simple language. Various advantages of FRP are identified. There are a few disadvantages with FRP, but with proper construction technology, constituents and a few additives these problems can be rectified to a great extent. Construction technology, joints, details and various construction practices are studied, knowledge gained by which is strengthened by chosen case studies from India as well as around the world.

The analysis of various roof forms is based upon FRP single skin Shell construction. A computer code developed in FORTRAN 90 language has been used for the complex mathematical formulation for the analysis of laminated single skin FRP shells.

Design of various roof forms are carried out with the help of this program. Further cost calculations are done, rates being based upon market trends and CPWD 2010 Delhi zone rate list.Detailed design of two sample structures is carried out in FRP and RCC to compare strength as well cost followed by comparative cost analysis with steel.

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A STUDY ON FIBER REINFORCED POLYMER (FRP) ROOF FORMS

CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

FRP is an acronym for Fiber Reinforced Polymer or Fiber Reinforced Plastic[1]. *FRP is a type of composite material. Composite materials are a combination of a Matrix (continuous phase) or binder material which is a polymer (thermosetting or thermoplastic) and some kind of reinforcement (dispersed phase).* (FELDMAN, D., 1989)

In recent times the use of composite materials for construction is gaining popularity specially Fiber Reinforced Polymer composites as a building material. Buildings have been made from the same small selection of materials for the last 100 years – most commonly masonry, timber, steel and concrete. However composites are emerging with an increasing role in building materials. In both new construction projects and renovation work, design professionals are continuing to discover the advantages of plastic composite building products, including durability, light weight, corrosion resistance, high strength, and low maintenance requirements.

Growing population of India demands development of cost effective materials for cost effective housing for urban and rural poor. Scarcity of timber demands for an alternative material. Research and development of FRP and its low cost derivatives, efficient design and construction practices is the need of the time to meet these demands. FRP is a high performance material, however it is slow to gain acceptance in structural applications. There is a lot of research and education is necessary in this field so that this high performance material FRP can be used in primary structural applications which can serve in multiple kinds of buildings and building applications.

Roof form and structure plays a very important role in designing a building. If we can use unique advantages of FRP in roof construction, this would open new possibilities for the designers. This dissertation is an attempt to study and analyze various roof forms made of FRP for buildings with respect to structural strength and cost.

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[1] So called because of the fiber content in a polyester, vinyl ester or other matrix.

1.2 IDENTIFICATION OF PROBLEM

Properties such as durability,high strength, light weight, corrosion resistance, weather resistance and low maintenance requirements etc. make FRP (Fiber Reinforced Polymer)a unique construction material with a promising future. The advantages of FRP composites have shown that they will play a significant role in future of architecture and building construction.

1.2.1 LIGHT WEIGHT AND HIGH STRENGTH

FRP has high specific stiffness and strength. The structures made with FRP are very light in comparison to its counter parts like concrete or steel. The loads thus on the supporting system is drastically reduced saving significant amount of weight in the supporting structure for roofs, walls, bridges etc. Lightweight structures save time in installation, are easy to transport and lift.

1.2.2 SUPERIOR DURABILITY

One of the major advantages of FRP is that it has high degree of durability properties.

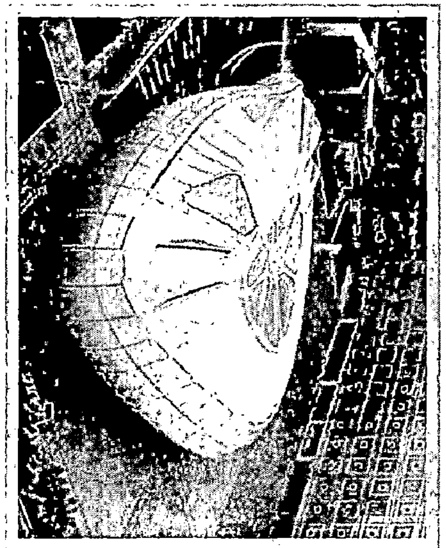
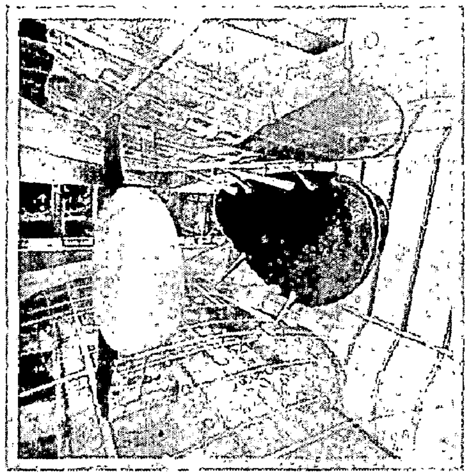
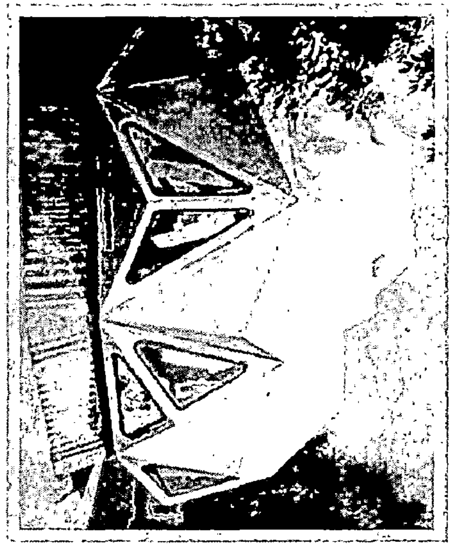
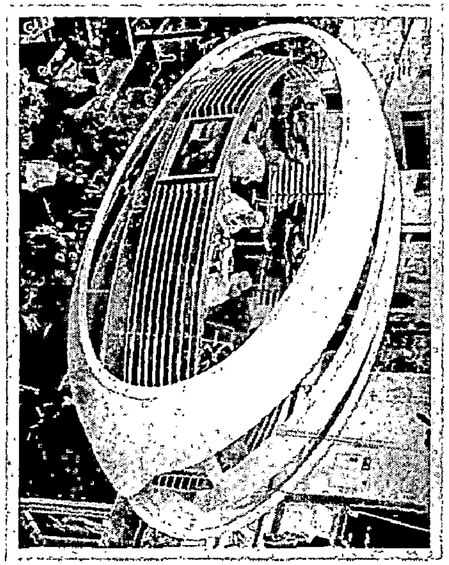
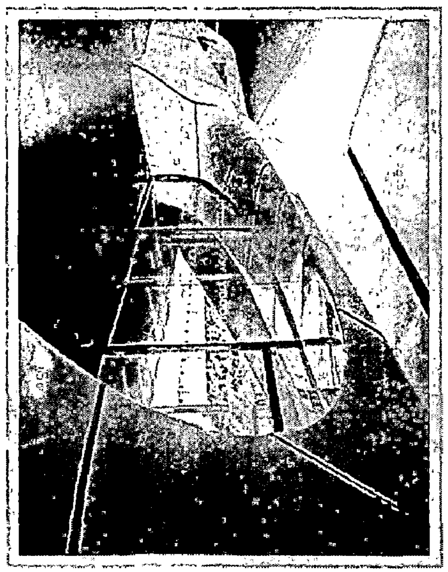
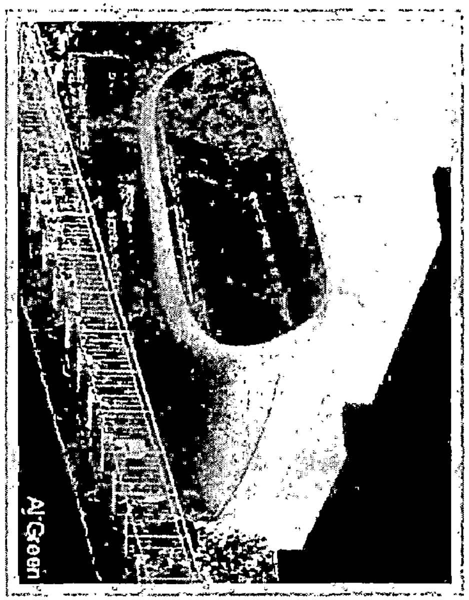
- Resistant to atmospheric degradation
- FRP is corrosion resistant, it does not rust away and it can be used to make long-lasting structures.
- Reduction in maintenance requirements, through-life costs and disruption, compared to traditional materials such as steel and concrete.

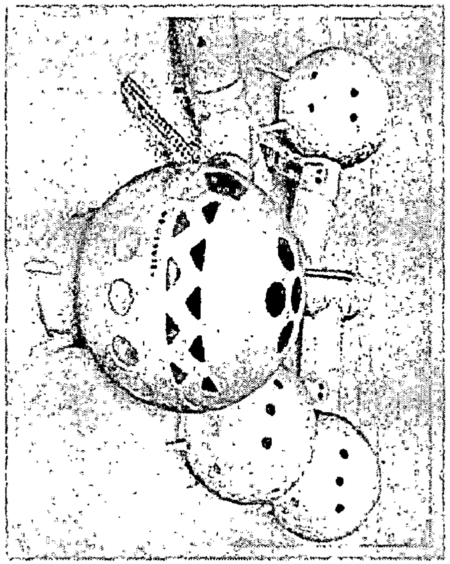
1.2.3 FORMABILITY/TAILOR-ABILITY

One of the great advantages of using FRP composites is the ability to mould complex shapes; enabling architects and designers more freedom to develop curved and unusual forms and also introduce decorative elements into the structures. It gives

- New aesthetic possibilities
- Geometrically more efficient solutions
- Tailor ability: the FRP elements can be tailored in any form , size, texture, color as required
- Possibility of inserting various services within the molds.

FORMABILITY



1.2.4 NEED FOR RESEARCH

- FRP materials are expensive than those conventionally used in building construction. However, by *producing highly efficient structures and changing the structural methodology*, FRP structures can be very competitive, and by benefits of weight reduction, the FRP solution will often be less expensive than the conventional one, especially for ***Roof structures.***
- Roof structure has the highest share on dead load of a building and the most crucial element governing whole of the design of the building. Thus if we can employ the unique features of FRP for roof structures, designers would be able to find new gateways in roof designing.
- The use of fiber reinforced composites for the new buildings and rehabilitation of structures require that ***appropriate design philosophies, guidelines and detailing*** be established and that the design is conducted using a **methodology** that ensures appropriate use of the material.
- With suitable design criteria FRP's significant advantages can be derived from the lightweight properties and their ease of handling and installation.

1.2.5 INDIAN SCENARIO

- FRP is a high performance material, however it is slow to gain acceptance in structural applications.
- Growing population of India demands development of cost effective materials for cost effective housing for urban and rural poor.
- Scarcity of timber demands for an alternative material. Research and development of FRP and its low cost derivatives, efficient design and construction practices is the need of the time to meet these demands.
- It is relatively ***new material*** for Indian building industry. There is ***absence of standards*** and building codes for this material.

There is need for research and development for creating knowledge bank for FRP and developing design guidelines for designers, architects and engineers involved in Indian building industry. Civil engineering, architecture and their extension programs must provide sufficient training on unique features of FRPs so that designers and engineers could design or specify them in construction.

1.3 AIM

Analyzing various roof forms made of FRP with respect to Function and Cost.

1.4 OBJECTIVES

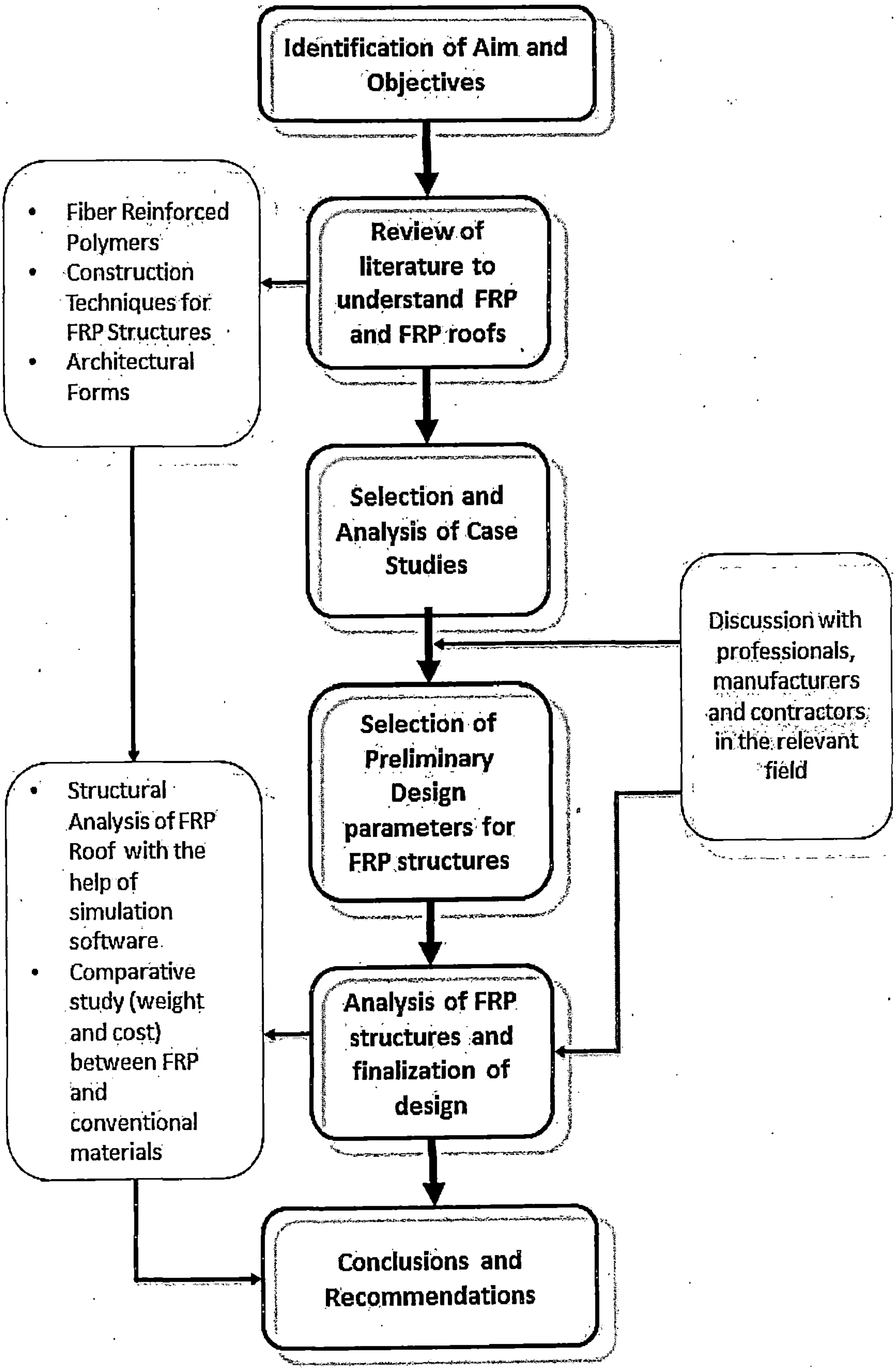
- To study construction techniques and joint details for FRP structures.
- To study FRP design parameters.
- To do parametric study of various roof forms made of FRP with respect to structural strength and cost.

1.5 SCOPE AND LIMITATIONS

Scope of the study includes:

- New construction with all FRP (self-supporting) structure is the scope of the study.
- Structural and cost analysis of single skin FRP shell structures of three forms dome, barrel vault and hyperbolic Paraboloid.
- In absence of suitable Indian Standards for FRP structures existing American and European Standards are referred.
- Digitization of structures and Finite element Analysis with higher order theory based computer program isused to analyze structures.

1.6 METHODOLOGY



CHAPTER 2. LITERATURE REVIEW

2.1 FIBER REINFORCED POLYMERS

FRP is an acronym for Fiber Reinforced Polymer or Fiber Reinforced Plastic[2]. *FRP is a type of composite material. Composite materials are a combination of a Matrix (continuous phase) or binder material which is a polymer (thermosetting or thermoplastic) and some kind of reinforcement (dispersed phase).* The incorporation of dispersed phases into the matrix which can be an engineering material such as fiber of glass, carbon, aramid, ceramic, metal or polymer is an effective method to increase strength and improve overall properties.(FELDMAN, D., 1989)

FRP composite materials used in construction industry typically consist of Glass (Glass Fiber Reinforced Polymer - GFRP or GRP), Carbon (Carbon Fiber Reinforced Polymer - CFRP) or Aramid (Aramid Fiber Reinforced Polymer - AFRP) encased in a matrix of epoxy, polyester, vinyl ester or phenolic thermosetting resins that have fiber concentrations greater than 30% by volume. (BANK., Lawrence C., 2006)

FRP composites have been used successfully in construction such as production of cladding panels, roof lights, canopies etc. Unfortunately, the use of FRP mostly in secondary structure has not fully exploited the structural benefits that can be achieved by using FRP composites. (KENDALL, D C, 2002)

2.2 APPLICATIONS

There are numerous applications of FRP in Marine Industry; Transportation- automobiles, aircrafts etc.; electrical, electronics; healthcare; Chemical plant and Pipes; Wind Mills and building and construction. Building and construction applications are mentioned below with brief explanations.

[2] So called because of the fiber content in a polyester, vinyl ester or other matrix.

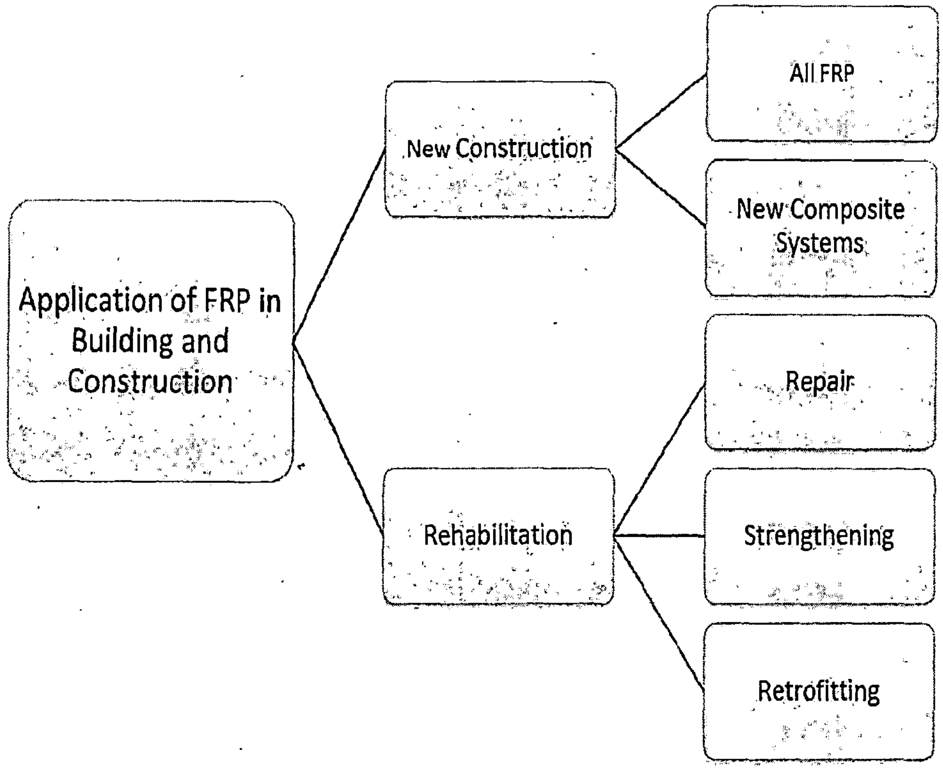


Figure 2-1 Applications of FRP in Building and Construction (EINDE, Lelli Van DEn et al., 2003)

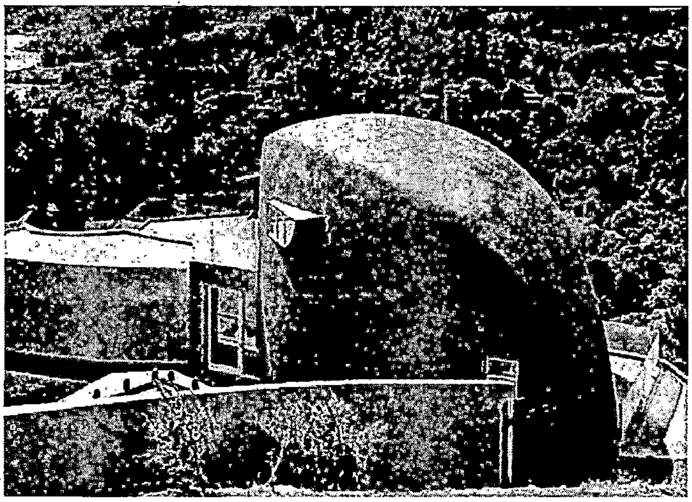
2.2.1 ALL FRP

FRP as a building material provide potential **lower lifecycle costs.** FRP Structures would be significantly lighter resulting in large savings in column and foundation costs and **enabling higher live load thus a very good choice for bridge structures.** FRP systems also have a high application potential in areas where **longer unsupported spans** are necessary or where lower weight would translate into lower seismic demands.

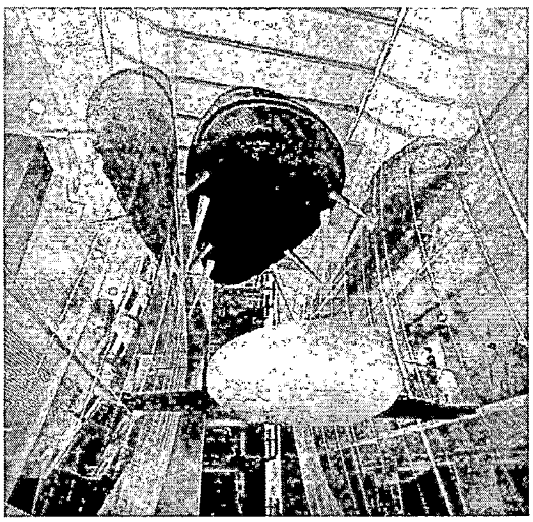
2.2.1.1 FRP Monocoque structures

Monocoque[3] construction technique has been used in automobiles and aircraft industry as FRP monocoque structures provide optimum structural efficiency to save weight, but the same philosophy can be used to increase efficiency to reduce costs, which is of greater interest in the construction industry. (KENDALL, D C, 2002)

[3]Monocoque is a construction technique that supports structural load by using an object's exterior, as opposed to using an internal frame or truss that is then covered with a non-load-bearing skin or coachwork.(WIKIPEDIA, 2011)



Illus. 1 Kreysler's award winning California Bay House is a monocoque structure consisting of nine custom molded, fire- retardant FRP sandwich panels

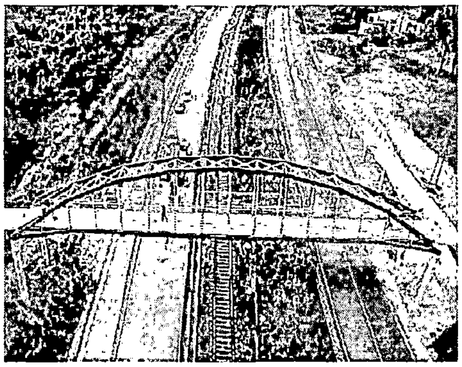


Illus. 2 Meeting Room Pods made of FRP monocoque structure

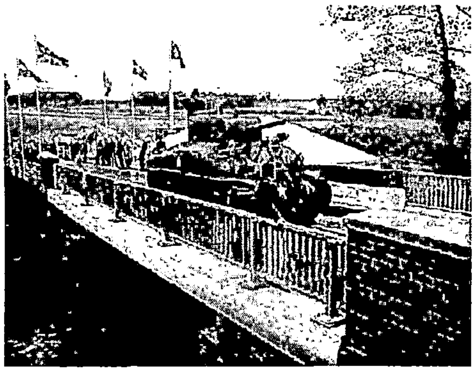
2.2.1.2 Structural Profiles

FRP profiles for new structures substitutes for conventional beams and columns in buildings and bridges. *(Refer3.1FRP Profiles)*

Illus. 3 All FRP house - Kemrock industries, Baroda



Illus. 4Composite pedestrian bridge in Lleida, Spain



Illus. 5West Mill Bridge, England

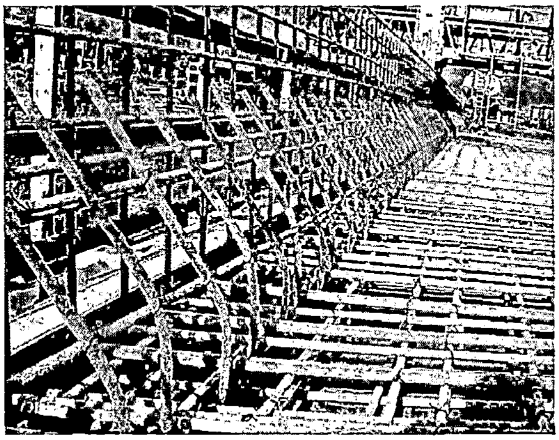
2.2.1.3 FRP Panels (Sandwich Panels)

Honeycomb is a fabricated cellular structure made of sheet material which is assembled to form nested hexagonal voids. In structural applications it is commonly used as a low-cost, low-density core in sandwich construction. Honeycomb can be fabricated from reinforced polymers. These can be used for walls, roofs etc. *(Refer 3.3.3Sandwich Construction)*

2.2.2 NEW COMPOSITES

2.2.2.1 FRP Bars or Grids for RCC

The use of FRP reinforcing bars and grids for concrete is a growing segment of FRP composites in structural engineering for new construction. FRP reinforcing bars for concrete with both glass and carbon fibers are produced by a number of companies in North America, Asia and Europe. (BANK., Lawrence C., 2006)



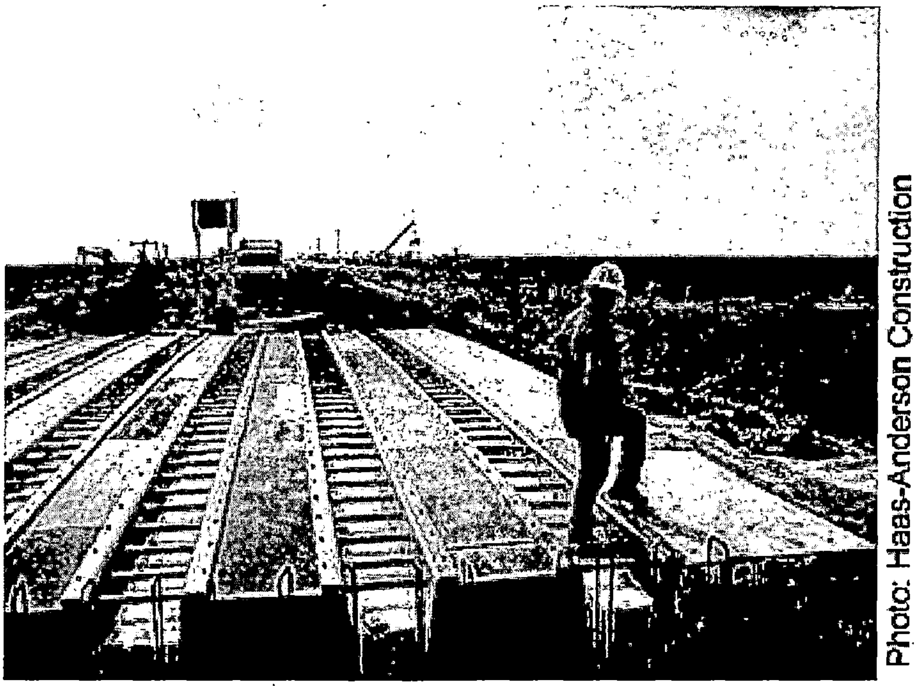
Illus. 6 FRP bars

2.2.2.2 FRP Tendons For Prestressed Concrete Members

FRP tendons for prestressed concrete members were developed in 1980.

2.2.2.3 Stay in place FRP formwork for RCC members

When used as a stay in place form, the FRP composite serves as the tensile reinforcement after the concrete has hardened. (BANK., Lawrence C., 2006)



Illus. 7 FRP stay-in-place formwork (WILLIAMS, Jim, 2011)

2.2.3 REHABILITATION

FRP materials used to strengthen and repair load- bearing structural members.

- **Strengthening:** It is applicable where the original structure's strength or ductility is increased from the loads for which it was originally designed. This increase may be necessitated by the desire of make the structure compatible with existing building codes (e.g. seismic codes) or may be desired due to changes in use of the structure.
- **Retrofitting:** FRP retrofitting is used to improve the performance of a structure when subjected to impact loading.
- **Repair:** FRP composite is used to repair an existing and deteriorated structure to bring its load carrying capacity back to the loads for which it was designed.(BANK., Lawrence C., 2006)

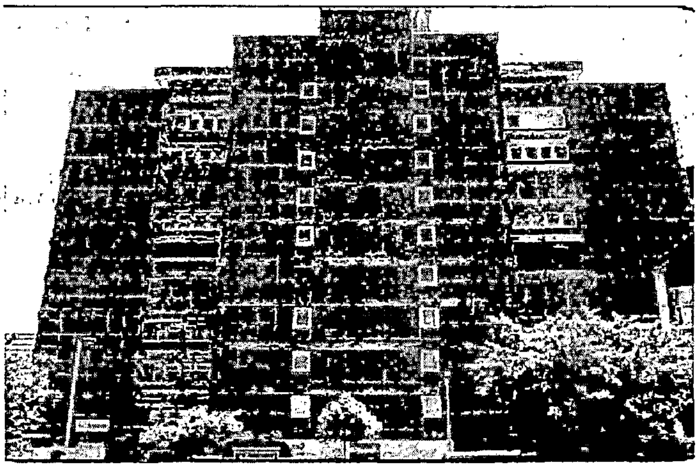
FRP rehabilitation or retrofitting has been used successfully on reinforced concrete structures, prestressed concrete structures, timber structures, and masonry and metal structures. These are primary methods for FRP retrofitting:

- **Premanufactured Rigid FRP Strips:** these are approx. 100mm wide and only 1.6 mm thick, adhesively bonded to the surface of the structural member.
- **Hand Layup:** in situ forming of the FRP composite on the surface of the structural member using flexible dry fiber fabrics or sheets of width 150-1500mm and liquid polymers.
- **NSM (Near Surface Mounting):** a thin narrow FRP strip (3mmx18mm) or small diameter round FRP bar (6mm) is inserted and then bonded adhesively into machined groove at the surface of the concrete member. (BANK., Lawrence C., 2006)

2.2.3.1 Seismic Retrofit- Clinical Services Building, NZ (2010)

The building's shear walls required a seismic upgrade and local strengthening to holes cut for new penetrations.

Fiber-wrap was applied to the areas of wall requiring strengthening. A combination of composite strips and bands of were installed around openings. The fabric strips allowed the strengthening detail to transition from wall to floor.



Illus. 8 Clinical Services Block Building, Wellington, NZ- Seismic Retrofit (FIBERWRAP, Tyfo)

2.2.3.2 Retrofitting of a Historic Masonry Load Bearing Structure in Lutyens' Delhi (May 2005)

Illus. 9 Seismic Retrofit of historic masonry load bearing structure in Lutyen's Delhi

Illus. 10 FRP composite hand lay up

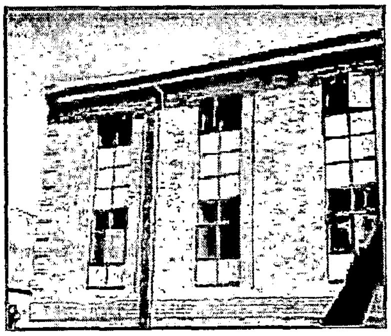
This historic mansion of prime heritage importance is located in the famed Lutyens' area of New Delhi. This sprawling one-storied mansion is a load bearing brick masonry structure with a typical brick jack-arch roof. The industrialist owner's requirement for this project was to structurally upgrade and architecturally revamp the entire structure while maintaining the heritage look and value of the mansion. The project was carried out by Fyfe India Pvt Ltd.

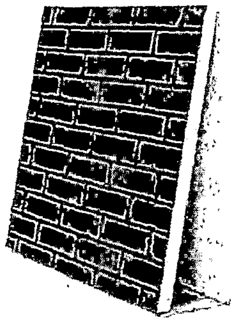
To impart ductility to the structure, the columns were encased with lightweight TYFO® SEH Composite, adding a total of only 1.3-2.4 mm to the existing profile, yet providing strength greater than steel. Walls were strengthened with the same composite to provide in-plane shear enhancement to unreinforced brick-masonry walls. (FIBERWRAP, Fyfe)

2.2.4 OTHER APPLICATIONS OF ARCHITECTURAL IMPORTANCE

FRP has diverse range of applications. These are as follows:

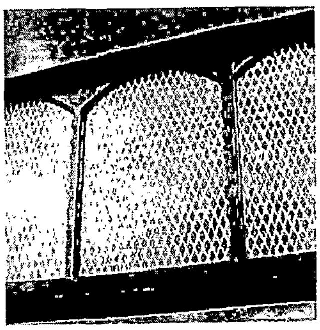
- **FRP Panels for Cladding:** FRP panels are very strong and durable (will not dent, rust or corrode) whilst maintaining an attractiveappearance.
    - Balcony panels
    - Door facings
    - Infill panels
    - Curtain walling
    - Patent glazing
    - Hygienic lining
    - Soffit panels
    - Fascia panels



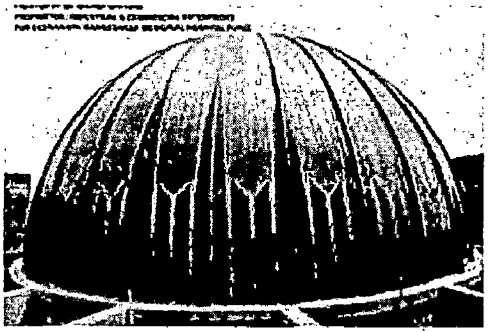


Illus. 11 FRP Cladding

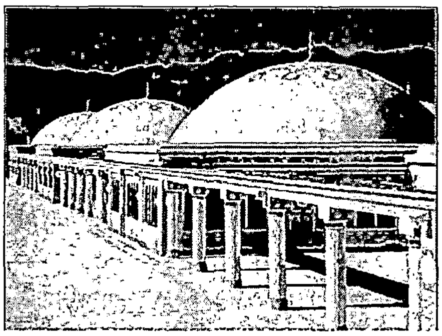
- **Glazing:** FRP products are among the toughest glazing panels available. These have high impact resistance.



- **Domes and Vaults:**



Illus. 12 The biggest Self Supporting Modular FRP Dome Skylight in India- Deenanath Mangeshkar Memorial Hospital Pune

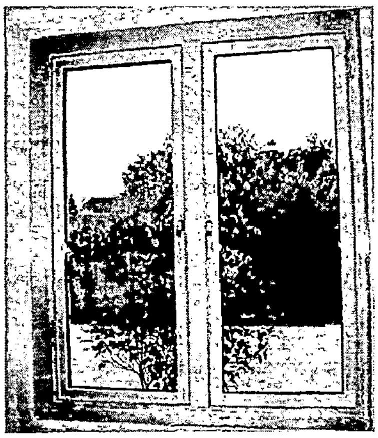


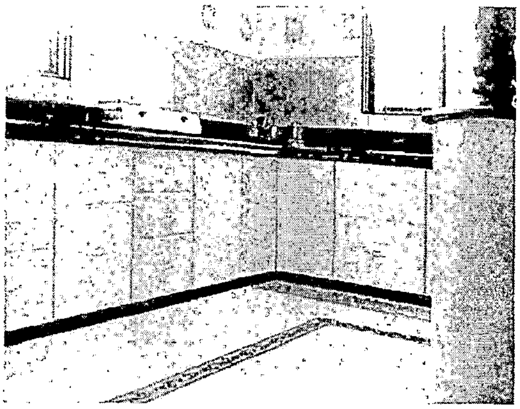
Illus. 13 Sliding Domes- the Prophet's Holy Mosque in Medina

- **Decorative Elements:**Decorative elements of the buildings like friezes, cornices, arches, decorative columns etc.

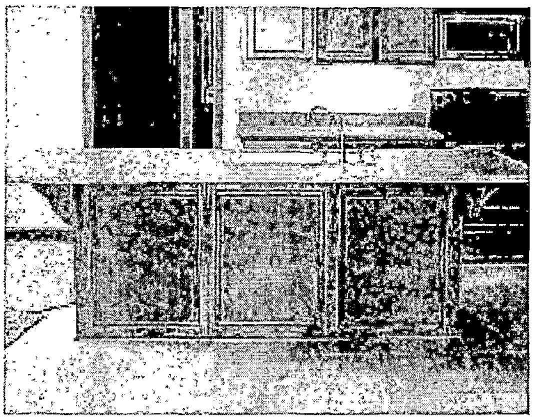
Illus. 14 The cheese Cake factory - FRP was used in all cornice, columns, medallions and finials (DEC)

- **FRP doors, Windows and Furniture:** The FRP doors and windows have the advantages of high strength,light weight, corrosion resistance, thermal barrier, sound insulation, shine/gloss preservation and durability.FRP is also used in shutters for modular kitchen cabinets.





Illus. 15 FRP modular kitchen cabinet shutters



Illus. 16 FRP solid surface kitchen work top

2.3 CONSTITUENTS

FRP composite materials are composed of two primary constituents[4] - *reinforcing fibers* and a *polymer resin matrix.*

Additionally composites contain quantities of other substances known as *fillers* and *additives,* ranging from 15-20% of total weight (and hence termed as resin system).(GANGARAO, Hota V S et al., 2007)

2.3.1 REINFORCING FIBERS

Fibers are the backbone of a composite. Diameter of fibers is very small- much thinner than human hair. Their small diameter is the reason for their extreme strength. The tensile strength of a single strand of fiber is approx. 500ksi. However thin diameter is also a major disadvantage as compressive strength is very less due to its vulnerability to buckling. (GANGARAO, Hota V S et al., 2007)

Three conditions must be met when designing with fiber reinforcement:

- Fiber type : Glass, Carbon, Aramid or others
- Fiber Form: roving, tow, mat, woven fabrics or others
- Fiber Architecture: orientation of fibers

[4] All the raw materials are produced at high temperatures in industrialized processes that require highly specialized equipment and controls.

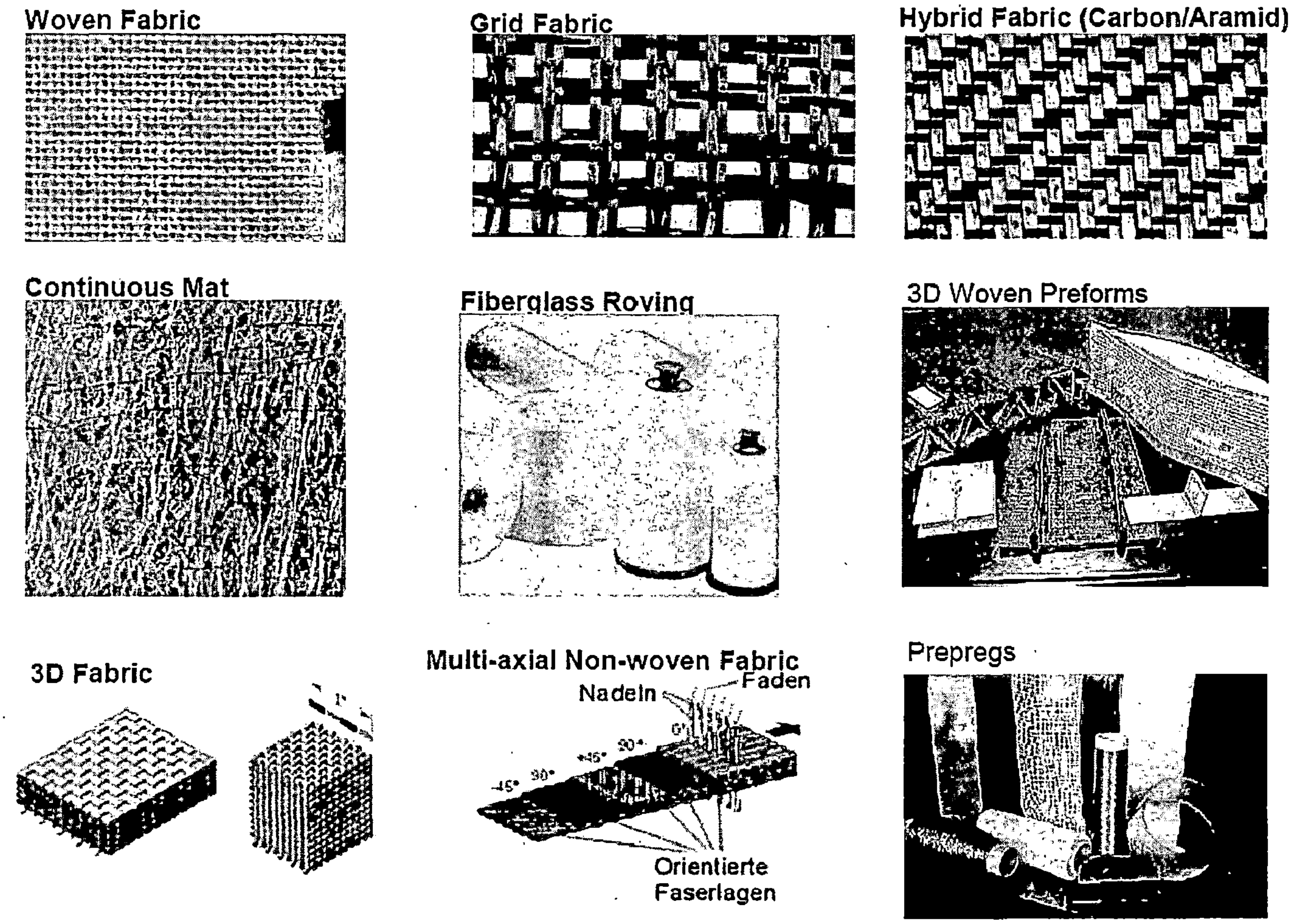


Figure 2-1 Fiber Reinforcement Forms(ZHOU, Aixi and Lesko, Jack, 2006)

2.3.1.1 Glass Fibers

Types of Glass Fibers are as follows:

- ***A-glass (alkali)***

It has High-alkali (25% soda and lime), very good resistance to chemicals, lower electrical properties.

- ***C-glass (chemical)***

It has extremely high chemical resistance. Mainly used as surface tissue in the outer layer of in chemical/water pipes and tanks

- ***E-glass (electrical)***

Low alkali, good electrical insulation and strong resistance to water (> 50% reinforcement is E-glass).

- ***S-glass (strength)***

It has 40-70% higher tensile strength than E-glass.

- ***D-glass (dielectric)***

Low dielectric constant with superior electrical properties, mechanical properties are not as good as E-glass. (ZHOU, Aixi and Lesko, Jack, 2006)

2.3.1.2 Carbon Fibers

Types of Carbon Fibers are as follows:

- ***PAN (Polyacrylonitrile) Type***

It is produced by carbonization of PAN precursor, having high tensile strength and high elastic modulus specifically designed for structural composites.

- ***Pitch Type***

It is produced by carbonization of oil/coal pitch precursor, having high heat conductivity, electric conductivity, high tensile strength and high elastic modulus. (ZHOU, Aixi and Lesko, Jack, 2006)

2.3.1.3 Aramid Fibers

- It is an organic polymer produced by spinning a solid fiber from a liquid chemical blend
- It has High strength and low density
- It has good resistance to impact (suitable for ballistic applications)

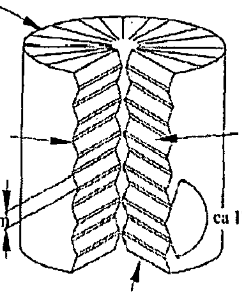


Figure 1-2 Structure of an Aramid Fiber (ZHOU, Aixi and Lesko, Jack, 2006)

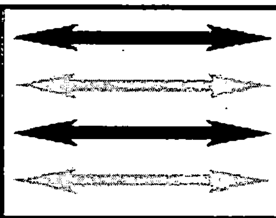
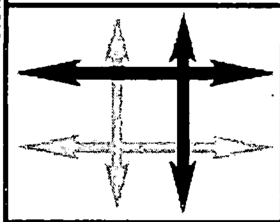
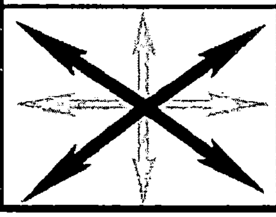
Table 1 Comparison of Fiber Properties (ZHOU, Aixi and Lesko, Jack, 2006)

Fiber	Density ρ(G/cc)	Young's Modulus E (GPa)	Strength σ(GPa)	Strength to Failure (%)	Specific Strength σ/ρ	Specific Modulus E/ρ	Diameter (micro meter)	Upper use Temperature (°C)
E-glass	2.6	69-72	1.7-3.5	3.0	1.18	27.6	5-25	350
S-glass	2.49	85	4.8	5.3	1.9	34.3	5-15	300
Carbon (HM)	1.96	517	1.86	0.38	0.95	264	7-8	600
Carbon(HS)	1.8	295	5.6	1.8	3-11	164	7-8	500
Kevlar 49 (Aramid)	1.45	135	3.0	8.1	2.1	93	12	250
Steel	7.9	200	0.45	20	0.05	25		
Aluminum	2.7	70	0.26	17	0.1	26		

2.3.1.4 Orientation of Fibers

The fiber architecture or fiber orientation refers to the position of the fiber relative to the axes of the element. Fibers can be rotated along the longitudinal axis of the element (at 0° to the longitudinal axis) , transverse to the longitudinal axis (at 90°) , or in any other direction at the designer's discretion to achieve optimum product efficiency. This gives them versatility in applications. In most cases elements are designed with the greatest strength in the direction of the greatest load for example bars and tendons.

Table 2 Fiber Orientation (FIBREGLASS, Companies Molded, 2009)

Unidirectional Fiber Orientation	Percentage of fiberglass reinforcement increases strength in direction of fiber orientation		**Reinforcement types:** Continuous strand roving **Processes:** Continuous pultrusion, compression molding
Bidirectional Fiber Orientation			**Reinforcement types:** Continuous strand roving **Processes:** Filament winding, compression molding **Reinforcement types:** Woven fabrics, woven roving **Processes:** Hand lay-up
Multidirectional Fiber Orientation			**Reinforcement types:** Chopped strands, continuous, chopped strand mat tri axial fabric **Processes:** Compression and injection molding, spray-up, pressure bag, preform

2.3.2 RESINS/ MATRIX

To harness the strength of fibers, they are encased in a tough polymer matrix, which gives the composite its bulk. The matrix serves to:

- Hold fibers together in a structural unit and spread the imposed loads to many fibers within the composite,
- To protect the fibers from environment degradation attributed to moisture, UV rays, chemicals, and
- To some extent, susceptibility to fire, and from damage to fibers during handling.

In a composite matrix shares a negligible amount of load but helps transfer the load to fibers through inter-laminar and in-plane shear. The entire load is practically taken by fibers alone. (GANGARAO, Hota V S et al., 2007)

The commonly used matrix is thermosetting polymers like Polyester, Epoxy, Vinyl ester, Phenolic, and Polyurethane.

Table 3 Approximate Properties of Thermosetting Polymer Resins (BANK., Lawrence C., 2006)

Resin	Density (g/cm³)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Glass Transition Temperature
Polyester	1.2	4.0	65	40-110°C
Epoxy	1.2	3.0	90	40-300°C
Vinyl ester	1.12	3.5	822	40-120°C
Phenolic	1.24	2.5	40	220-250°C
Poly-urethane	varies	2.9	71	-

Based on their respective properties and other practical aspects the polymers resins are used in different components as listed below:

Table 4 Applications of Various Resins in FRP products

Resin Type	Applications
Unsaturated Polyester	FRP composite material parts, Pultruded FRP profiles, FRP Rebars
Epoxy	FRP products for structural applications. With Carbon fiber used for Strengthening, FRP tendons for prestressed concrete structures, FRP stay cables for bridges, aerospace applications
Vinyl ester	FRP rebars, FRP pultruded Profiles, FRP strengthening strips, FRP rods for near surface mounting,
Phenolic	Walkway gratings for offshore platforms, FRP strengthening strips for timber structures, Plywood, engineered wood products
Poly-urethane	Structural polymer foam

2.3.3 RESIN SYSTEM

Supplementary constituents are added to cause the polymerization reaction to occur during manufacture of FRP, to modify the processing variables, and to tailor the properties of the final FRP product. (BANK., Lawrence C., 2006)

2.3.3.1 Polymerizing Agents

These are organic peroxides and are used to delay the curing reaction so that the resin does not cure in the resin bath. For example MEKP (methyl ethyl ketone peroxide). (BANK., Lawrence C., 2006)

2.3.3.2 Fillers

Fillers are particulate materials whose major function is not to improve the mechanical properties of the composite but rather to improve aspects such as extending the polymer and reducing the cost of the plastic compound. For example wood flour or fine sawdust, calcium carbonate, talc etc.

Hollow glass spheres are used to reduce weight. Clay or mica are used to reduce cost, and carbon particles for protection against UV radiation. (ZHOU, Aixi and Lesko, Jack, 2006)

Alumina Trihydrate is used for flame and smoke suppression etc.

2.3.3.3 Coupling Agents

Coupling agents are used to improve the fiber surface wettability with the matrix and create a strong bond at the fiber matrix interfacial strength through physical and chemical bonds to protect them from moisture and reactive fluids. For example: silanes. (GANGARAO, Hota V S et al., 2007)

2.3.3.4 Stabilizers

Stabilizers are added to inhibit degradation of polymers from environmental exposure to oxygen or UV radiation or high temperature etc.

2.4 PROPERTIES

PMC's (Polymer Matrix Composites) combine a resin system and reinforcing fibers, the properties of the resulting composite material will combine something of the properties of the resin on its own with that of the fibers on their own. (GURIT, 2010)

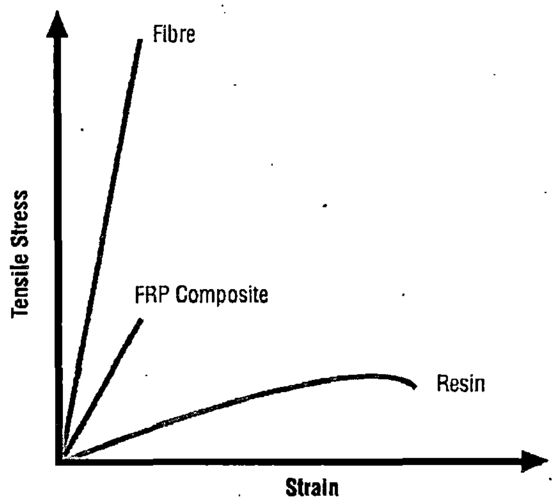


Figure 1-3 Stress strain relationship of Fiber, Resin and Composites(GURIT, 2010)

Overall, the properties of the composite are determined by:

- The properties of the fiber
- The properties of the resin
- The ratio of fiber to resin in the composite (Fiber Volume Fraction)
- The geometry and orientation of the fibers in the composite

The ratio of the fiber to resin derives largely from the manufacturing process used to combine resin with fiber. It is also influenced by the type of resin system used, and the form in which the fibers are incorporated. Since the mechanical properties of fibers are much higher than those of resins, the higher the fiber volume fraction the higher will be the mechanical properties of the resultant composite. (GURIT, 2010)

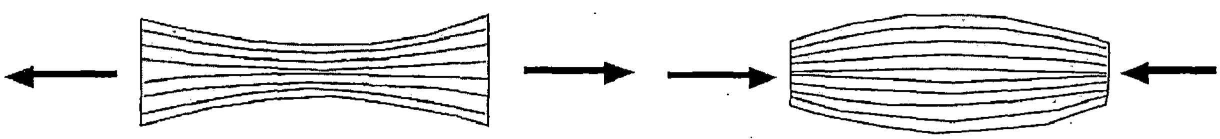
The geometry of the fibers in a composite is also important since fibers have their highest mechanical properties along their lengths, rather than across their widths. This means that it is very important when considering the use of composites to understand at the design stage, both the magnitude and the direction of the applied loads.

It is also important to note that with metals the properties of the materials are largely determined by the material supplier, and the person who fabricates the materials into a finished structure can do almost nothing to change those 'in-built' properties. However, a composite material is formed at the same time as the structure is itself being fabricated. This is a FUNDAMENTAL distinction of composite materials and MUST always be considered during design and manufacturing stages. (GURIT, 2010)

2.4.1 LOADING

2.4.1.1 Tension

The response of a composite to tensile loads is very dependent on the tensile stiffness and strength properties of the reinforcement fibers, since these are far higher than the resin system on its own. (GURIT, 2010)

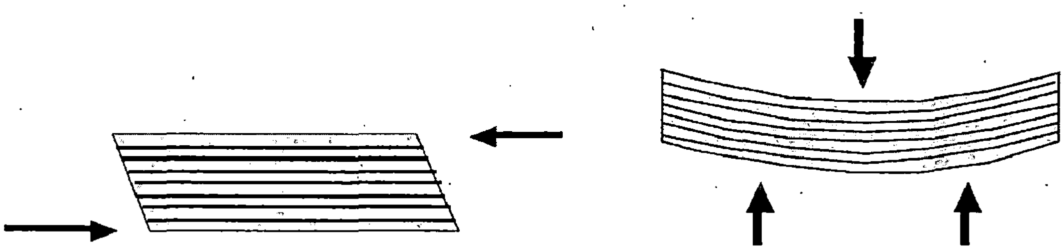


2.4.1.2 Compression

it is the role of the resin to maintain the fibers as straight columns and to prevent them from buckling.

2.4.1.3 Shear

For the composite to perform well under shear loads the resin element must not only exhibit good mechanical properties but must also have high adhesion to the reinforcement fiber. (GURIT, 2010)



2.4.1.4 Flexure

When loaded as shown below, the upper face is put into compression, the lower face into tension and the central portion of the laminate experiences shear.

2.4.2 STRESS- STRAIN

Typical stress- strain graph of FRP composite is shown below:

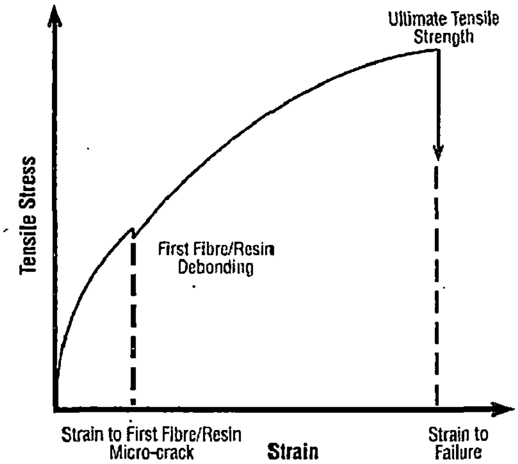


Figure 1-4 Typical Stress- Strain graph for FRP Composites (GURIT, 2010)

The strain that a laminate can reach before micro cracking depends strongly on the toughness and adhesive properties of the resin system. This can be observed from the above graph.

Increased resin/fiber adhesion is generally derived from both the resin's chemistry and its compatibility with the chemical surface treatments applied to fibers. Here the well-known adhesive properties of epoxy help laminates achieve higher micro cracking strains. (GURIT, 2010)A comparison between various resin systems is shown in Figure below.

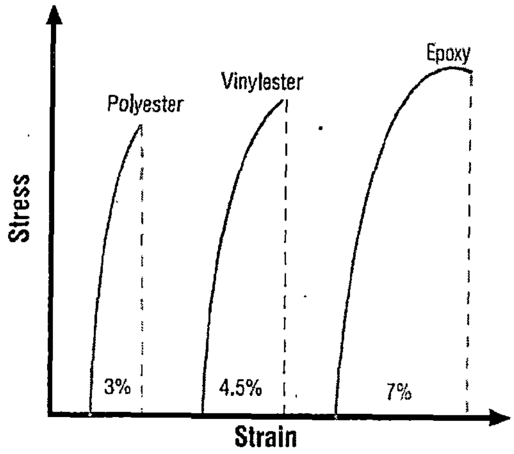


Figure 1-5 Typical Resin Stress/Strain Curves (Post- cured for 5 hrs @80 deg. C (GURIT, 2010)

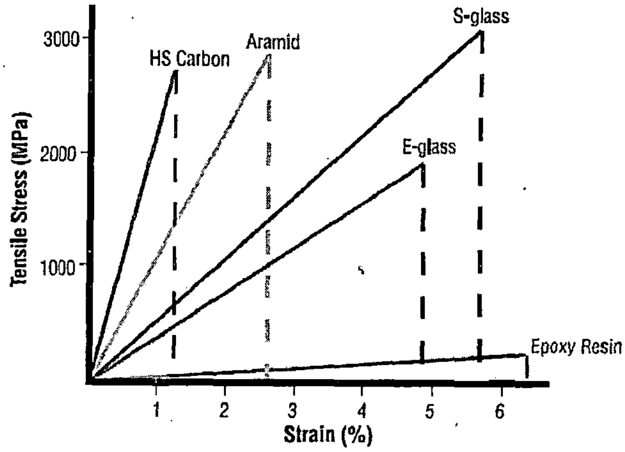


Figure 1-6 Typical Strains Failure(GURIT, 2010)

Figure above gives the strain to failure for E-glass, S-glass, aramid and high-strength grade carbon fibers on their own (i.e. not in a composite form). Here it can be seen that, for example, the S-glass fiber, with an elongation to break of 5.3%, will require a resin with an elongation to break of at least this value to achieve maximum tensile properties. (GURIT, 2010)

The FRP composite properties as given by several standards and organizations

Table 5 comparison of strength and weight properties of various building materials with FRP (BUSEL, John P., 2009)

Material	Density (kg/m³)	Tensile (N/mm²)	Compression (N/mm²)
FRP	1440	206.7	172.25
Steel A36	8000	248.04	248.04
Concrete	2400	6.89	68.9
Limestone	2720	20.67	172.25

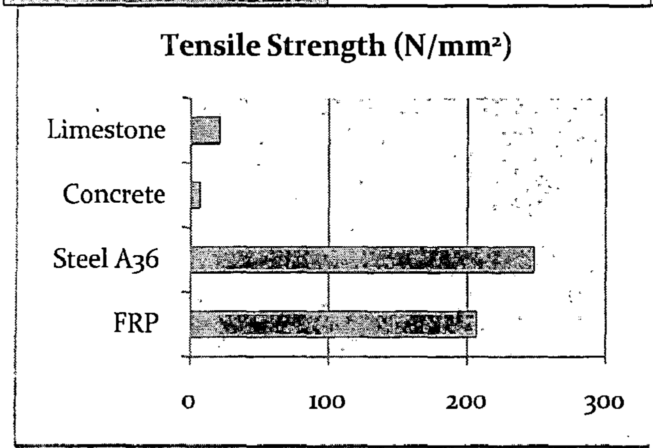


Figure 1-7 Comparison of Tensile Strength of various building materials with FRP

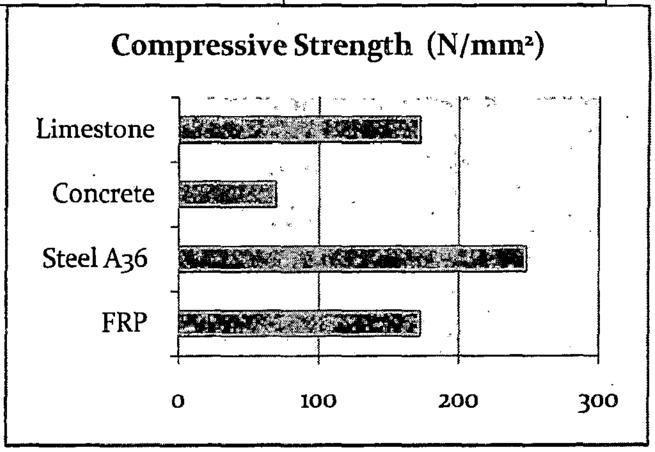


Figure 1-8 Comparison of Compressive Strength of various building materials with FRP

The above bar chart shows that tensile strength of FRP is far much greater than concrete and comparative to high strength steel.

The above bar chart shows that compression strength of FRP is far much greater than concrete and comparative to high strength steel.

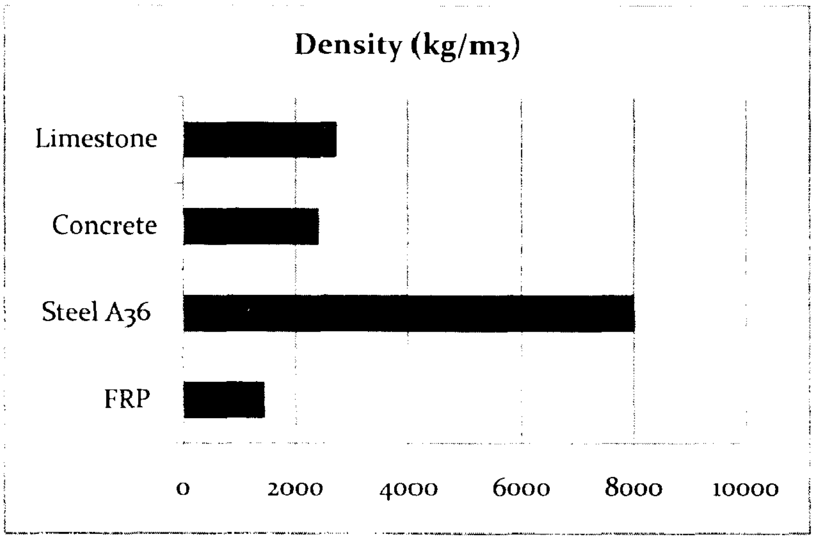


Figure 1-9 Comparison of Density of various building materials with FRP

The above bar chart shows that the density of FRP is very less in comparison to high strength steel, concrete and limestone etc. this High strength light weight property of FRP makes it a superior construction material in context with applications where dead load of the structure is to be reduced, durability is required. The standards provided by TIFAC are given below

Table 6 Mechanical/Chemical Properties of FRP Pultruded Sections Vs. Other Structural Materials(BAKSI, Sangeeta et al., 2010)

Meachanical Properties	Pultruded FRP Polyester	Pultruded FRP Vinyl Ester	Mild Steel	Wood
Tensile Strength (N/mm2)	382	401	340	80
Flexural Strength (N/mm2)	468	508	380	12
Specific Gravity	1.8	1.8	7.8	0.52
Safe Working Temperature	120	170	600	160

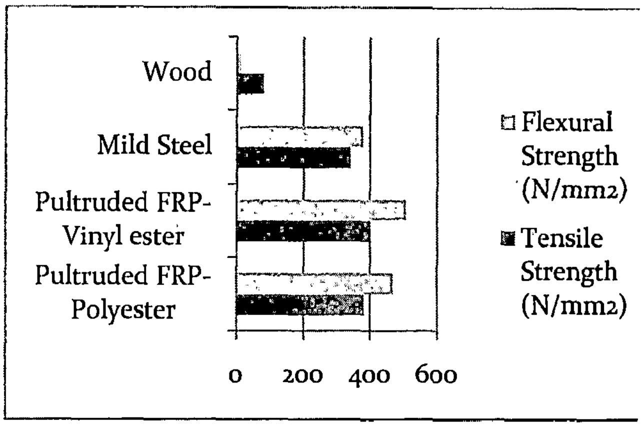


Figure 1-10Comparison of Flexural and Tensile Strengths of FRP composites and other structural materials(BAKSI, Sangeeta et al., 2010)

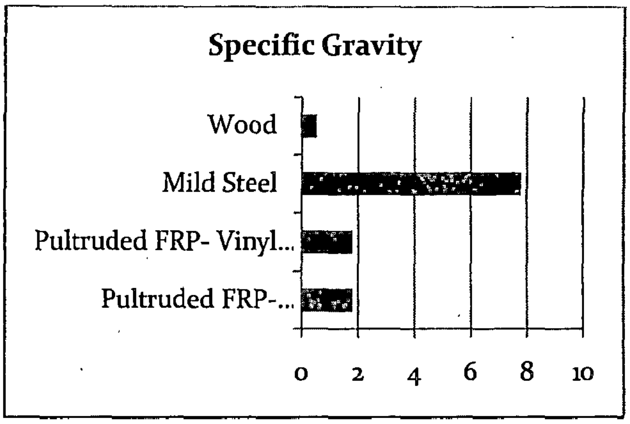


Figure 1-11 Comparison of Specific gravities of FRP composites and other structural materials (BAKSI, Sangeeta et al., 2010)

2.4.3 BEHAVIOUR OF FRP IN CASE OF FIRE

- One of the characteristics of FRPs is their low glass transition temperature[5] (Tg). When exposed to fire, FRP materials may suffer charring, melting, delamination, cracking and deformation. (BENICHOU, N. et al., 2010)
- Resins heated above Tg or Tm (glass melting temperature) will rapidly lose dimensional and mechanical integrity.
- The poor thermal conductivity of most resins, and consequently most of reinforced polymers, means that under high radiant heat high surface temperatures are reached and degradation soon becomes rapid.
- Most organic resins will degrade with the evolution of volatiles at temperatures typically between 300 and 400ºC.
- Figure below shows that for some types of matrices, debonding can be well advanced at 200°C. It also shows that the fibers themselves lose strength with rising temperatures, with carbon fiber losing the least.

  (FIBERGLASS, Industrial, 2011)

[5] Tg is the midpoint of the range of temperatures over which the FRP polymer matrix undergoes a change from hard and brittle to viscous and rubbery.

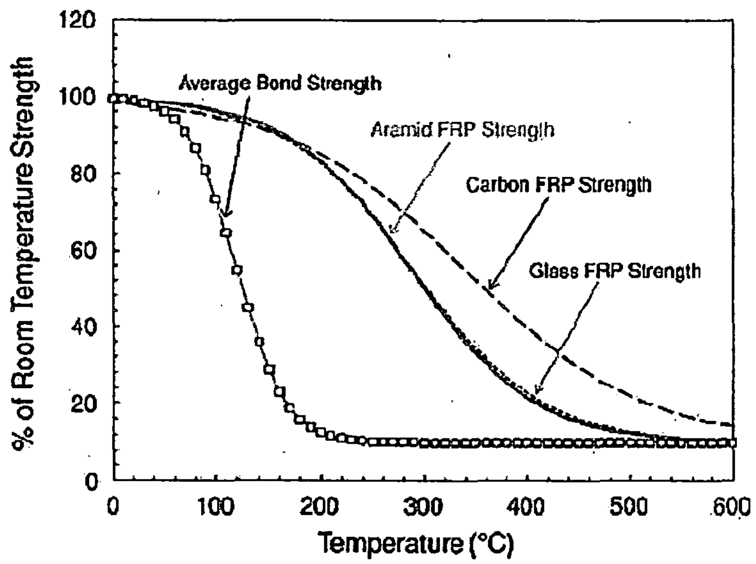


Figure 1-12Change in FRP strength and bond strength with temperature increase(BENICHOU, N. et al., 2010)

2.4.3.1 Improving fire performance

- Composites can be designed to meet the most stringent fire regulations by the use of special resins and additives. Properly designed and formulated composites can offer fire performance approaching that of most metals.
- Attempts to reduce or eliminate the tendency to burn can involve careful choice of resin and of the nature and physical form of the reinforcement, but the main emphasis is usually on including special additives in the resin composition.
- Originally fire retardant polyester resins were made with halogenated raw materials such as *tetrabromophthalic anhydride, tetrachlorophthalic anhydydide* or *chlorendic acid orb anhydride.* These products performed well until toxicity issues became important.
- In order to satisfy the needs for low toxicity products, non-halogenated products such as *alumina trihydrate (ATH)* are used. This filler is the key component in meeting the fire retardant and toxicity requirements.
- Various manufacturing companies have produced several fire retardant products. For example Architectural Fiberglass, Inc. manufactures Fiberglass Reinforced Polymer (FRP) composite products with Class 1 fire retardant resins that meet a flame spread rating of 25 or less and smoke density under 450 as characterized by the ASTM E-84[6] Tunnel Test at typical 1/8" glass mat laminate.

2.4.3.2 Smoke Control- low smoke generation and low toxicity

[6] ASTM E 84 "Surface Burning Characteristics of
Building Materials" is a standard test for general fire resistance and is widely recognized.

(FIBERGLASS, Industrial, 2011)

- **The ATH alternate:** A filler, such as ATH (aluminum trihydrate), can be added to the resin in very high concentrations (upto 50%) of the total resin volume. This makes composite fire retardant as well as reduces the smoke development. It has its share of disadvantages too thus not suitable for all kinds of applications
- **Intumescent paint:** is applied as a thin filmcoating to the exterior of FRP member. When exposed to a fire, the paint expands to a "char foam"that has 30 to 50 times its normal paint film thickness. This intumescent coating then acts as aprotective insulating barrier. Smoke generationvalues of 100 or less may be achieved through the use of intumescent coatings.
- **Furan Resin:** Frp composites made with furan resin exhibits very good high temperature strength retention properties. These also show properties of excellent inherent low flame spread and low smoke generation.
- **Phenolic Resin:** As a class of resins used for reinforced composites, the phenolics have exceptional fire retardancy, low smoke generation, and low smoke toxicity. The ignition point for phenolics is almost twice that of standard polyesters and vinylesters. It is for this reason that phenolic laminates have been used extensively in subways, underground tunnels and the "Chunnel" connecting Great Britain and France.

  In standards such as the ASTM E-84 tunnel test, the phenolic laminates routinely have a smoke generation of 10 or under. The phenolics generate only 1% to 2% of the total smoke that is typically generated by other laminates, such as the polyesters, vinylesters, and epoxies.

  (FIBERGLASS, Industrial, 2011)

2.4.4 ADVANTAGES OF FRP

2.4.4.1 Lightweight Structures

Composites can be used to save significant amounts of weight for structures supporting distributed loads such as facades, roofs and bridges. This is due to the strength and stiffness to weight of the materials and also the ability to use sandwich construction, which is a highly efficient method of supporting distributed loads. Lightweight structures can allow quicker installation, reduced temporary works or installation in difficult to access areas. (GURIT, 2010)

2.4.4.2 Formability & Accuracy

The ability to form complex shapes offers advantages to architects, giving them more freedom to develop curved forms and also introduce decorative elements into the structures. Building facades over the last 20 years have been dominated by glazed facades. There is a trend for architects to explore facades with more interesting windows than simple square windows in a rectilinear system, and this provides an opportunity for molded composites. (GURIT, 2010)

2.4.4.3 Longevity

Composites resistance to corrosion and environmental degradation offers the opportunity for reduced maintenance compared to traditional materials such as steel and concrete. (GURIT, 2010)

2.4.4.4 Toughness

Composite panels are relatively tough and impact resistant compared to traditional façade panels. In addition they are easy to repair if damaged on site or during installation. Glass fiber Reinforced Concrete (GRC) or aluminium cladding panels often have to be replaced if damaged as it is difficult to repair or re-finish them. (GURIT, 2010)

2.4.4.5 Chemical resistance

FRP is minimally reactive, making it ideal as a protective covering for surfaces where chemical spillages might occur. Structures dealing with chemicals like petroleum industries, chemical and water treatment plants, tanks, pipers, covers etc. can be constructed in FRP.

2.4.4.6 Corrosion resistance:

Unlike metal, FRP does not rust away and it can be used to make long-lasting structures.

2.4.4.7 Weatherproof:

The chemical and corrosion resistance of FRP combined with the gel-coat finish on most products make FRP ideal for using outdoors. FRP can be made UV rays proof by adding some chemicals.

2.4.4.8 Other Advantages

- Low maintenance
- Long term durability
- Part consolidation
- Small to large part geometry possible
- Tailored surface finish
- Radar transparency
- Non-magnetic
- Electrical insulation

2.4.5 PROPERTIES SUITABLE FOR ARCHITECTURE AND BUILDING INDUSTRY

2.4.5.1 Reduced mass:

- Easier, faster and more economic installation - smaller cranes required
- Due to light weight larger sections are possible to bring to the site easily, saving time and cost.
- Less disruption during installation
- Reduction in size and cost of supporting structure, foundations, etc.

- Reduced energy in transportation to site

2.4.5.2 Ability to mold complex forms:

- Complex forms can be made with FRP easily.
- Geometrically more efficient solutions
- New aesthetic possibilities

2.4.5.3 Offsite fabrication and modular construction

- Better quality control
- Improved Health & Safety.
- Faster build times
- Manufacture can take place concurrently with ground-works on site
- Services can be factory fitted into the structure
- Ability to automate and mechanize production

2.4.5.4 Superior durability:

- Resistant to atmospheric degradation
- Reduction in maintenance requirements, through-life costs and disruption

2.4.5.5 Special surface finishes and effects:

- Special finishes and wide range of aesthetically pleasing surface effects can be integrated while molding itself.

2.4.5.6 Sustainability:

- Possibility of lower embedded energy
- Possibility of recycling
- Possible use of natural fibers and resins

2.4.6 DISADVANTAGES

- High initial costs
- Low to moderate application temperature (-20 up to 80 °C)
- Hygroscopic degeneration: (under continuous long term exposure of moisture e-glass/epoxy composites in moist environment leads to certain degradation of its mechanical properties)
- Low fire resistance (sometimes with unhealthy gases)

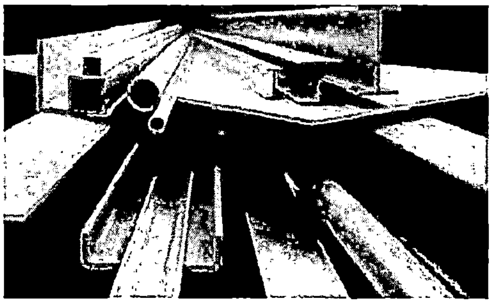
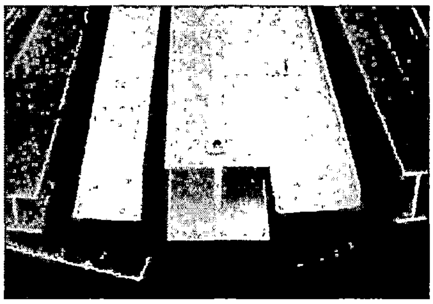
CHAPTER 3. CONSTRUCTION TECHNIQUES FOR FRP STRUCTURES

FRP can be used in various forms, shape and size for structural purposes in a building. For study we can take two major types of FRP structures viz. FRP profiles, and FRP panels or sheets.

FRP profiles are used as framed structure, and FRP sheets or panels are used for monocoque structure, roofing, and cladding and as infill panels for frame structures.

3.1 FRP PROFILES

- Most structural profiles produced in conventional profile shapes are similar to metallic materials.
- There is similarity in geometry and properties; however there is no standard geometry, mechanical and physical properties used by all manufacturers.

Illus. 17 Structural profiles (DR. ANN SCHUMACHER, 2009)

EXAMPLES

- The first large structures constructed from FRP profiles were single story gable frame structures for EMI test laboratories because of the electromagnetic transparency properties of FRP, for example EMI **building for Apple Computers** (1985, by CTI- Composite Technology Inc.)

Illus. 18 FRP gable frame structure under construction(BANK., Lawrence C., 2006)

- The next major application of FRP pultruded profiles is in cooling tower structure.
- A multi-storeyed frame building called the**Eyecatcher** was constructed by Fiberline composites in Basel, Switzerland in 1999 for Swissbau Fair as a demonstration of the potential for FRP profile shapes.

Illus. 19The Eyecatcher building

- **Startlink housing**

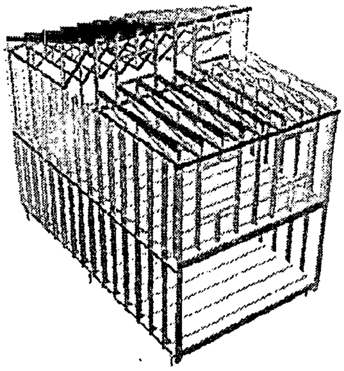


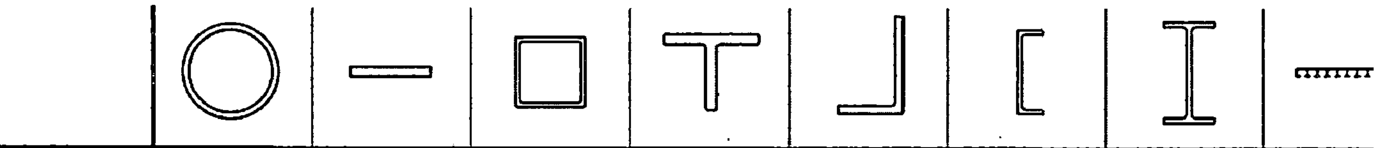
Figure 3-1Startlink housing prototype house-structure made of FRP profiles

PULTRUDED PROFILES

Production of High quality profiles with constant cross-section along the length is called Pultrusion and profiles thus produced are pultruded profiles. FRP profiles are produced with Pultrusion process which is cost effective method for manufacturing FRP structural / non- structural members.

CONVENTIONAL PULTRUDED PROFILES

- Commonly produced conventional pultruded profiles that are usually available from stock inventories include
  - Tubes
  - Flat Profiles
  - Square Tubes
  - T- Profiles
  - Angle
  - Chanel or U Profile
  - I/IL Profile
  - Plank
- Standard profile range from 2 inch x 2 inch (50mm x 50mm) to approx. 12 inch x 12 inch (300mm x 300 mm) and have thickness of ¼ inch to ½ inch (6mm-13mm) and conventional length of 12m.(BANK., Lawrence C., 2006)



Name	Tubes	Flat - Profiles	Square Tubes	T - Profile	Angle	U / UL - Profile	I / IL - Profile	Plank
Dimensions [mm]	Ra = 37.5 / 45 T = 5	B = 30 - 1220 H = 6 -12	H = 50 - 240 T = 5 - 12	H = 60 / 90 B = 60 / 72 T = 6 / 10	H = 50 - 150 B = 50 - 150 T = 6 - 12	H = 120 - 360 B = 60 -180 T = 6 - 18	H = 120 - 360 B = 60 -180 T = 6 - 18	B = 500 H = 40

Figure 3-2 Conventional pultruded profiles (DR. ANN SCHUMACHER, 2009)

- Special custom made cross-sections can be designed and ordered, for which special tools have to be designed.

3.1.1 ADVANTAGES OF PULTRUDED PROFILES

Table 7Advantages of Pultruded Profiles (RAJEEV KULKARNI, DK FIBER FORMS LTD. PUNE, 2009)

Features	Description	Benefits
Strong	Unit strength in tension & compression is approx. 20 x that of steel when these properties are combined on the basis of unit density	Optional strength as desired. Exceptionally high impact strength reduces damage potential
Light Weight	Density of pultruded components is about 20% of steel and 60% of aluminium	Higher performance at less weight. Lower shipping, handling & installation costs. Less operational energy demand.
Corrosion Resistant	Unaffected by exposure to a great variety of corrosive environment & chemicals.	Minimum maintenance costs. Long term safety. Longer life.
Electrical Insulation	Provides strength & rigidity with dielectric properties.	Lesser no. of components. Non-magnetic & safe. Predictable insulation values for wide range of frequencies.
Thermal Insulation	Pultruded components have a low thermal conductivity, 1/250 of aluminium & 1/60 of steel.	Reduces installation thickness. Eliminates condensation problems. Reduces energy operation requirements.
Consolidation	Many individual components can be combined into a large profile.	Reduced assembly cost. Reduced inventory. Fewer parts improve reliability.
Dimensional	Pultruded components are highly	No permanent deformation under high

3.1.2	**Stability**	resistant to warping stretch/swelling over a wide range of temperature & stresses.	stress. Close tolerances.
	Safety F A	The pultruded components are very strong & safe to work with. They are microbes and insect proof.	Many gratings suffer from the problem of microbes etc. due to wet or unhygienic working conditions.

CTURERS[7]

Table 8 List of FRP profiles Manufacturers (DR. ANN SCHUMACHER, 2009)

Europe	• Fiberline Composites, Denmark (www.fiberline.com) • Fiberline Design Manual (www.fiberline.dk) • Top Glass, Italy (www.topglass.it)
North America	• Strongwell, USA (www.strongwell.com) • Creative Pultrusions, USA (www.creativepultrusions.com) • Bedford Reinforced Plastics, USA (www.bedfordplastics.com)
India	• TIFAC in partnership with M/s. Sucro Filters Ltd., Pune with technology support from National Chemical Laboratory, Pune • Kemrock India (http://www.kemrock.com)

3.1.3 CODES AND GUIDELINES

At this time there are no consensus codes and guidelines for the design of framed structures using either conventional or custom pultruded structural profiles available (only EN13706, about testing and notation is available).

However, two design manuals that have been developed by consensus procedures are available:

- **The Structural Plastics Design Manual (ASCE- American Society of Civil Engineers, 1984)**
- **Eurocomp Design Code and Handbook (Eurocomp, 1996)**

3.2 JOINTS AND CONNECTIONS

[7] For Detailed List Refer Annexure

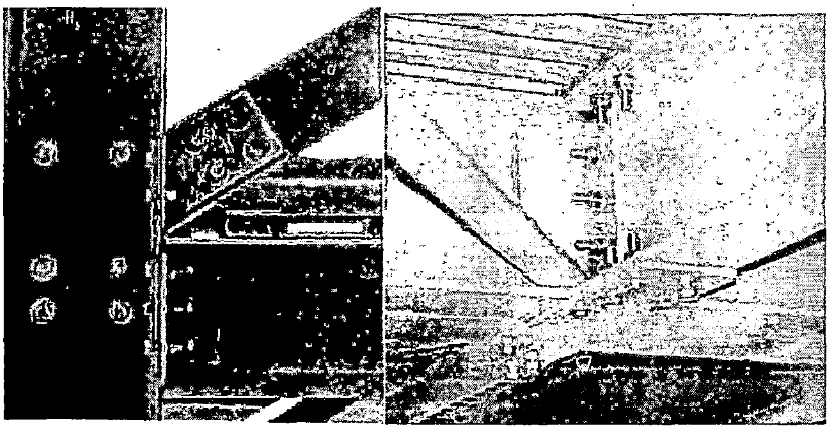
The mechanical properties of pultruded FRP are not the same as those of steel which is isotropic. FRP is anisotropic (i.e. it is directional and not the same in every direction like steel). FRP cannot be welded.(BANK., Lawrence C., 2006)

The key to bringing Pultruded FRP profiles into building construction is to find a way of joining them that is as effective as welding metals.

There are three types of connections given by Eurocomp Design Manual 1996

- Mechanical Connections- Bolted Connections
- Bonded Connections – Science of Adhesion
- Combined Connections

3.2.1 BOLTED CONNECTIONS



Illus. 20 Braced frame bolted connection(BANK., Lawrence C., 2006)

- In Bolted connections the stress concentration is in the profile and the bolt.
- It is necessary to ensure that the bolts and the profile can withstand this concentrated local stress compression.
- It is necessary to ensure that the region surrounding a group of bolts will not be torn out of the profile.
- The design procedure is comparable to the one for steel connections, but since there exist no standard GFRP material this is why each manufacturer has its own design rules for bolted joints.
- These points should be kept in mind while designing bolted connections
    - The direction of pultrusion and the direction of the force is relevant because FRP is an anisotropic material.
    - Do not cut threads in the composite material.
    - Use screws with shafts.
- Calculation of load bearing capacity of bolts depends upon:
    - Shear in longitudinal direction (0°)

- Shear in transverse direction (90°)
- Tensile force
- Minimum distances

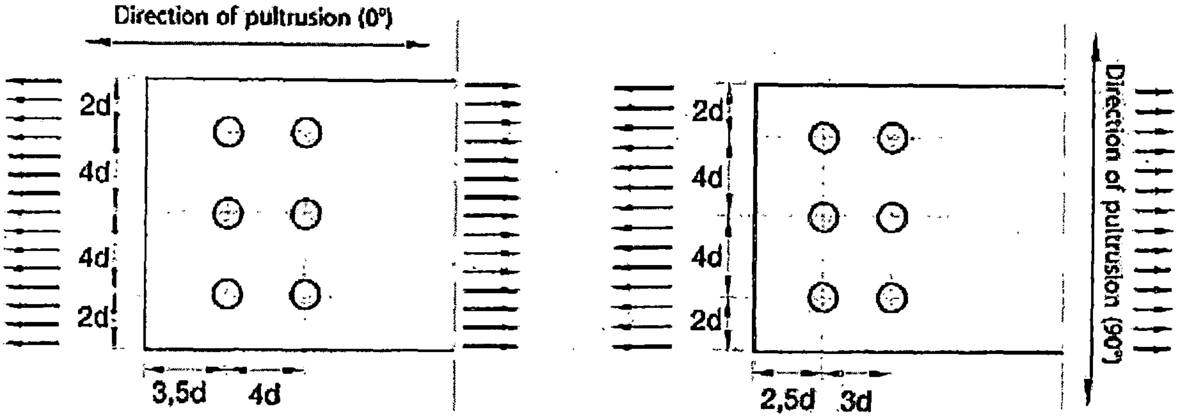


Figure 3-3 Minimum distances for bolts(DR. ANN SCHUMACHER, 2009)

3.2.2 BONDED CONNECTIONS

Reasons for selecting adhesive bonding over mechanical fastening or other joining methods include:

- Since composite materials are often used in weight critical applications, therefore methods of joining and fastening components should not add unnecessary weight to a structure.
- Cosmetic - design aesthetics
- Technical - joint performance, assembly complexity
- Economic - cost of assembly, reduced part count (GURIT, 2010)

3.2.2.1 Pre -treatment prior to bonding

For achieving strong and durable bond by adhesion adequate preparation of surfaces is very important. Some of the techniques for surface treatment are given as follows:

Table 9 Techniques for Surface Treatment prior to bonding(GURIT, 2010)

Techniques	Methods
1. **Degreasing**	• Soap + water • Pressure washing • Ultrasonic cleaning • Solvent wipe • Vapour degreasing
2. **Mechanical abrasion**	• Hand abrade • Hand tools • Grit blasting
3. **Chemical cleaning**	• Alkaline cleaning • Acid etching

	• Conversion coatings • Anodising (Sulphuric, Chromic or Phosphoric acid) • Organo-silane adhesion promotors • Proprietary polymer treatments (eg Tetra Etch)
4. Gas phase treatment	• Flame • Corona discharge • Plasma

3.2.2.2 Types of Adhesives

- Epoxies and toughened epoxies
- Polyurethanes
- Acrylics and methacrylates structural adhesives
- Polyesters
- Urethane-acrylates
- Heat stable adhesives: Bismaleimides, polyimides, cyanate esters
- Anaerobics and cyanoacrylates (GURIT, 2010)

3.2.2.3 Joint design

The bonded joints taken are made from FRP elements (adherents) subjected to axial force. The main consideration when designing bonded joints is load transfer paths. Adhesiveswork well in compression and shear loading but are not generally good in tensile loadsituations. Some simple examples of joint consideration are shown below:

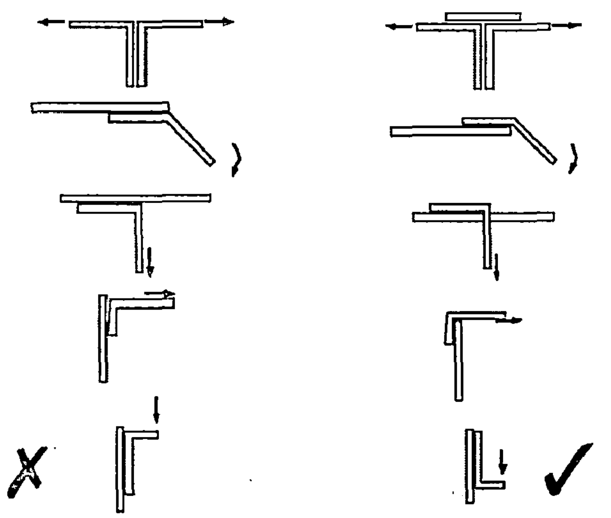


Figure 3-4 Bonded Joint configurations (GURIT, 2010)

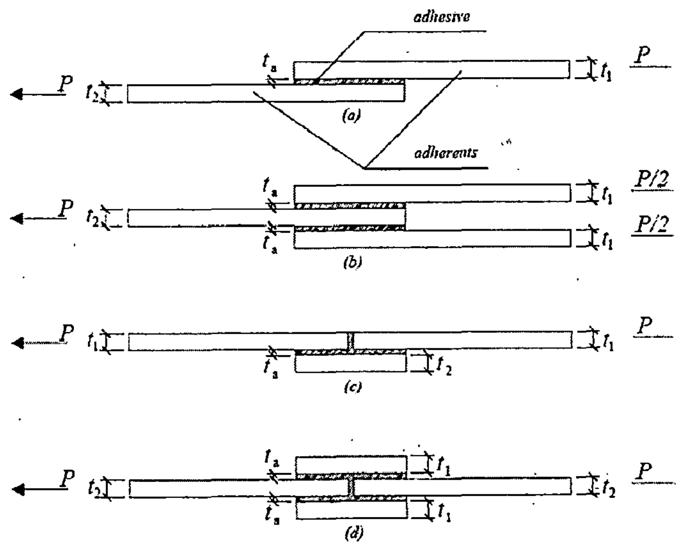


Figure 3-5 Common Types of Bonded Joints(ADVISORY COMMITTEE ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION , NATIONAL RESEARCH COUNCIL OF ITALY, 2007)

The most common types of bonded joints are:

a) Simple-lap

b) Weighted double-lap

c) Simple covered-joint

d) Double covered-joint

(ADVISORY COMMITTEE ON TECHNICAL RECOMMENDATIONS FOR CONSTRUCTION , NATIONAL RESEARCH COUNCIL OF ITALY, 2007)

3.2.3 CUSTOM PULTRUDED CONNECTIONS- SNAP-FIT

Adhesive bonding requires factory conditions to be clean and environmentally controlled to laboratory standards. Time is also needed for curing. Bolted connections have limitations because bolting is problematic for Pultrusion, which are not malleable like metals and the bolt head may not develop sufficient friction to secure the fastening.

SNAP- FIT

"A snap-fit is a mechanical joint system where part-to-part attachment is accomplished with locating and locking features (constraint features) that are homogenous with one or the other of the components being joined. Joining requires the (flexible) locking features to move aside for engagement with the mating part, followed by return of the locking feature toward its original position to accomplish the interference required to latch the components together. Locator features, the second type of constraint feature, are inflexible, providing strength and stability in the attachment. Enhancements complete the snap-fit system, adding robustness and user-friendliness to the attachment."(BONENBERGER, Paul R., 2000)

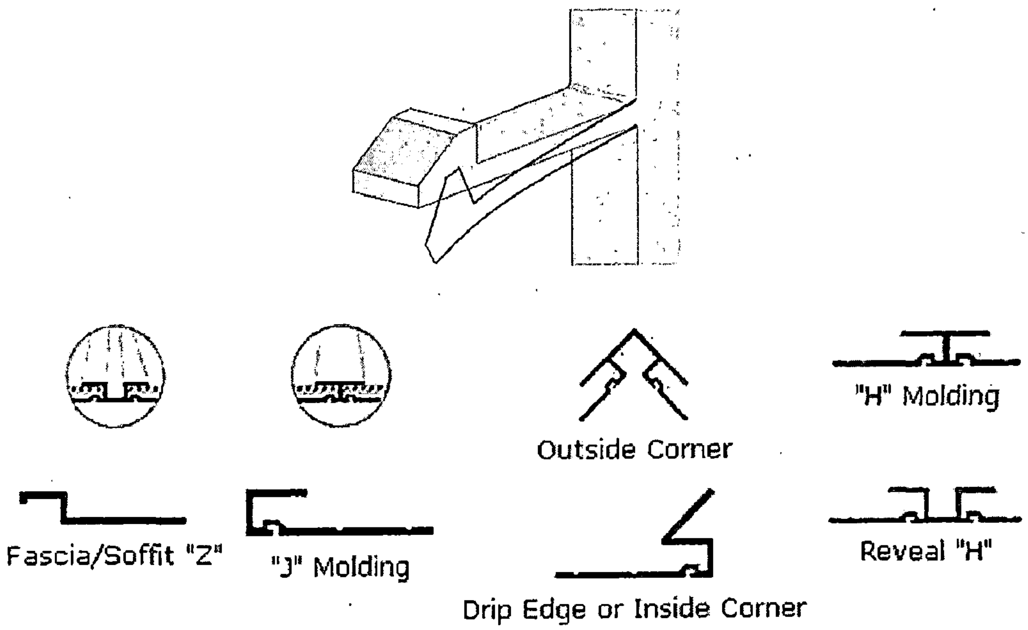


Figure 3-6 Types of Snap fit Joints (BONENBERGER, Paul R., 2000)

- Thin profiles are slightly flexible which enable the facility of ***'snap-fit'*** with its great potential for labor-saving.
- This jointing method enables components to interlock continuously along the joint line without risk of their coming apart.
- Integral gasket seals make the joints both waterproof and airtight.(SINGLETON, Mark and Hutchinson, John, 2009)

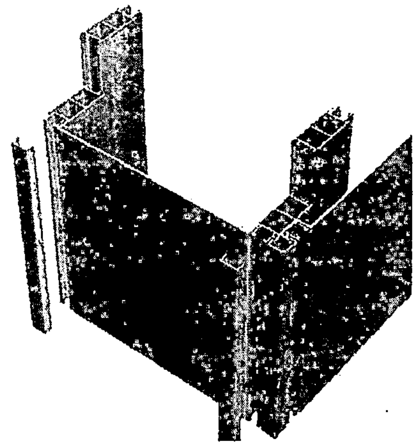


Figure 3-7 Snap-Fit Assembly (SINGLETON, Mark and Hutchinson, John, 2009)

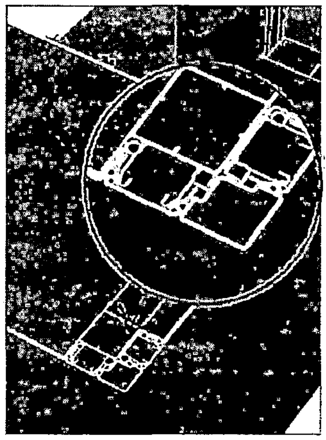


Figure 3-8 Gasket seal (SINGLETON, Mark and Hutchinson, John, 2009)

3.2.4 ADVANTAGES AND DISADVANTAGES OF DIFFERENT TYPES OF CONNECTIONS

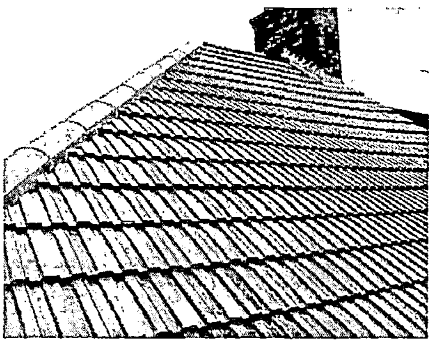
Table 10 Typical features of Different Connections between FRP members (from Eurocomp 1996 Design Manual)(EUROCOMP, 1996)

Advantages	Disadvantages
Mechanical connections	
• Requires no special surface preparation • Can be disassembled • Ease of inspection • Quasi ductile behaviour	• Low strength to stress concentrations • Special practices required in assembly; results in time consuming assembly • Fluid and weather tightness normally requires special gaskets or sealants • Corrosion of metallic fasteners
Bonded connections	
• High joint strength can be achieved • Low part count • Fluid and weather tightness • Potential corrosion problems are minimized • Smooth external surfaces • Stiffness	• Cannot be disassembled • Requires special surface preparation • Difficulty of inspection • Temperature and high humidity can affect joint strength • BRITTLE
Combined connections	
• Bolts provide support and pressure during assembly and curing • Growth of bondline defects is hindered by bolts	• Structurally bolts act as backup elements - in an intact joint, bolts carry no load

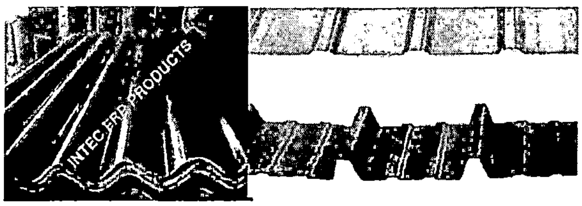
3.3 FRP SHEETS AND PANELS

FRP sheets or panels are very thin in relation to their overall dimension and thus considered as membrane or shell structures. This implies it cannot carry stress otherwise than in the plane of the membrane itself, so rigidity becomes a significant problem to basic design. Curvature is the simplest and most economical means of providing rigidity to thin sheet materials.*(Refer: 3.3.4Architectural Form)* Rigidity can be attained by several construction techniques. Some of them are discussed in the following sections.

3.3.1 TROUGHING



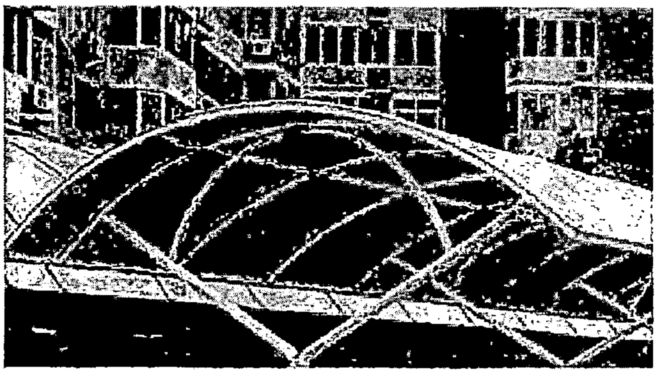
Illus. 21 FRP Roofing Panels



Illus. 22 FRP Troughed Sheets (Source: Intec FRP Products Inc.

Corrugated sheet is an example of single dimension curvature. An advance on simple corrugations can easily be achieved by shaping corrugations in the longitudinal sense so that an element of two-dimensional curvature is introduced. The troughs then become more like elongated dishes.

(LEGGATT, A.J., 2006)



Illus. 23 Curved Corrugated Sheet Roofing

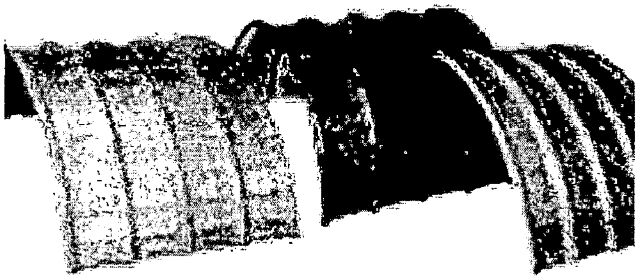


Figure 3-9Curved corrugated FRP sheets

3.3.2 RIBBING

Ribbing is a form of troughing whereby troughed sections are added to one side of a flat sheet in order to give it rigidity. It is a useful technique where it is absolutely essential to provide a flat finished surface to the FRP unit and where sandwich construction is inappropriate.

3.3.3 SANDWICH CONSTRUCTION

A sandwich structure consists of two high strength skins separated by a core material. Inserting a core into the laminate is a way of increasing its thickness without incurring the weight penalty that comes from adding extra laminate layers.However, sandwich construction is more expensive than single skin construction. (GURIT, 2010)

The core acts like the web in an I-beam, where the web provides the lightweight 'separator' between the load-bearing flanges.

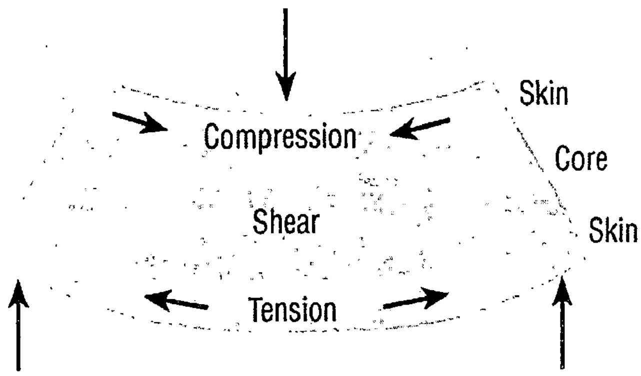


Figure 3-10 Sandwich Panel Loading*(Source:* **(GURIT, 2010)**

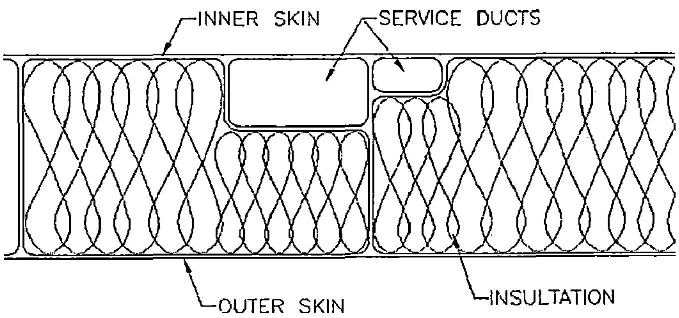


Figure 3-11Composite Panel with integral service ducts, insulation etc.*(Source:* **(KENDALL, D C, 2002)**

One of the most important properties of a core is its shear strength and stiffness. In addition, particularly when using lightweight, thin laminate skins, the core must be capable of taking a compressive loading without premature failure. This helps to prevent the thin skins from wrinkling, and failing in a buckling mode. Foamed plastic, timber (balsa wood), void-formers fashioned from paper or cardboard etc. are used as core material.(GURIT, 2010)

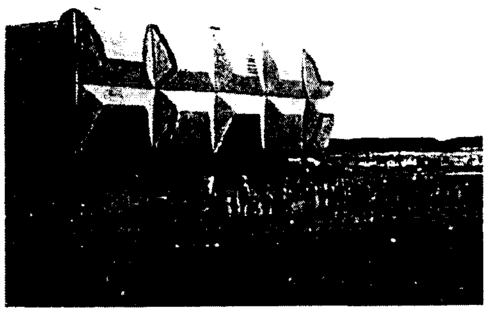
3.3.4 ARCHITECTURAL FORM

The comparatively low modulus of elasticity of FRP makes it unsuitable for use in conventional structural forms, such as, for instance, beam and slab construction.

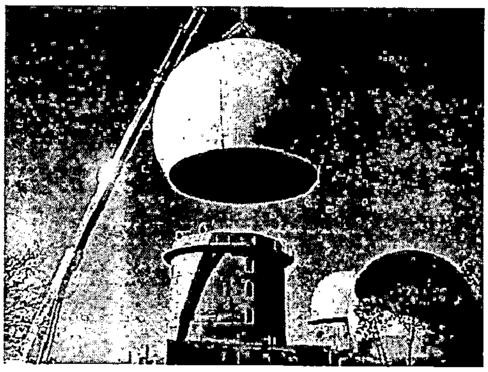
"Although troughing, ribbing and sandwich construction are widely used to achieve rigidity they are sometimes necessitated by functional constraints on the geometry of the finished unit, but perhaps more often they are indication that the designer has not allowed his imagination to venture into much more elegant realm of overall curvature or shape of the unit .... The designer will surely obtain the maximum satisfaction from his work when he achieves a shape which is an elegant synthesis of ***visual*** *pleasure,* ***rigidity, functional performance*** *and* **economy** *of material. "*(LEGGATT, A.J., 2006)

The use of mouldedFRP opens up new possibilities to producedramatic geometric forms *(broadly classified into three types, viz;* ***Folded Plate structures, Shell Structures, and Stressed Skin Tensile Structures****)*as illustrated in the following **examples**:

Figure 3-12 Spherical Shell Structure- 'Igloo' buildings. (Picture courtesy of Intravision AS.)



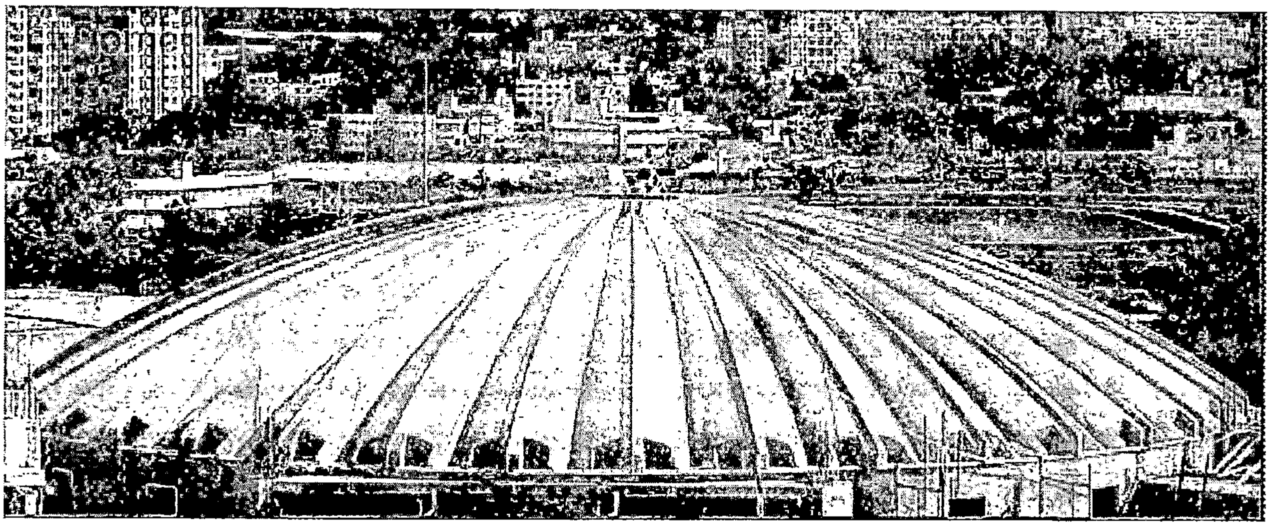
Illus. 24 Prismoidal Folded Plate FRP Façade-Shore-side Building, Finland(BENJAMIN, B.S., 1982)



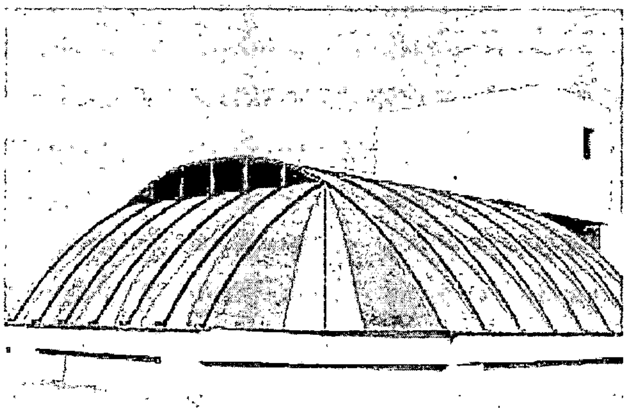
Illus. 25 Radome Structure(KENDALL, D C, 2002)

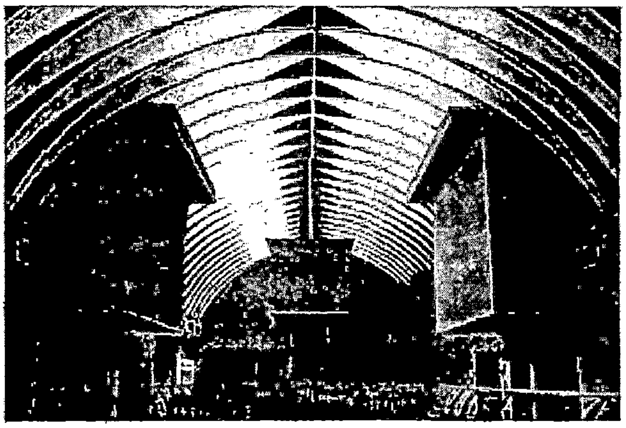
Illus. 26 Shell Structure- Home Planet Zone, 36m Dia. FRP building- Millenium Dome, London (KENDALL, D C, 2002)

- **'Igloo' concept** (Figure 3-12) developed by Intravision Architects in Norway , could provide some very inspirational buildings in addition to being remarkably efficient and cost effective.
- **The Home Planet Zone** (Illus. 26) was a 36 m diameter clear span FRP shell structure capable of supporting full wind and snow loading as the intention was to relocate it after the exhibition in 2000. Such a structure could be used for numerous applications such as schools, offices, industrial, retail, exhibitions, etc. (KENDALL, D C, 2002)

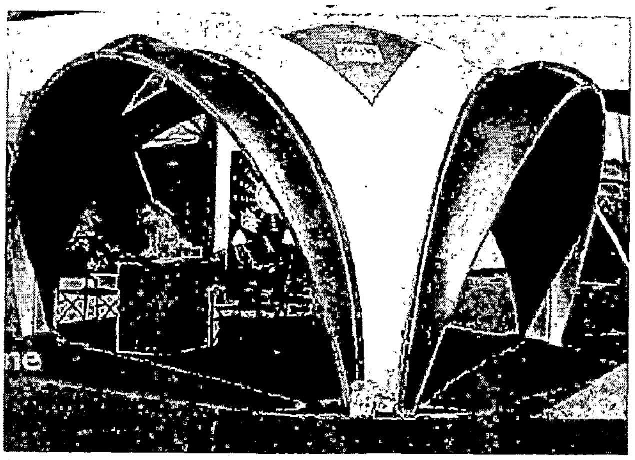


Illus. 27 FRP Composite Folded Plate Dome Structure ***(Source: http://www.ice-Fiberglass.com/html/photo_skylight.html)***

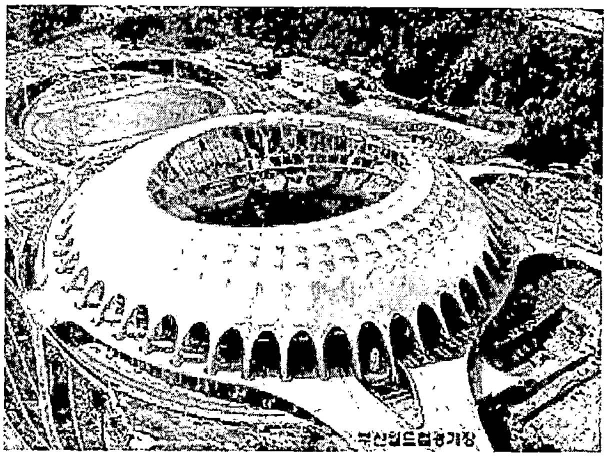




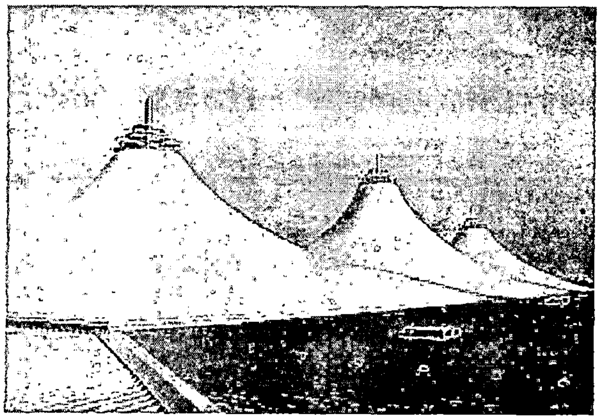
Illus. 28 FRP Vault Structure - Skylight *(Source:* http://www.ice-Fiberglass.com/html/photo_skylight.html*)*



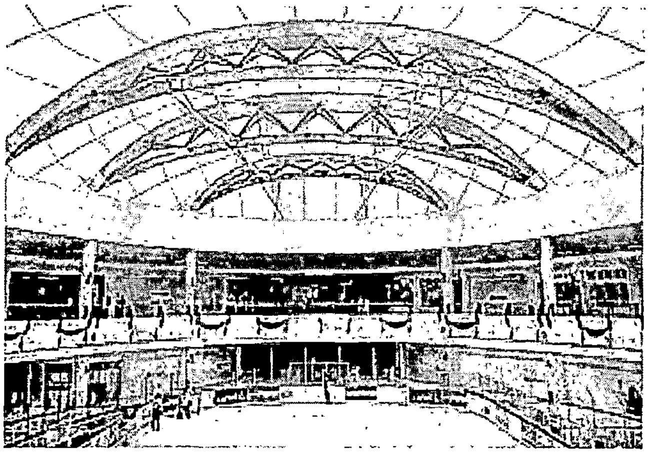
Illus. 29 Synclastic Shell Structure: FRP outdoor Shelter ***(source: http://www.ice-Fiberglass.com)***



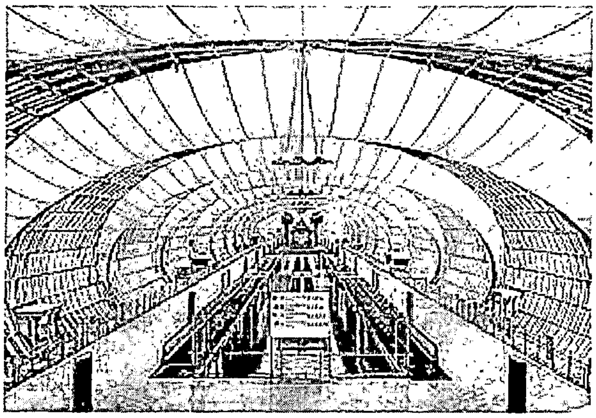
Illus. 30 Tensile Structure- PTFE coated Fiberglass fabric in District Mosque in Kota Samarahan



Illus. 31 Tensile Structure- PTFE Coated Fiberglass- Alain, Ceremonial Hall



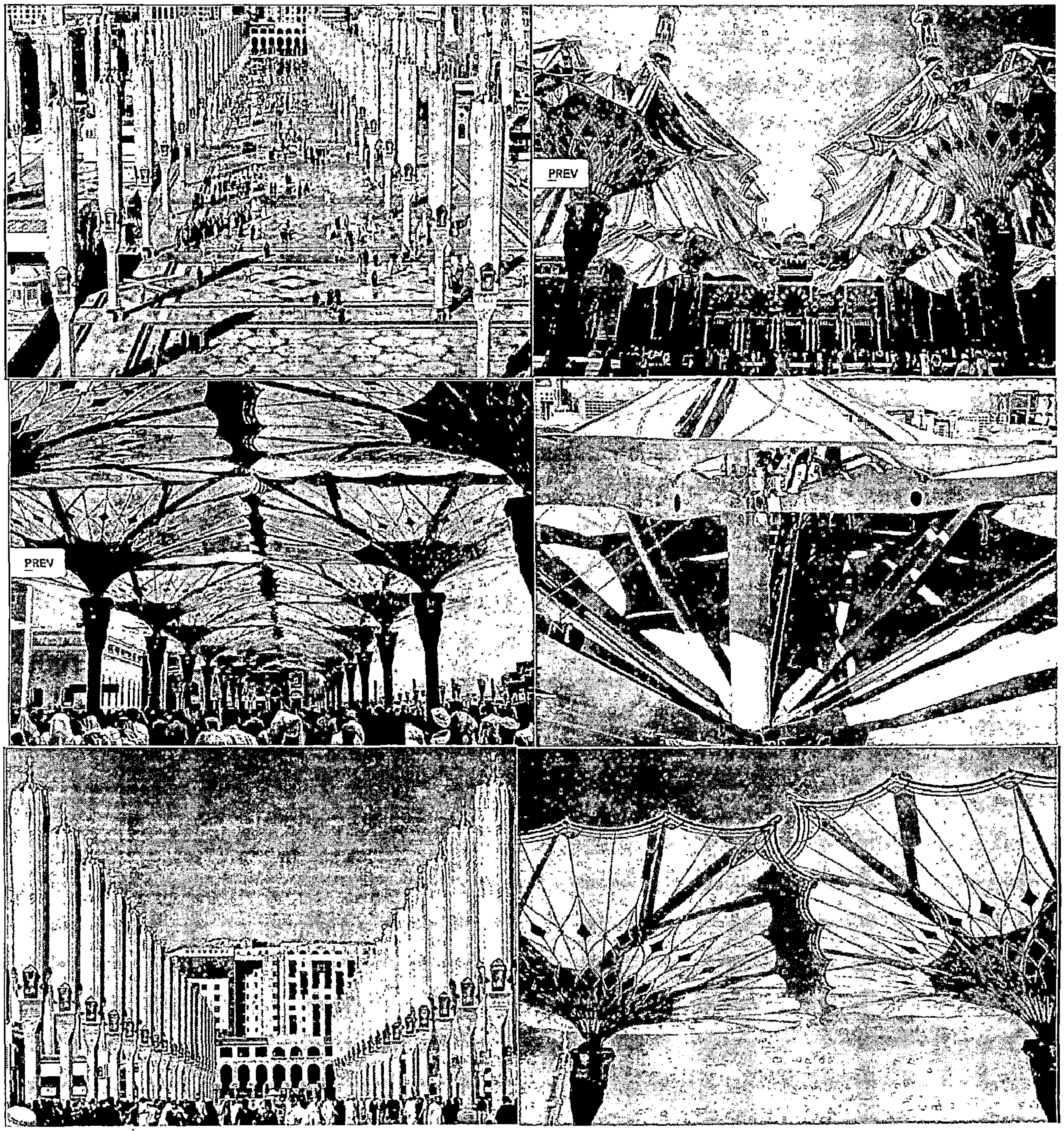
Illus. 32Tensile Structure- PTFE coated Fiberglass fabric- Auchan Food Market



Illus. 33 Tensile Structure- PTFE coated Fiberglass- Suvarnabhumi Airport Bangkok

- Medina Haram Piazza Shading Umbrellas(2007 – 2010)(PCT, 2011)
  - These 250 umbrellas provide a convertible roof (Stressed Skin Structure)that shelter 106,000m2 of the piazza from the elements and also improve climatic conditions.

- One single open umbrella structure spans an area of 625 m^2. When closed, the arms cover the membrane while additional claddings on top of the arms form a prismatic casing to protect the folded membrane.
- The arm claddings and cladding attachments are built from a lightweight composite sandwich structure of glass Fiber epoxy resin laminate, providing high torsional stiffness. They are then fixed to the flexible umbrella arm systems.
- The Fabric used is Teflon coated Fiberglass.

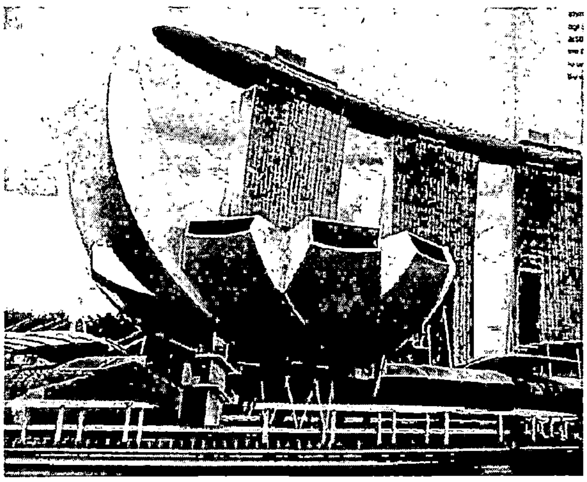


Illus. 34Medina Haram Piazza Shading Umbrellas*(Source:*
***http://www.pct.ae/architectural_composites.php?section=4*)**

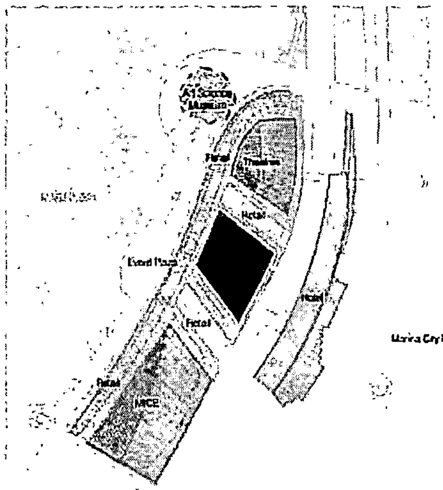
CHAPTER 4. CASE STUDIES

4.1 INTERNATIONAL

4.1.1 ART AND SCIENCE MUSEUM- SINGAPORE



Illus. 35 Art Science Museum (Part of Marina Bay Sands), Singapore(SAFDIE, Moshe, 2011)



Illus. 36 Site Plan(SAFDIE, Moshe, 2011)

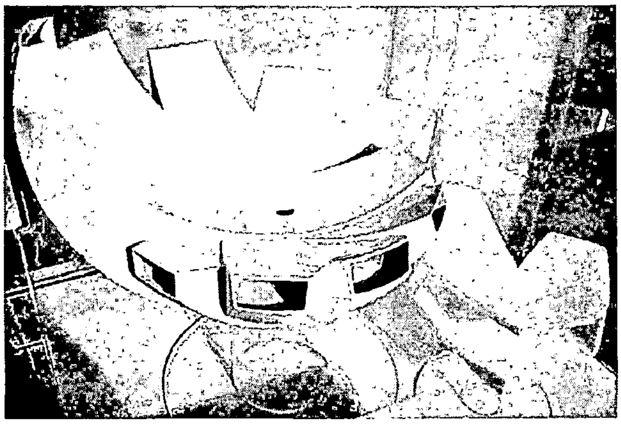
4.1.1.1 Introduction

This building is surrounded by a 40,000-square foot lily pond reflecting pool, with views of Marina Bay Sands in backdrop. Below isbasic information of the building (SAFDIE, Moshe, 2011)

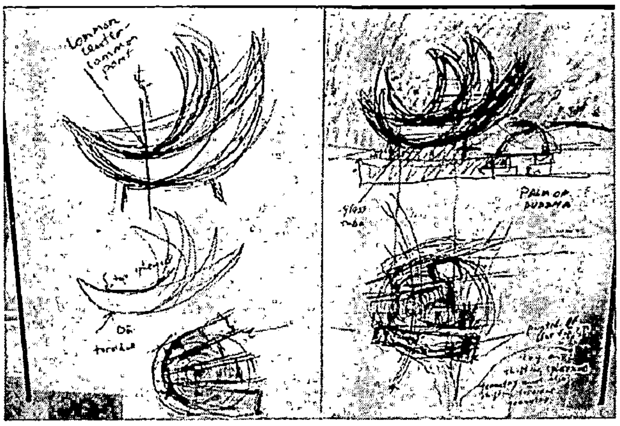
Location:	Singapore
Use:	Exhibition
Client/Owner:	Marina Bay Sands Ltd. (Las Vegas Sands Corp.)
Architect :	Moshe Safdie - Safdie Architects
Façade Engineers:	Arup Facades
Built up Area:	6000 sqm
Height:	Highest level 62m
Building Envelope Skin material:	Glass Fiber Reinforced Polymer (12500 Sqm)
Completed in	February 2011

4.1.1.2 Design and Form

- It has a form of Lotus flower with 10 Petals or Fingers, also described as "The Welcoming Hand of Singapore" by Mr. Sheldon Adelson, the visionary chairman of Las Vegas Sands Corp.

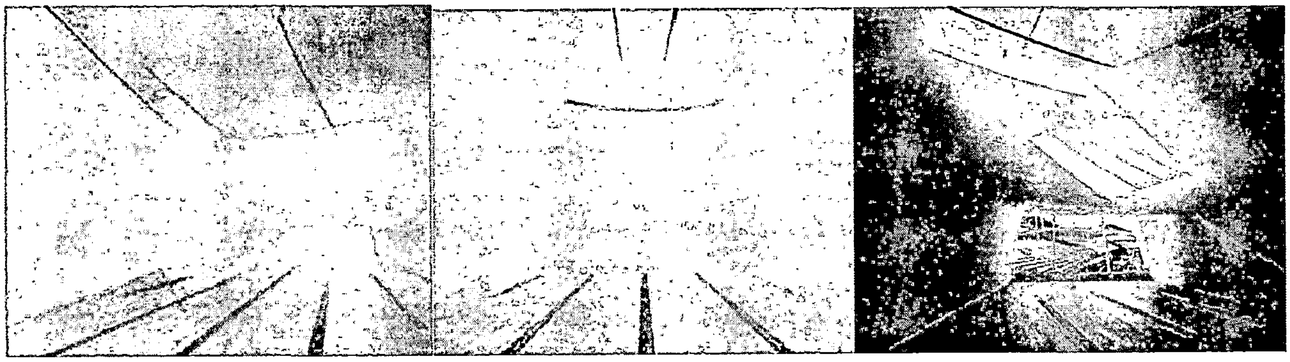


Illus. 37 Model of Lotus form of Artscience Museum(ARCHITSTUDENT, 2011)



Illus. 38 Concept Development for the Form by Moshe Safdie- the Architect(ARCHITSTUDENT, 2011)

- These fingers/ petals are anchored by a round base in the middle. The design of each finger possesses different gallery spaces featuring skylights at the "fingertips" that illuminate the curved interior walls.



Illus. 39Skylights at finger tips and interior curve walls of galleries (MARINABAYSANDS, 2011)

- The museum is entered through a free-standing glass pavilion. Large elevators and escalators convey the public to the lower and upper galleries. In total, there are three levels of galleries.

(SAFDIE, Moshe, 2011)

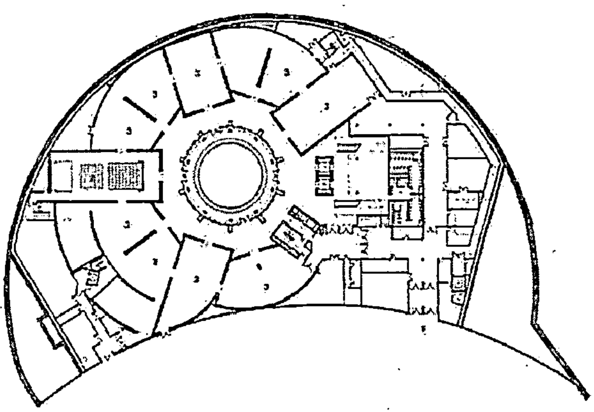


Figure 4-1 Basement Floor Plan (SAFDIE, Moshe, 2011)

1	*Main Entrance*
2	*Assembly Hall*
3	*Gallery*
4	*Pond*

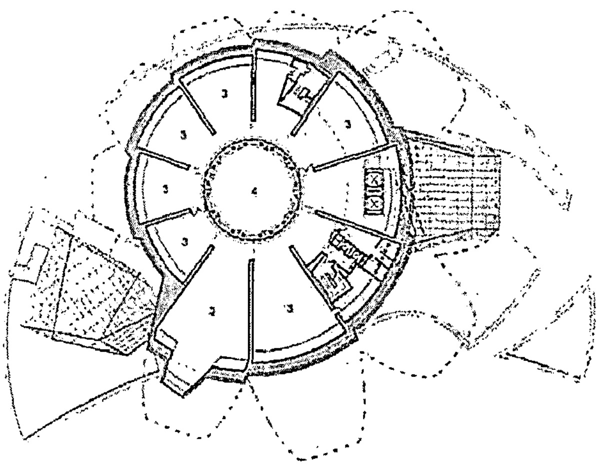


Figure 4-2 Third Floor Plan (SAFDIE, Moshe, 2011)

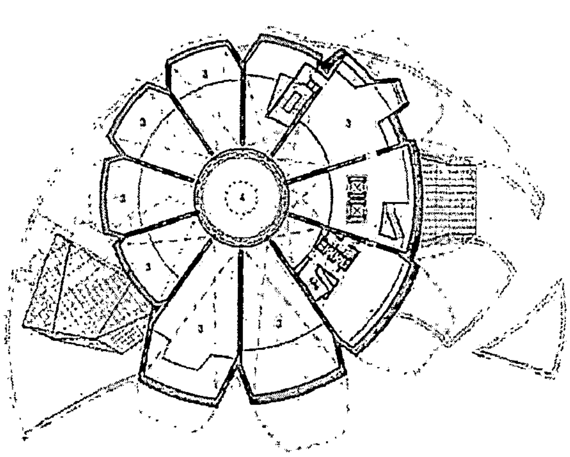


Figure 4-3 Fourth Floor Plan (SAFDIE, Moshe, 2011)

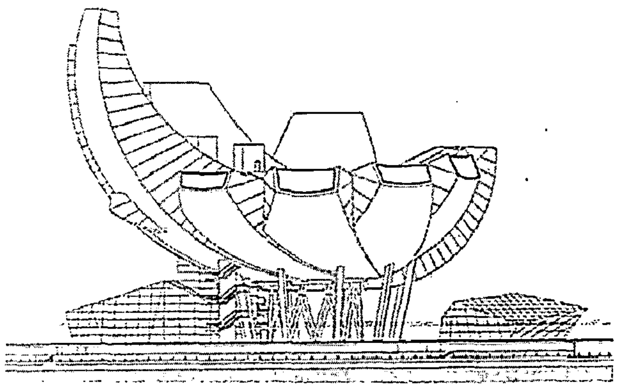


Figure 4-4 West Elevation (SAFDIE, Moshe, 2011)

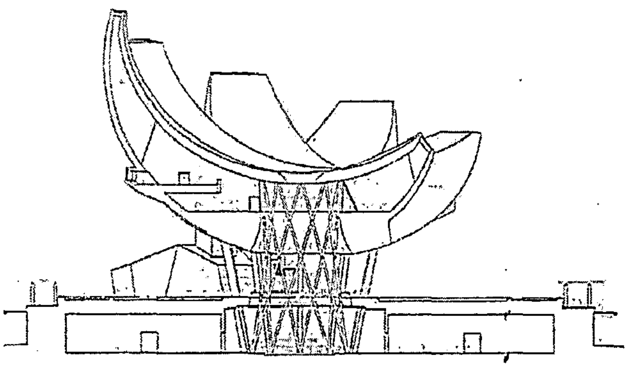
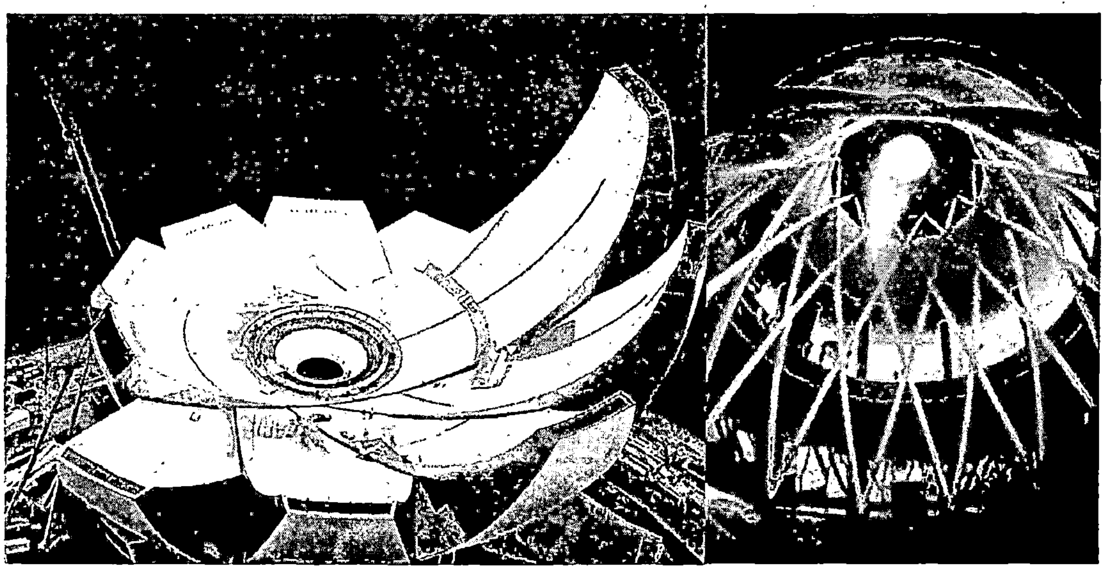


Figure 4-5 Section (SAFDIE, Moshe, 2011)

- The Museum's dish-like roof channels rainwater through the central atrium of the building creating a 35-meter water drop into a small, reflecting pool. The rainwater is then recycled for use in the building's restrooms.(MARINABAYSANDS, 2011)



Illus. 40Museum's dish-like roof channels rainwater through the central atrium(MARINABAYSANDS, 2011)

4.1.1.3 Structure and Construction

- The design of the Museum is composed of two principle parts. The base (an 11m **vertical support**) below waters and reflecting pool surrounding the structure, and a flower-like structure made of 10 petals, generated by the geometry of **spheroids of varying radii** that seemingly floats above the landscaped pond base. (SAFDIE, Moshe, 2011)
- The flower structure is supported by ten columns and tied down at its center by a basket-like diagrid–that accommodates the asymmetrical forces that the building's form generates.

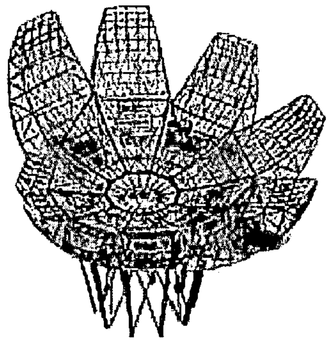
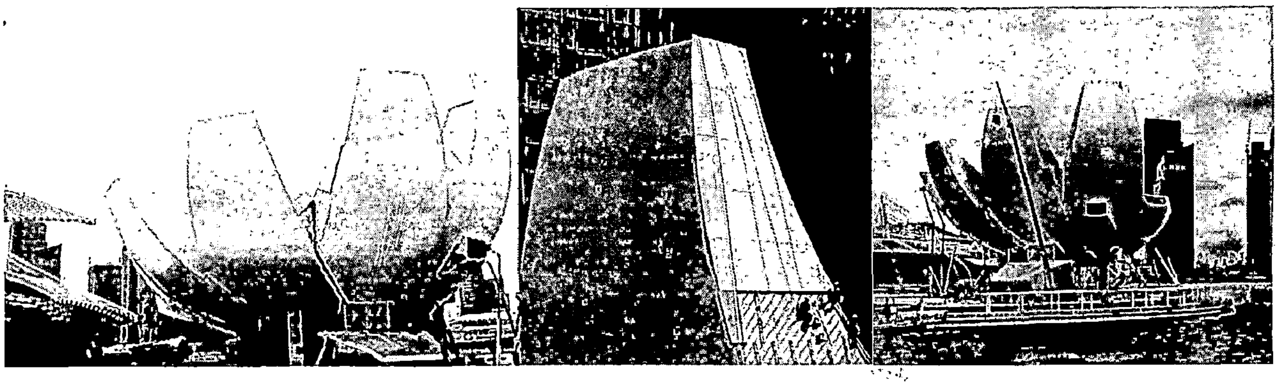
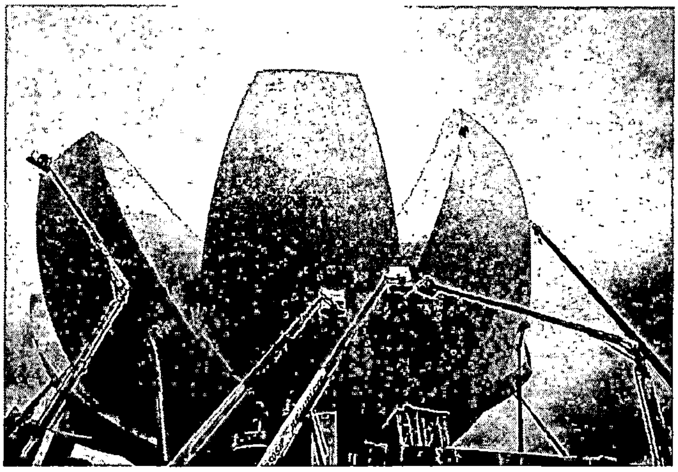


Figure 4-6 Lattice Structure(ARUP, 2011)

- Trying to make a building stand upside down was a challenge, explains Peter Bowtell, Buildings Leader for Arup. "*With one side of the 'lotus flower' bigger than the other, the structure naturally wants to fall to one side. To get around this we had to design a rational and simple way of holding these galleries in the air. The final solution involved balancing the structure in space, dealing with very complex geometry and* ***selection of lightweight yet strong material i.e. FRP for building envelope.***"(ARUP, 2011)
- The museum's envelope is composed of **double-curved Fiber Reinforced Polymer** [FRP] skin.
- The result in an efficient resolution of the structural forces for the building, giving it a seemingly weightless quality.(SAFDIE, Moshe, 2011)



Illus. 41 Building under construction



Illus. 42 Application of Gel Coat

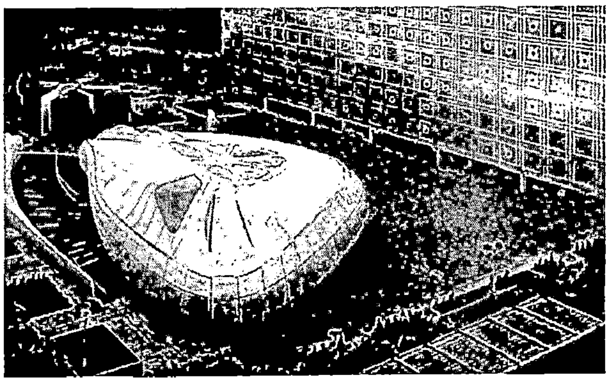
4.1.1.4 Inferences

- Light weight structure with sail-like surfaces and joint-less continuous skin, it is made possible by the use of FRP only.
- The naturally unbalanced form is possible because of the complex geometrical structure as well as use of lightweight and yet very strong material FRP as building envelope.

4.1.2 CHANEL PAVILION BY ZAHA HADID

4.1.2.1 Introduction

Fiber-reinforced polymer composite panels provide the sleek building fabric of Zaha Hadid's travelling pavilion.*"This building is made from FRP because it contains the structure within the form"* says Vietzke (Associate Architect).Mobile Art, the Chanel Contemporary Art Container toured Hong Kong in February 2008, Tokyo in July 2008 and New York in 2010.*(DESIGNBOOM)*



Illus. 43Aerial View of Chanel Pavilion

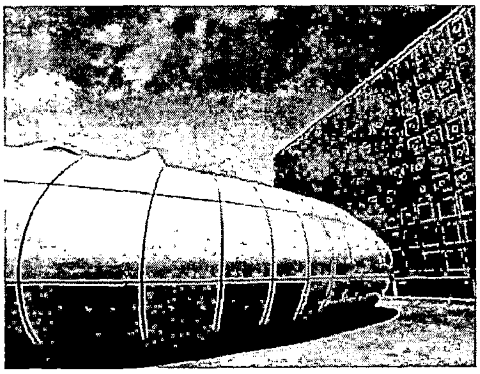
Below is the basic information of the building:

Location:	Institute du Monde Arabe,Paris (travelled Hong Kong,Tokyo, New York etc.)
Use:	Exhibition
Client/Owner:	Chanel S.A. (Fashion house)

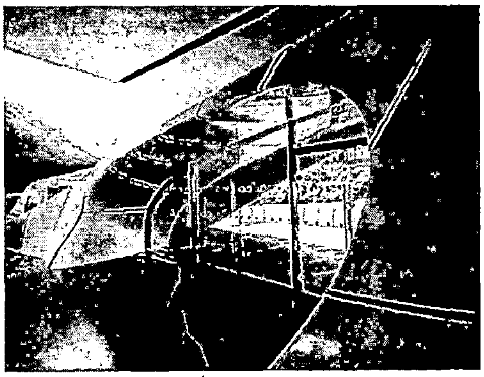
Architect :	Zaha Hadid Architects
Building Envelope material:	FRP sandwich Panels
Assemble duration	3 weeks
Disassemble duration	2 weeks
FRP Engineering	Optima Projects, UK
FRP panel Manufacturer	Stage one, UK

4.1.2.2 FRP Cladding:

- The pavilion is clad in 400 FRP panels, each with a unique digital geometry.
- The panels are doubly curved and some engage in a swift transition from the convex to the concave.
- FRP was selected for the Chanel pavilion for its **formability, robustness, lustrous finish** and above all **lightness,** as the pavilion needs to be transported to each venue.



Illus. 44 Closer view Chanel Pavilion

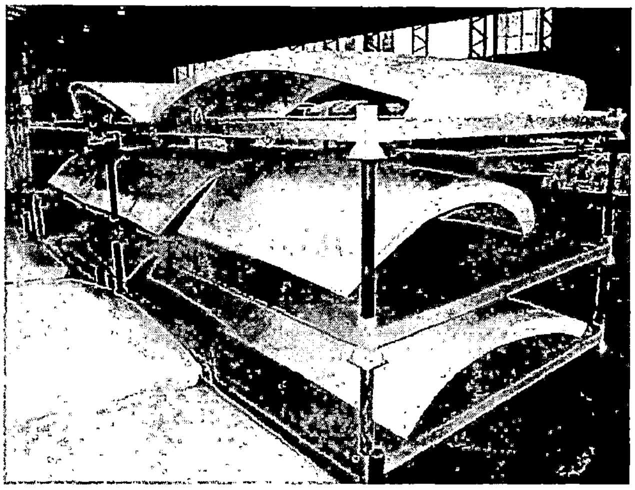


Illus. 45 Entrance - Chanel Pavilion

4.1.2.3 FRP Wall and roof Panels:

- The FRP panels for the Chanel pavilion are detailed as a rain screen with the waterproofing and Insulation provided by an unseen blanket-like construction.
- The wall panels range in size and are approx. 1.5m x 2m while the roof panels are 2m x 4m.(OROUSSOFF, Nicolai, 2008)
- The panels were engineered by optimizing the laminate construction, while achieving the stiffness required by the performance specification for the most exposed venue.

- In establishing the grid system to define the size of the components, there were two oppositional considerations. First, the shapes needed to be small enough not to waste space (and therefore money) in transportation and the second parameter is that the pieces needed to be large enough to make assembly and jointing on site practical.
- To decide upon the size of unit the practice used a script in the 3D model called the "minimum bounding box".



Illus. 46 FRP Roof and Wall Panels stacked for transportation (no need of wrapping or covered packing to protect scratch or glossy finish)*(HUNTER, Will, 2008)*

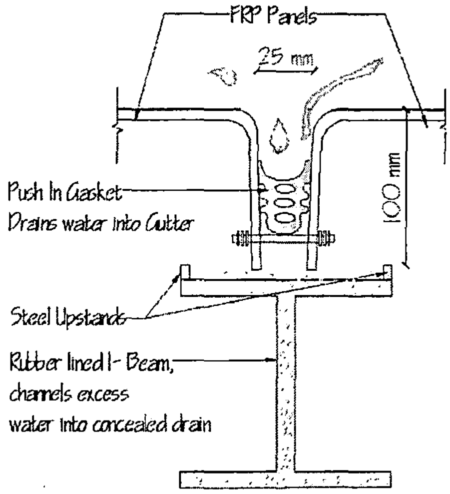
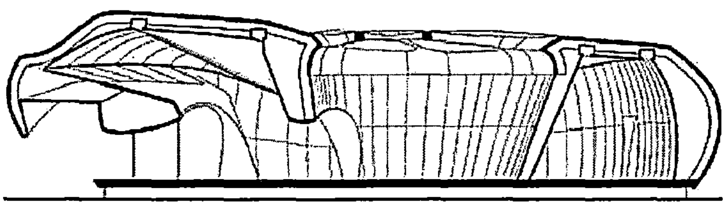


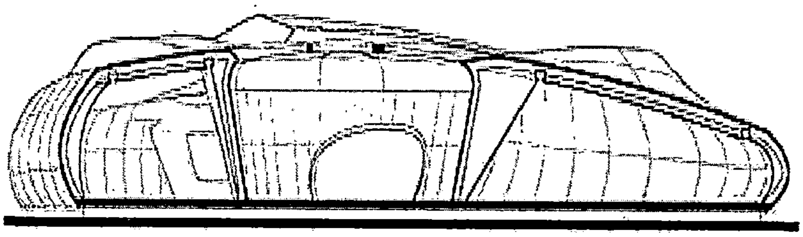
Figure 4-7 Sketch showing Roof and Cladding Joint Detail *(HUNTER, Will, 2008)*

4.1.2.4 FRP Structure:

- The panels are reinforced by glass fibers in combination of biaxial stitched cloth and chopped strand mat.
- The glass fibers are held in a matrix of fire retardant polyester resin.
- The panels have sandwich construction with a 5mm-thick core of low density, non-woven continuous strand mat containing micro-balloons (tiny plastic balls) to achieve a high bending stiffness to weight ratio.



Illus. 47 Short Section*(DESIGNBOOM)*



Illus. 48 Long Section *(DESIGNBOOM)*

- FRP panels can be readily detailed to provide a high level of thermal insulation.

4.1.2.5 Exterior and Interior Finish:

- The FRP panels are sprayed with a high gloss fluorescent white acrylic paint.
- This glossy finish is visually very demanding, revealing the geometry of each FRP panel and the accuracy has been made.
- The individual molds for each panel were CNC machined from polyurethane foam, a cost-effective mold material.
- The panels were sanded by hand after they were de-molded to achieve the fine finish.

4.1.2.6 Inferences

- FRP Sandwich Panels are chosen for the roof and walls of the building because of its high strength, durability and lightness for easy assembling, disassembling and transportation.
- The geometry of each panel is different because of the creative form of the building and FRP is the only material with this weight and strength ratios in which this kind of construction is possible till date.
- The size of the unit plays a very important role; it should not be too large to be difficult for transportation and not too small to be difficult for assembling and disassembling. So proper strategy should be employed to decide upon the size.
- Sandwich FRP paneled roof and walls provide high level of thermal insulation.
- There is no danger of FRP panels to get a scratch or loss of gloss. This gives high level of durability to the structure as well as cost and time saving in transportation.

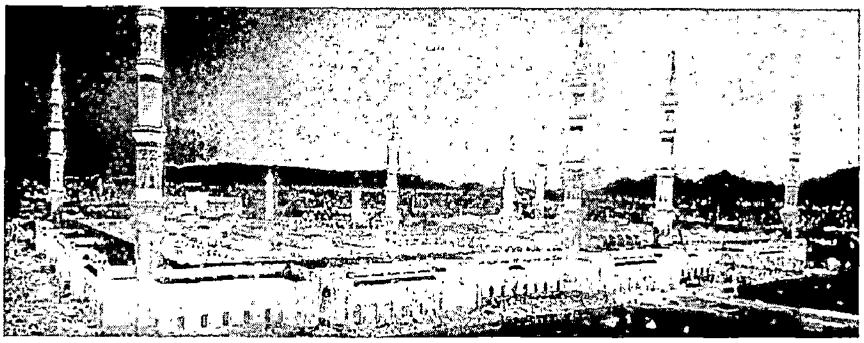
4.1.3 PROPHET'S HOLY MOSQUE, MEDINA- SAUDI ARABIA

4.1.3.1 Description

Innovative techniques were developed for the production of 27 sliding domes for the Prophet's Holy Mosque in Medina. The project completed in 1990.

Location:	Medina, Saudi Arabia
Use:	Religious
Client/Owner:	Holy Prophet mosque, Medina

Dome Designers and Manufacturers	Premier Composites
Dome material:	Sandwich of glass-Fiber/epoxy resin composites with a thermoplastic, honeycomb core
Year of Execution	1990



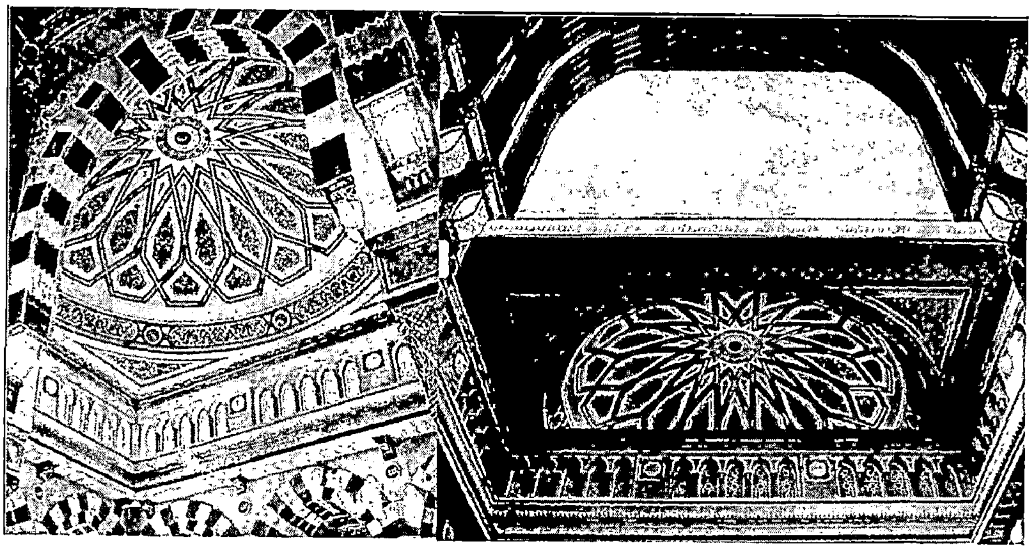
Illus. 49Prophet's Holy Mosque in Medina (Source: http://www.pct.ae/composite_projects.php?project=9)

- The lightweight composite domes provide a mobile roof to the internal courtyards, sliding open and closed to counteract extreme temperature changes and control and support the air-conditioned environment of the mosque. (PCT, 2011)
- The domes rest on a steel framework on 4 wheeled carriages and moved on high grade steel tracks. It is powered by digitally controlled electric motors.

Illus. 50Friday Prayer(Source: http://www.pct.ae/composite_projects.php?project=9)

- Domes are high-tech structures made from a sandwich of glass-Fiber/epoxy resin composites with a thermoplastic, honeycomb core.This material is strong, durable and extremely lightweight with as little as 85% of the weight of an equivalent dome built in concrete. Low thermal expansion means there are no shrinkage problems and edge flanges give them stiffness for a bolted panel-to-panel connection. (PCT, 2011)

Illus. 51 The Sliding Domes(Source: http://www.pct.ae/composite_projects.php?project=9)



Illus. 52 Sliding FRP Domes- Prophets Holy Mosque (Source: http://www.pct.ae/composite_projects.php?project=9)

- The richly decorated interior domes are fabricated in maple wood veneer and western red cedar.
- Inner dome surfaces are richly decorated in Moroccan hand-carved ornaments with gold leaf highlights and studded with turquoise coloured Amazonite stones set in gilded bezels. Each dome is capped by a gold-plated finial.(PCT, 2011)

4.1.3.2 Inferences

- Almost 85% reduction in weight can be achieved by using FRP as Structural Material instead of conventional materials.
- The dynamic features like sliding can be achieved in the structures by virtue of light and strong material like FRP.
- Intricate decorative features can be incorporated while fabrication and molding. Thus saves time of finishing activities on site.

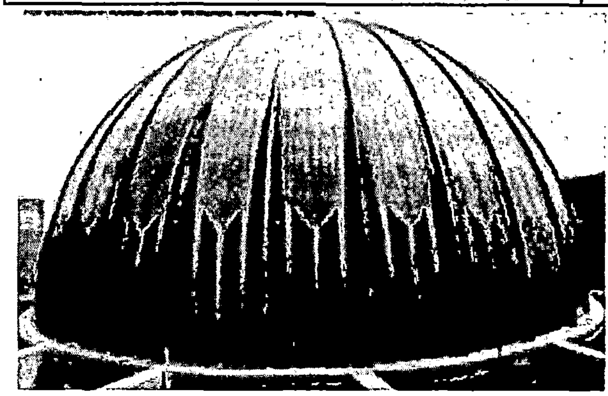
4.2 INDIAN

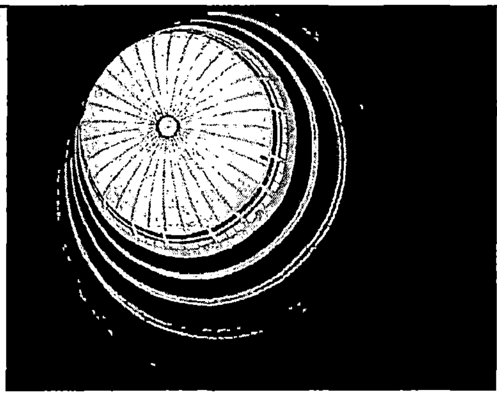
4.2.1 DEENANATH MANGESHKAR HOSPITAL DOME, PUNE

4.2.1.1 Introduction

The Dome of Deenanath Mangeshkar Hospital, Pune is the largestself-supporting FRP dome existing in India. Below is the basic information of the project:

Location:	Erandwana, Pune.
Use:	Hospital
Client/Owner:	Lata Mangeshkar Medical Foundation.
Architect :	V.V Architects
FRPDesigners and Manufacturers	Mr. Milind Upasani - Industrial and commercial enterprises, Pune
Dimensions	14m diameter, 7m height
Dome material:	FRP (self supporting dome)
Year of Execution	2000-01

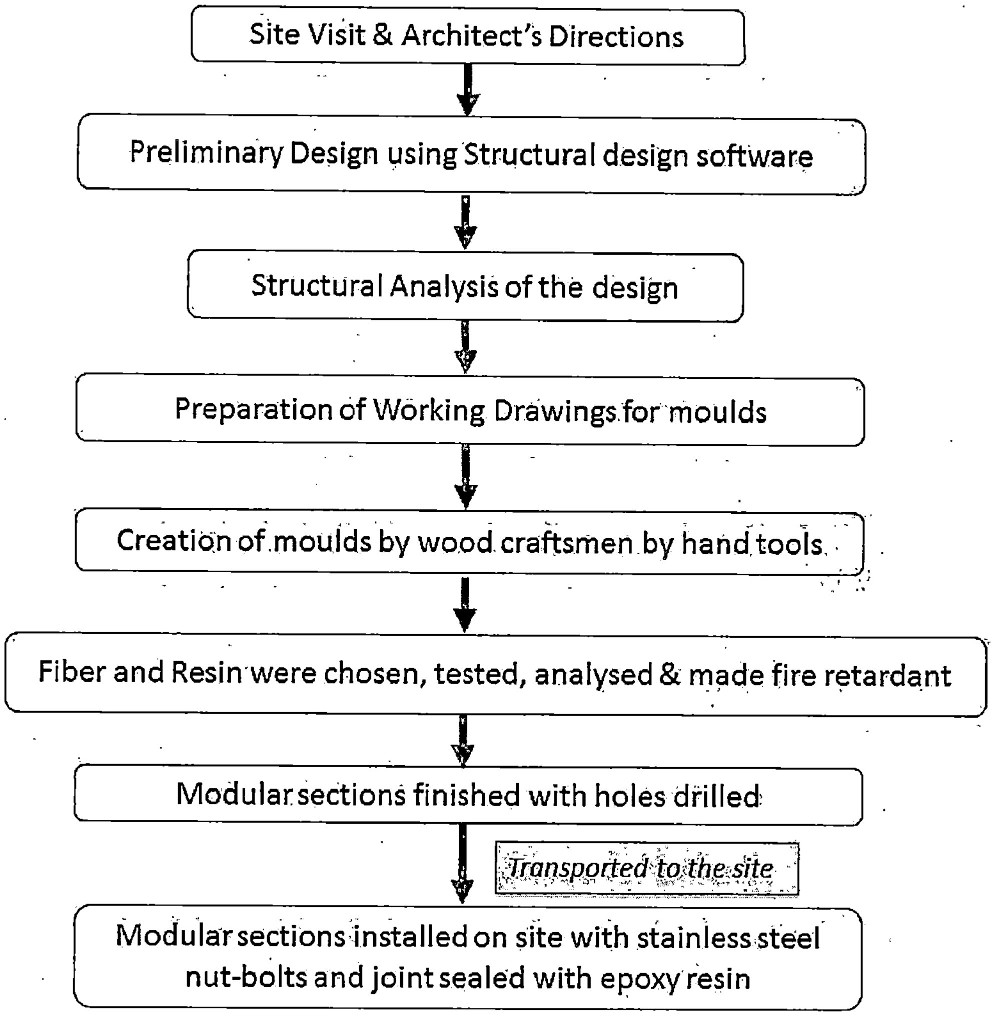




Illus. 53 Biggest self supporting modular FRP dome in India ***(UPASANI, Milin, 2008)***

4.2.1.2 Design Process

The various stages of the process of construction of the dome of Deenanath Mangeshkar Hospital, Pune are as follows :



Illus. 54 Design Process for FRP Dome employed in DNM Hospital Pune ***(PUNE, Structural Engineer Industrial and Commercial Enterprises, 2011)***

4.2.1.3 Inferences

- The whole process is entirely manual and does not consume thermal or electric power at any stage and can therefore be adopted even in the rural areas.
- The composite structure gives a value addition to the building by improving its aesthetics.
- This is just a beginning in India; there is a long way to go in this field.

4.3 SUMMARY AND CONCLUSIONS

4.3.1 SUMMARY

Project	Use	Form	Material/Structure	Remarks
Artscience Museum, Singapore	Exhibition	Lotus (Composition of spheroids of variable radii)	Double curved GFRP panels on a lattice structure of steel	Best suited for such complex form due to lightweight and high strength properties
Chanel Pavilion by Zaha Hadid	Traveling Exhibition	Irregular (creative form	FRP sandwich Panelswith a 5mm-	Suitable for traveling building because of

		each panel with different geometry)	thick core of low density	light weight, durability, high strength and ease of assembly, disassembly and transport
Prophet's Holy mosque Medina, Saudi Arabia	Religious	Dome	Sandwich of glass-Fiber/epoxy resin composites with a thermoplastic, honeycomb core	For mobile roof light weight composites is a good alternative to conventional materials reducing almost 85% the dead load of the dome. Richly Decorated interiors are faster to construct.
Deenanath Mangeshkar Hospital Dome Pune	Hospital	Dome	Self-Supporting Modular FRP Dome	Time and Cost saving benefits of modular FRP construction.

4.3.2 CONCLUSION

- In all the above mentioned buildings the lightweight and high strength properties of FRP played a major role in the selection of this material.
- Very creative and challenging forms are possible by using FRP as we can see in Art science museum or Chanel pavilion or Prophets Holy mosque etc, opening new gate of creativity for architects.
- Type of FRP its structure is governed by the form and scale of the structure, like we see sandwich FRP system in Chanel pavilion, mosque and modular FRP in dome in Pune.
- Size of the unit is important, not too large and not too small as in the mobile art Chanel pavilion.
- The technology in India is not well developed, in spite of FRP being used in large scale in transportation sector it's not being mirrored in building industry.

CHAPTER 5. ANALYSIS OF FRP ROOF FORMS

The objective of this chapter is to discuss various architectural forms for use with FRP, structural and cost analysis of some basic types of forms and comparative analysis with conventional materials. Due to FRP's high ultimate strength and formability it can be made into any architectural form such as synclastic, anticlastic shells, stressed skin systems, folded plates etc. by virtue of their form they give adequate stiffness.

5.1 TYPES OF ARCHITECTURAL FORMS SUITABLE FOR FRP ROOF

There are three broad classes of structural forms namely Shell structures, folded plate structures and Stressed skin Structures. These can further be divided into various types of forms, described as follows.

5.1.1 SHELL STRUCTURES

Shell structure is defined as a structure with a thickness which is small compared to its other dimensions and in which deformations are not large compared to thickness. In the unstressed state, the shell structure has a curvature; thus Membrane action in a shell is primarily caused by in-plane forces. Shell structures are analogous to a cable which resists loads through tensile stresses. *(CHEN, Wai-Fah, 1997)*

This is the most favorable form to be used with FRP because of the above mentioned; for analysis of FRP roof forms shell structures have been chosen.

Shell structures can be of two types: singly curved and doubly curved, *seeFigure 5-1.*

5.1.1.1 Singly curved shells

Behavior of singly curved shell depends upon its span / length ratio. A long shell structure behaves more like a beam while short does not. Examples of singly curved shell are barrel vaults (which can have different types of cross sections – semicircular, segment of circle, parabola etc. *seeFigure 5-2, Figure 5-3*), cone, groined vault, rib vault etc. The analysis and design of single skin FRP semicircular and segmental barrel vault are considered in detail in later section of this chapter.

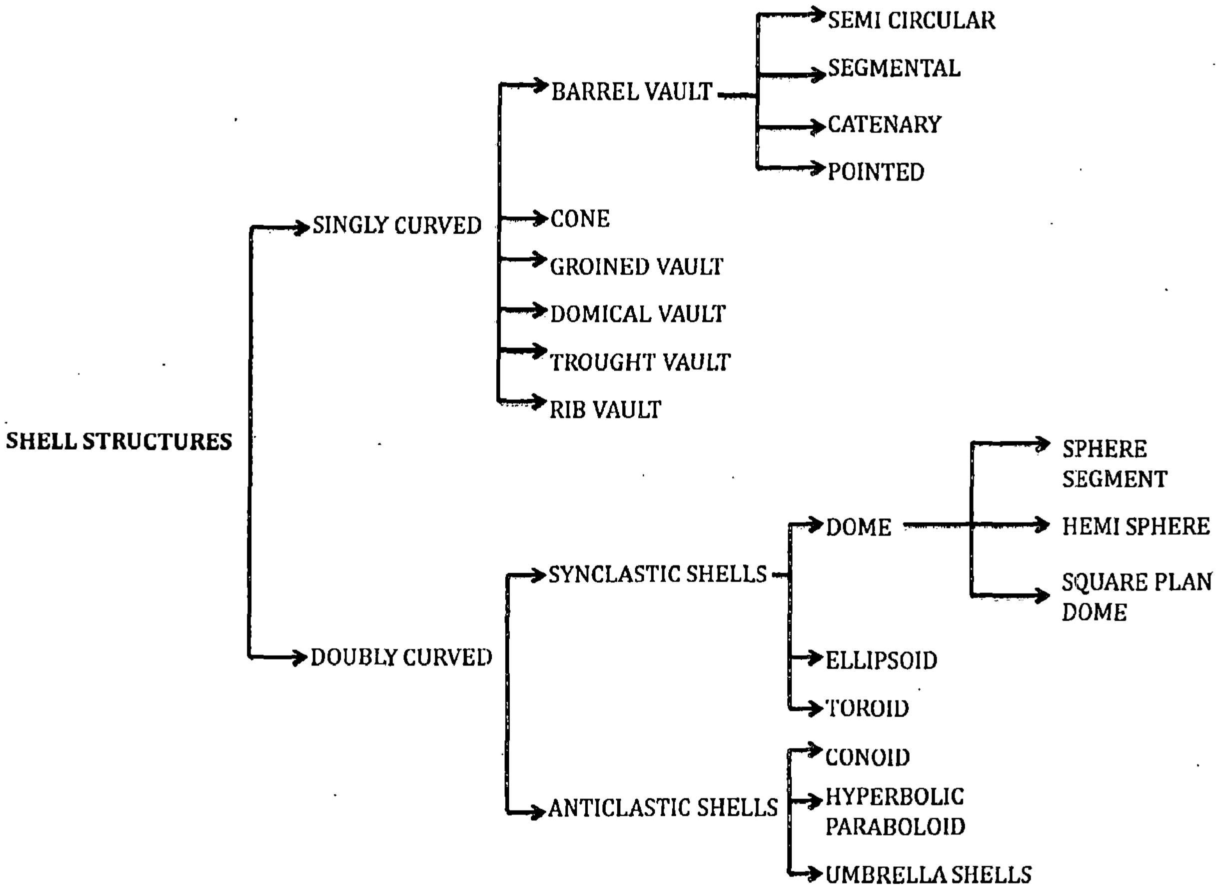


Figure 5-1 Types of Shell Structures

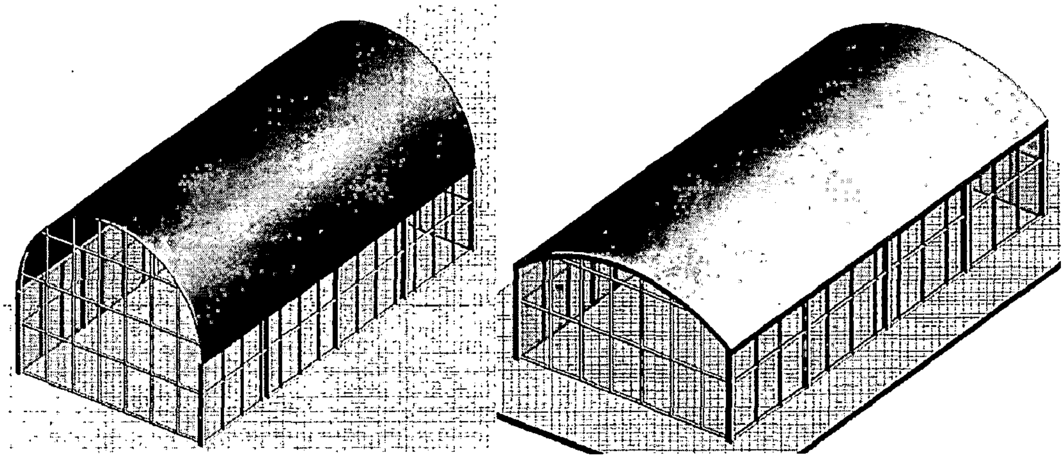


Figure 5-2 Semicircular vault and Segmental vault

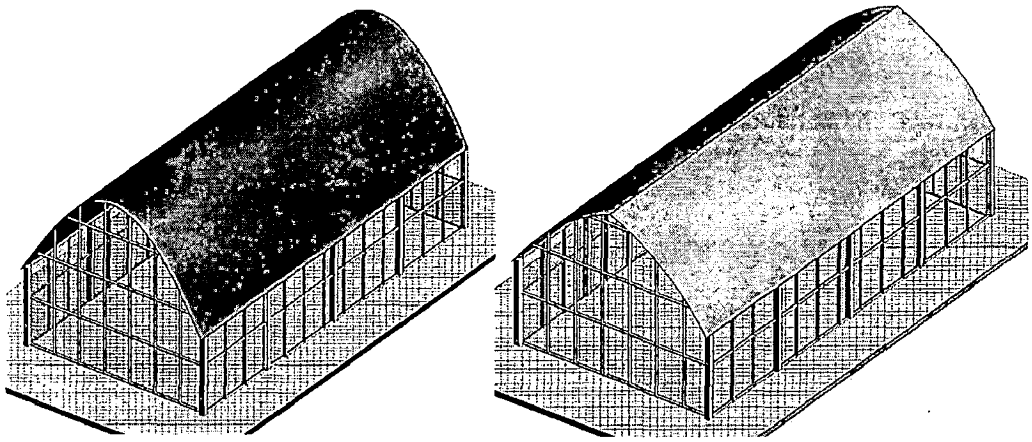


Figure 5-3 Catenary and Pointed vault

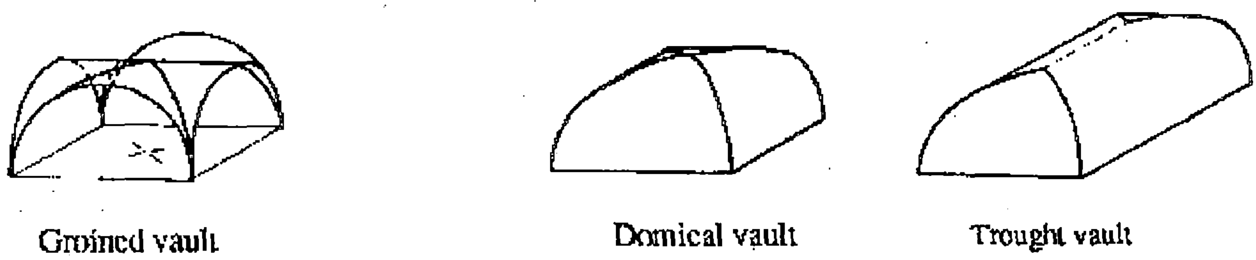


Figure 5-4 Singly curved shells*(KETCHUM, Milo S. and Ketchum, Mark A., 1997)*

5.1.1.2 Doubly Curved Shells

Doubly curved shells have two principle curvatures thus more stable than singly curved, but a bit difficult for construction. This type of structure provides exciting possibilities.

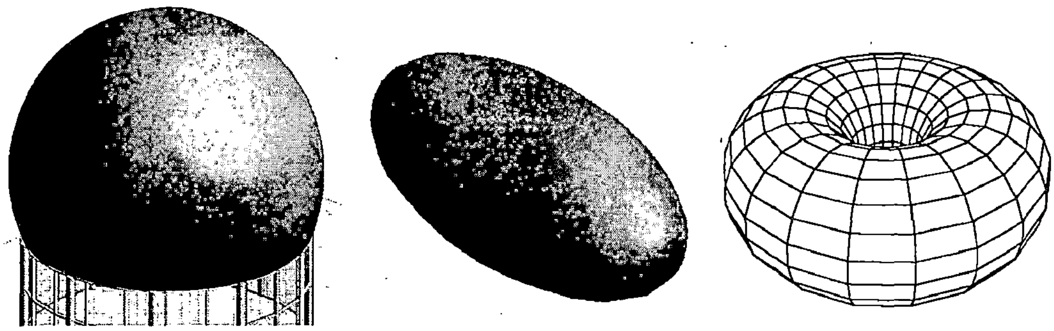


Figure 5-5 Doubly curved synclastic shells

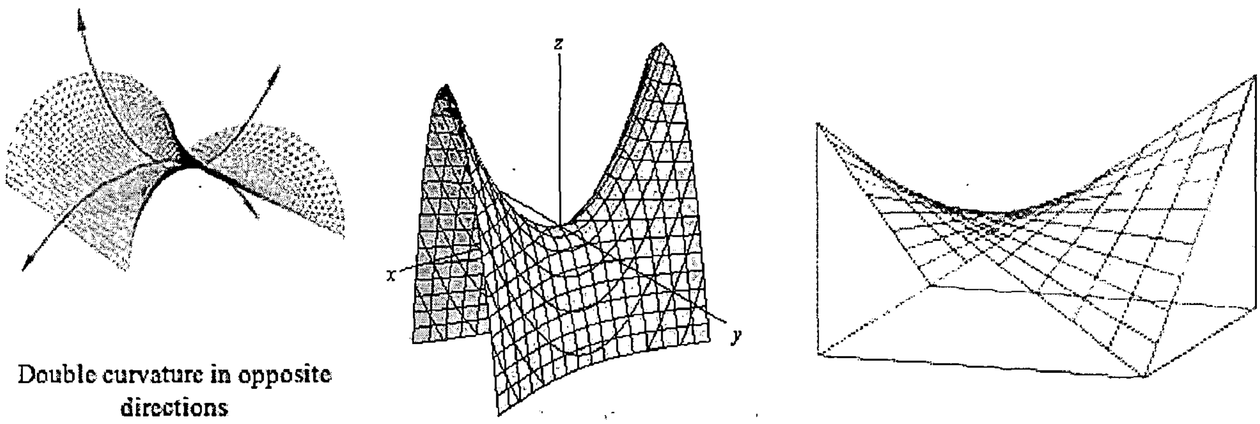


Figure 5-6 Doubly curved anticlastic shells ***(http://geometrica.com/en/architectural/geometry)***

5.1.2 FOLDED PLATE STRUCTURES

Folded plates due to composed of flat surfaces very easy to fabricate, joints are also very simple. These are basically of two types prismatic (2, 3 , 5 plate units) and non- prismatic (Pyramidal, prismoidal &composite).

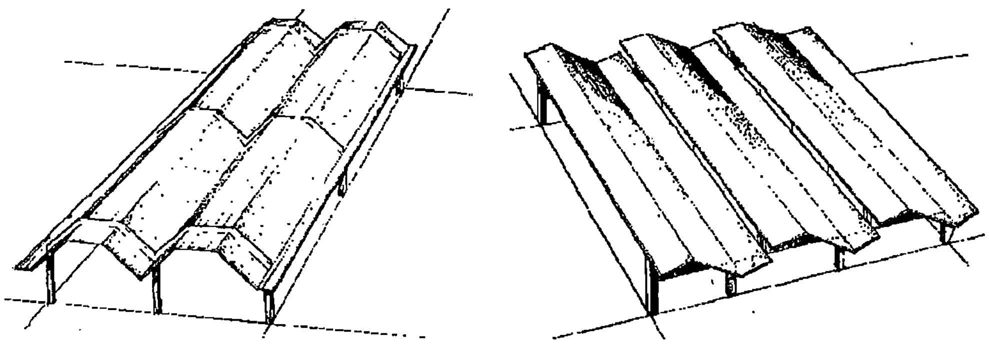


Figure 5-7 Folded Plate structures ***(KETCHUM, Milo S. and Ketchum, Mark A., 1997)***

5.1.3 STRESSED SKIN STRUCTURES

FRP can be used in combination with other materials like steel , aluminium etc to form stressed skin structures or tension structures. In these FRP acts as the skin and steel/aluminium acts as cables/ supports.

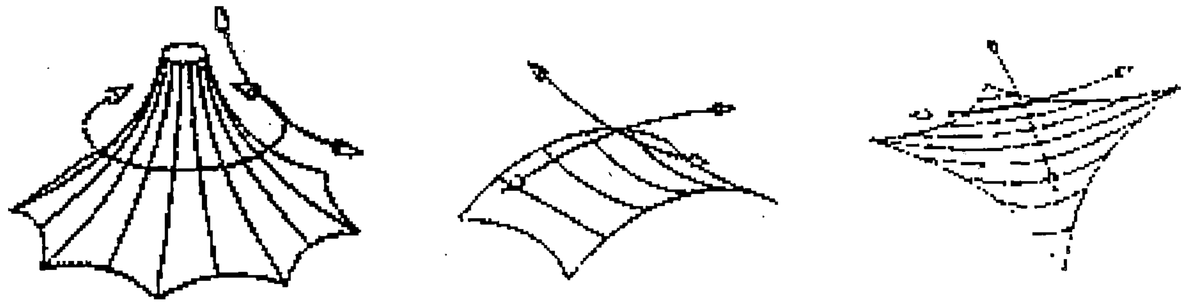


Figure 5-8 Stressed Skin Structures - conical, vault, Hypar resp.*(http://geometrica.com/en/architectural/geometry)*

5.2 TYPES OF ROOF FORMS ANALYSED

As mentioned above shell structures provide maximum possibilities of various kinds of roof forms and FRP's mold ability can easily be exploited in these kinds of structures. For feasibility of analysis and design under the scope of this thesis some basic forms of roof have been chosen. With help of these roof forms we will be able to understand some basic concept of designing roof with FRP. Further innumerable types of roof forms including the ones mentioned above and many others can be derived from these basic roof forms, wherever your imagination takes you.

5.2.1 DOMES

Dome is one of the most stable forms of structures. Domes can be spherical, spherical segment, elliptical, square at base, rectangle at base etc.With FRP, domes are one of the most common forms whether it is the spectacular sliding domes of prophet's holy mosque Saudi Arabia or the early FRP applications, the Radome. However construction of a dome requires much more skills than that with the other types of forms.

For analysis purpose three types of Rise/Span ratios of spherical dome are taken into considerations viz. Hemi Spherical Dome (R/S=0.5), Spherical Segment Dome (R/S=0.25), and Spherical Dome with R/S= 0.75. Following are the cases which have been considered:

5.2.1.1 Dome - A (Diameter = 10m)

- ***A-01***

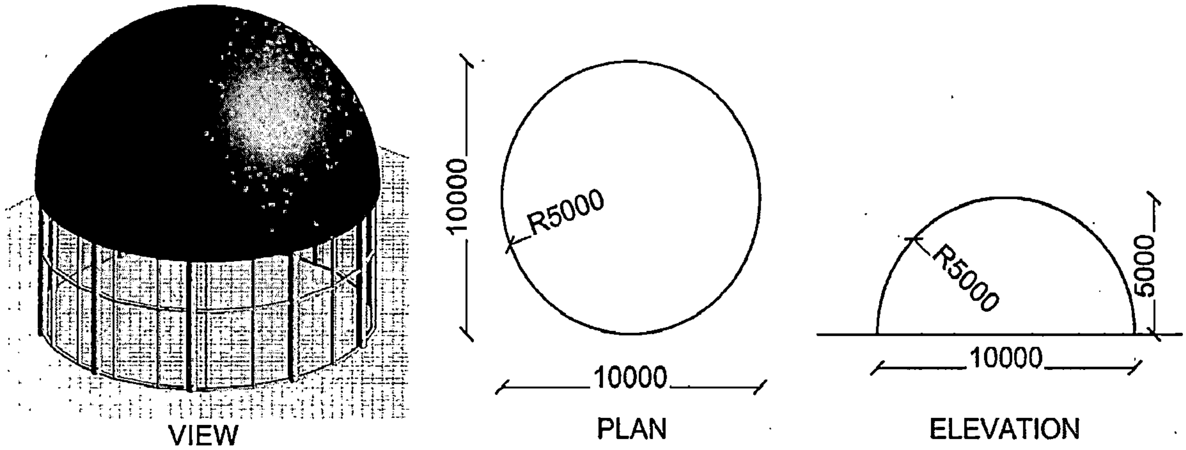


Figure 5-9DomeA-01

Span= Diameter	**10000 mm**
Rise	5000 mm
Rise/Span	**0.5**
Radius of Curvature	5000 mm
Surface Area	157.14 sq. m

- ***A-02***

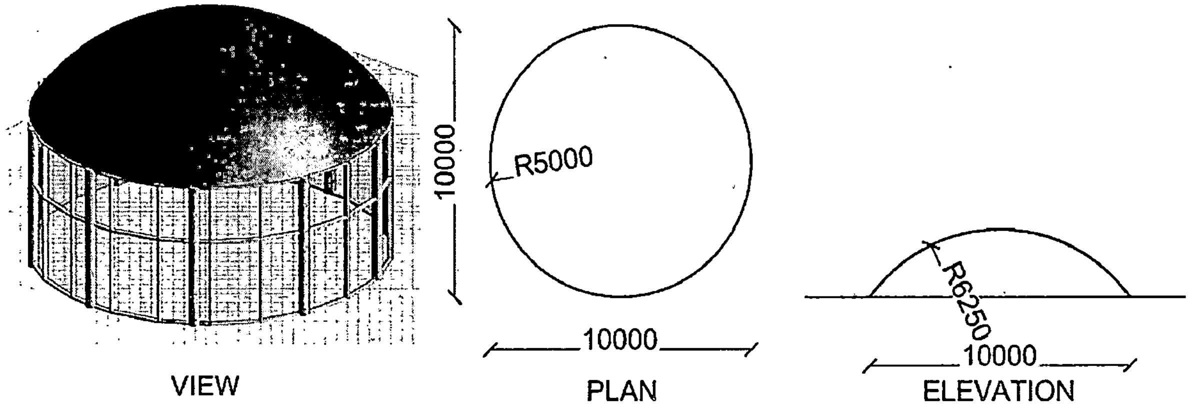


Figure 5-10DomeA-02

Span= Diameter	**10000 mm**
Rise	2500 mm
Rise/Span	**0.25**
Radius of Curvature	6250 mm

Surface Area	98.214 sq. m

- ***A-03***

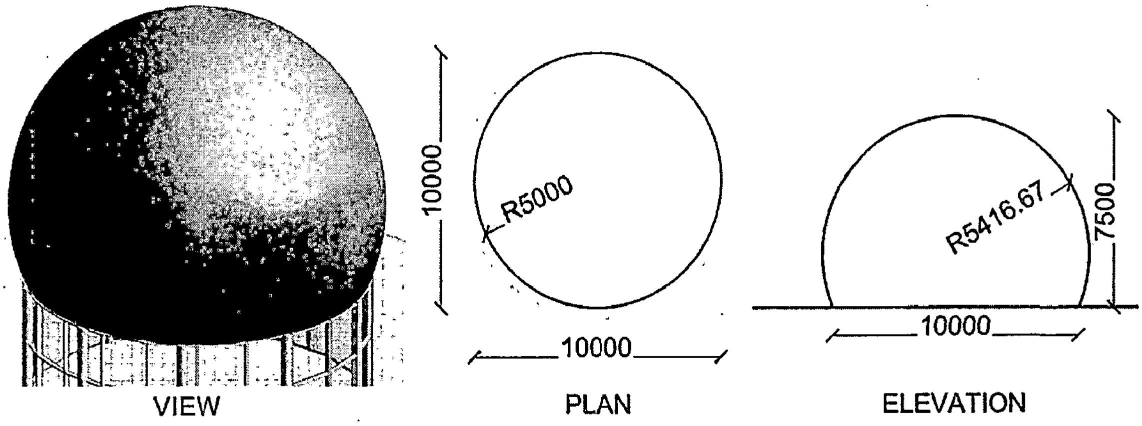


Figure 5-11DomeA-03

Span= Diameter	**10000 mm**
Rise	7500 mm
Rise/Span	**0.75**
Radius of Curvature	5416.67 mm
Surface Area	255.36 sq. m

5.2.1.2 Dome - B (Diameter = 15m)

- ***B-01***

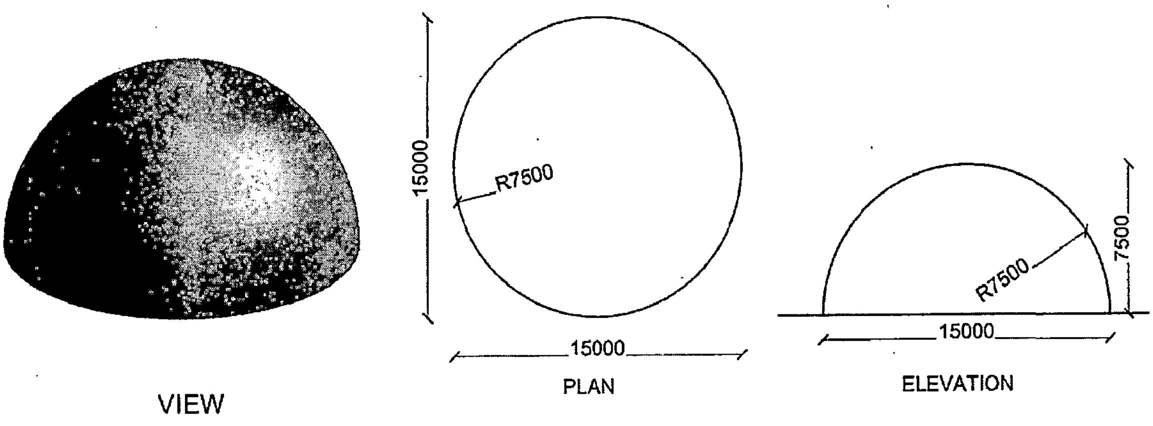


Figure 5-12 Dome B-01

Span= Diameter	**15000 mm**
Rise	7500 mm
Rise/Span	**0.5**
Radius of Curvature	7500 mm
Surface Area	353.57 sq. m

- ***B-02***

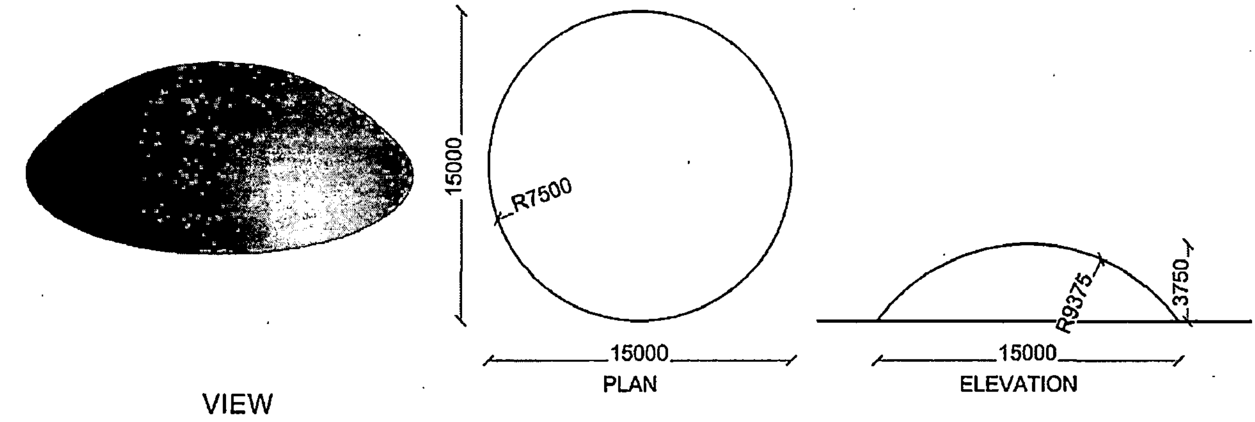


Figure 5-13Dome B-02

Span= Diameter	**15000 mm**
Rise	**3750 mm**
Rise/Span	**0.25**
Radius of Curvature	**9375 mm**
Surface Area	187.83 sq. m

➢ *B-03*

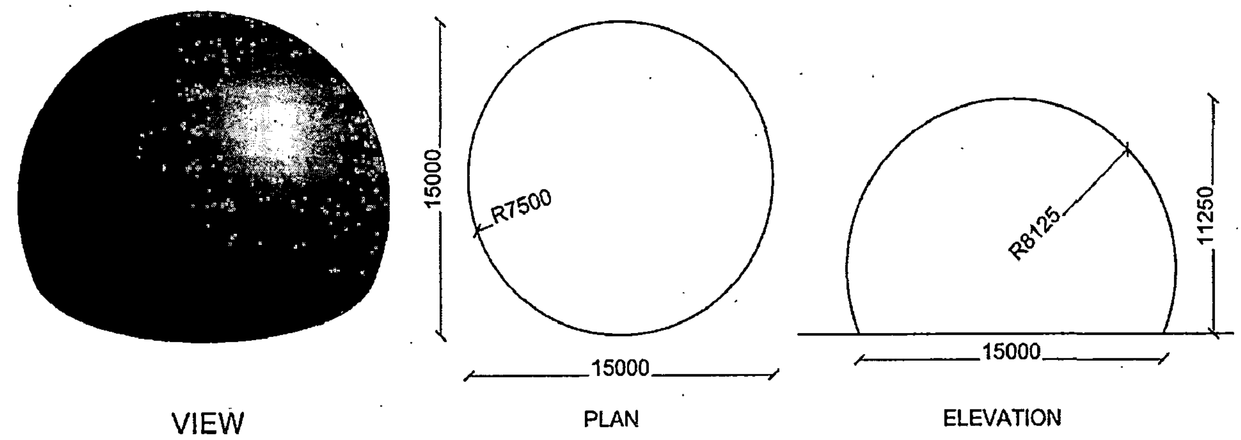


Figure 5-14Dome B-03

Span= Diameter	**15000 mm**
Rise	**11250 mm**
Rise/Span	**0.75**
Radius of Curvature	**8125 mm**
Surface Area	574.55 sq. m

5.2.1.3 Dome – C (Diameter = 20m)

➢ *C-01*

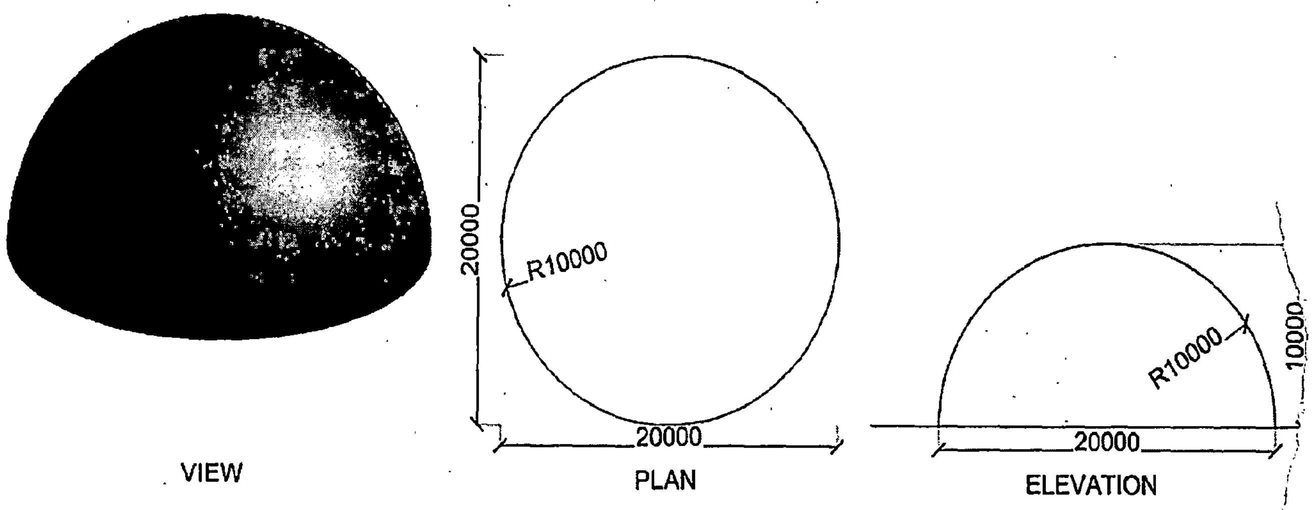


Figure 5-15Dome C-01

Span= Diameter	**20000 mm**
Rise	10000 mm
Rise/Span	0.5
Radius of Curvature	10000 mm
Surface Area	628.57 sq. m

➢ *C-02*

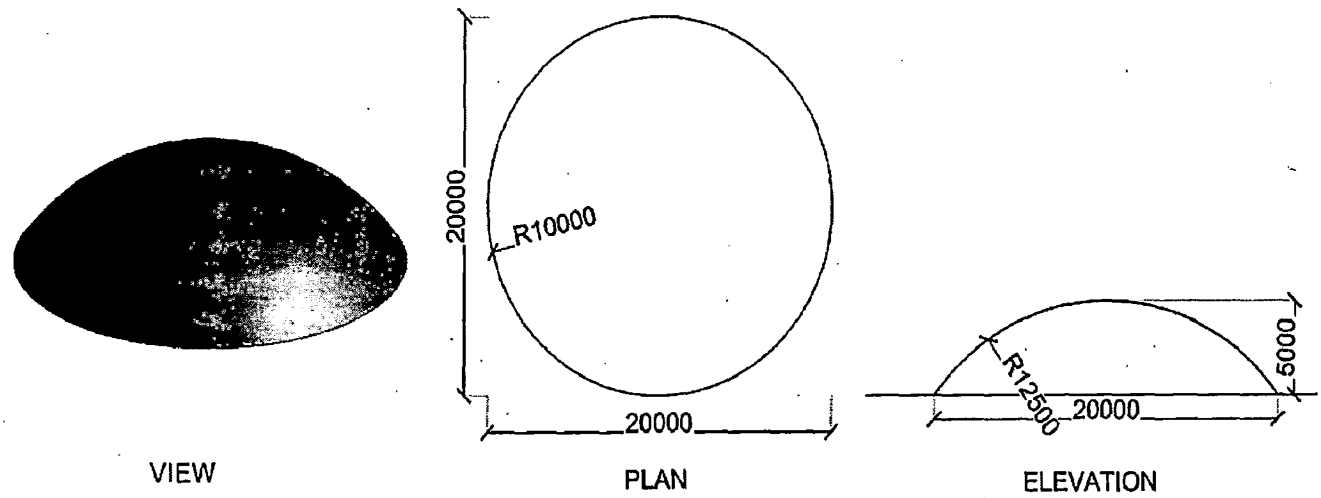


Figure 5-16Dome C-02

Span= Diameter	**20000 mm**
Rise	5000 mm
Rise/Span	0.25
Radius of Curvature	12500 mm

Surface Area	392.86 sq. m

➢ *C-03*

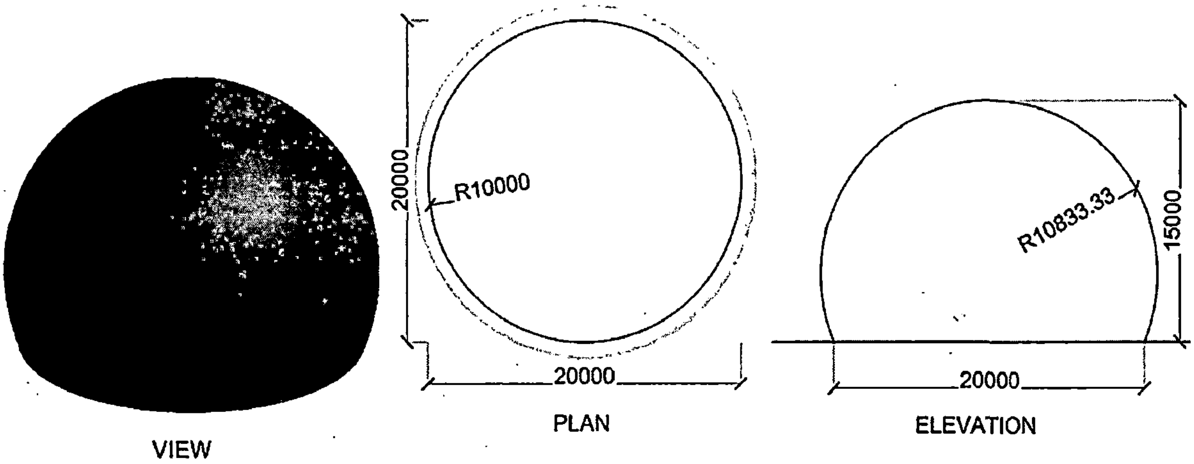


Figure 5-17Dome C-03

Span= Diameter	**20000 mm**
Rise	15000 mm
Rise/Span	0.75
Radius of Curvature	10833.33 mm
Surface Area	1021.43 sq. m

5.2.1.4 Dome – D (Diameter = 30m)

➢ ***D-01***

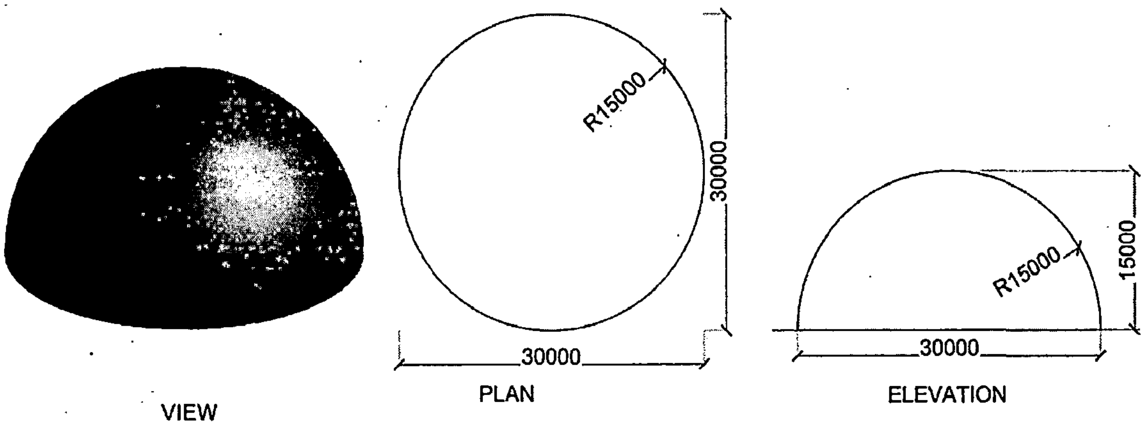


Figure 5-18Dome D-01

Span= Diameter	**30000 mm**
Rise	15000 mm
Rise/Span	0.5
Radius of Curvature	15000 mm

Surface Area	1414.29sq. m

- ***D-02***

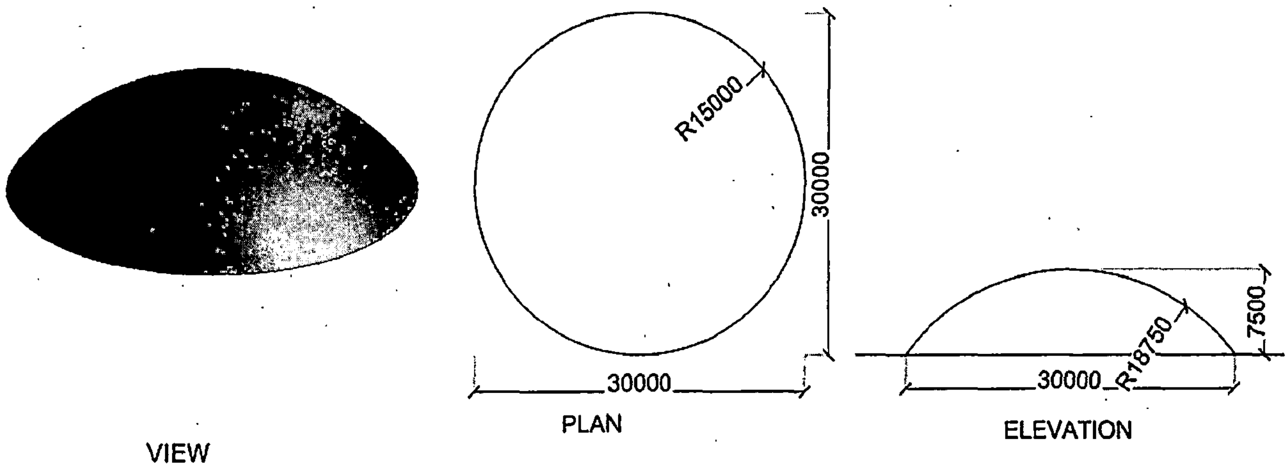


Figure 5-19Dome D-02

Span= Diameter	**30000 mm**
Rise	15000 mm
Rise/Span	**0.25**
Radius of Curvature	18750 mm
Surface Area	883.93 sq. m

- ***D-03***

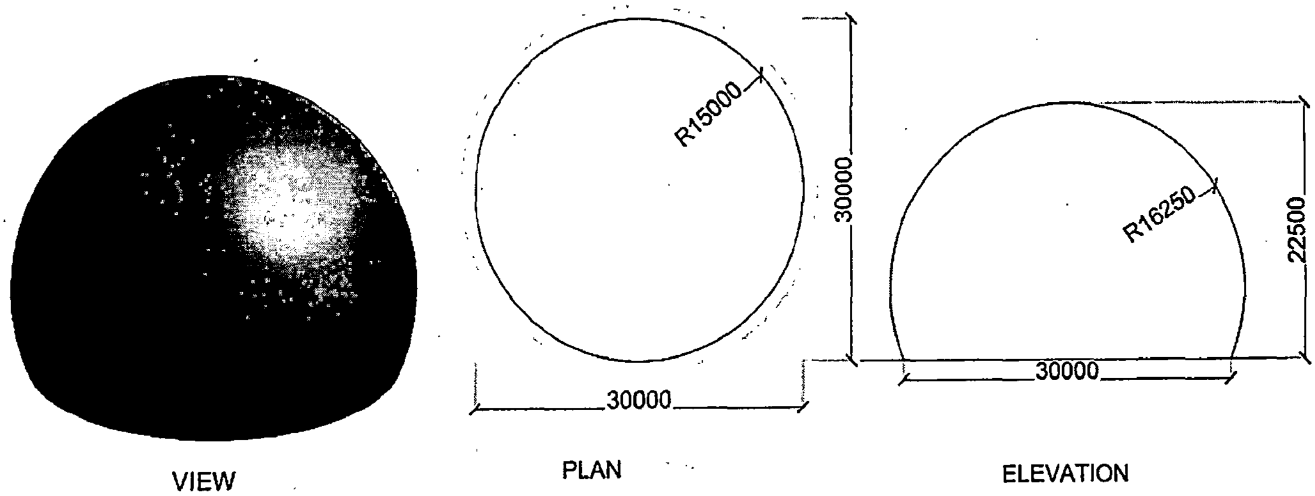


Figure 5-20DomeD-03

Span= Diameter	**30000 mm**
Rise	22500 mm
Rise/Span	**0.75**
Radius of Curvature	16250 mm

Surface Area	2298.22 sq. m

5.2.2 VAULTS

Vault especially barrel vault is also a very much used form. It is suitable for rectangular plans preferably for Length: Width > 2:1. The ideal ratio of Length to width however is 1:3 or more as far as structural behavior is concerned.

For analysis and design purpose two Length to width ratio have been chosen 2:1 and 3:1, and three Rise/Span ratio have been chosen viz. 0.5, 0.25 and 0.75. All the considered cases are described as follows.

5.2.2.1 Vault – E (5m x 10m)

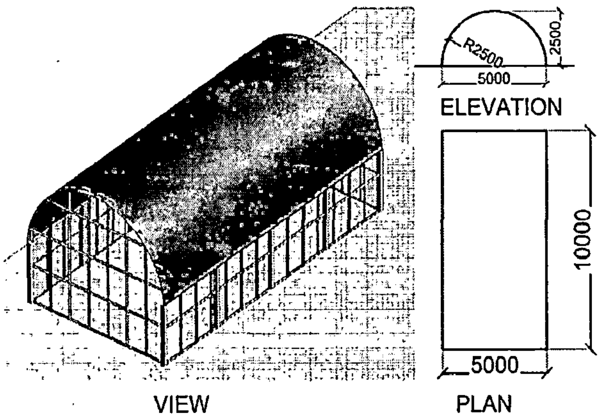


Figure 5-21 Vault E-01

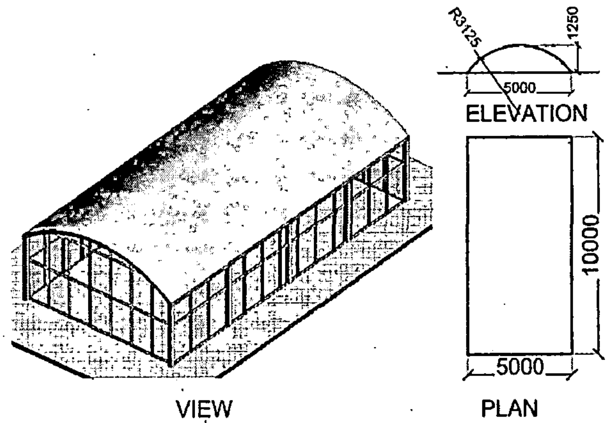


Figure 5-22 Vault E-02

Span=Breadth	**5000 mm**
Length	10000 mm
Length/Breadth	2
Rise	2500 mm
Rise/Span	0.5
Radius of Curvature	2500 mm
Surface Area	78.5398sq. m

5.2.2.2 Vault E-02 (5m x 10m)

Span=Breadth	**5000 mm**
Length	10000mm
Length/Breadth	2
Rise	1250mm
Rise/Span	0.25

Radius of Curvature	3125 mm
Surface Area	57.956 sq. m.

5.2.2.3 Vault E-03(5m x 10m)

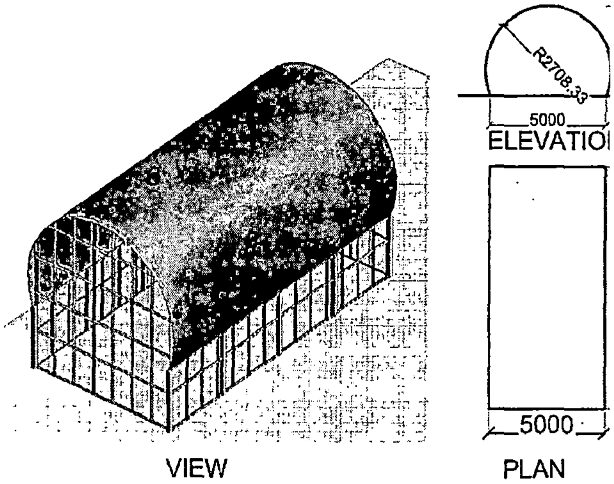


Figure 5-23 Vault E-03

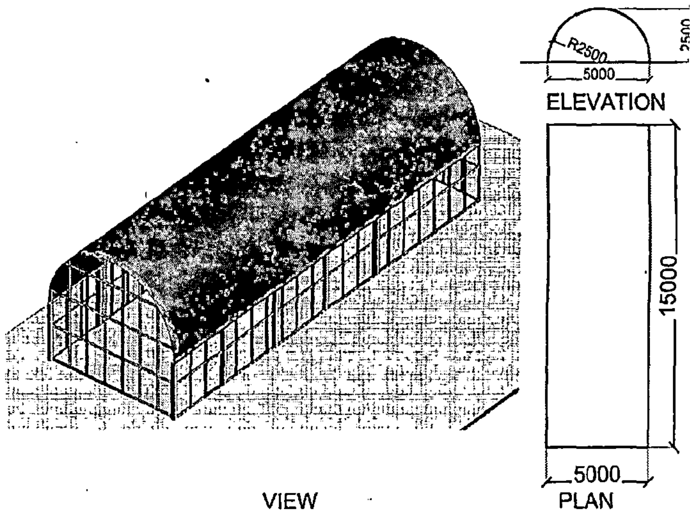


Figure 5-24 Vault F-01

Span=Breadth	**5000mm**
Length	10000mm
Length/Breadth	2
Rise	3750mm
Rise/Span	0.75
Radius of Curvature	2708.33 mm
Surface Area	106.4693sq. m

5.2.2.4 Vault F-01(5m x 15m)

Span=Breadth	**5000 mm**
Length	15000mm
Length/Breadth	3
Rise	5000 mm
Rise/Span	0.5
Radius of Curvature	5000 mm
Surface Area	117.8097sq. m

5.2.2.5 Vault F-02(5m x 15m)

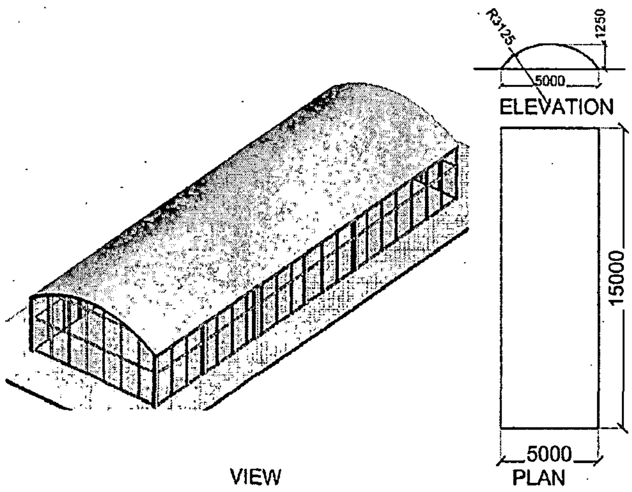


Figure 5-25 Vault F-02

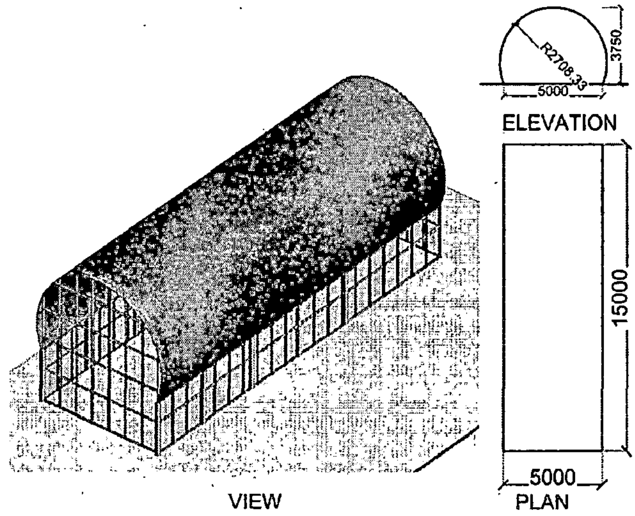


Figure 5-26Vault F-03

Span=Breadth	**5000 mm**
Length	15000 mm
Length/Breadth	3
Rise	1250mm
Rise/Span	**0.25**
Radius of Curvature	3125 mm
Surface Area	86.934sq. m

5.2.2.6 Vault F-03(5m x 15m)

Span=Breadth	**5000mm**
Length	15000mm
Length/Breadth	3
Rise	3750mm
Rise/Span	**0.75**
Radius of Curvature	2708.33 mm
Surface Area	sq. m

5.2.2.7 Vault G-01(7.5m x 15m)

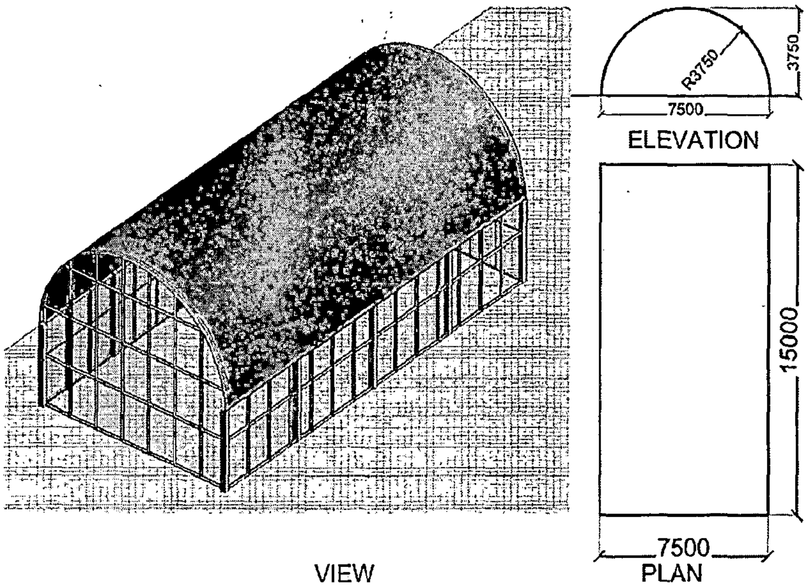


Figure 5-27Vault G-01

Span=Breadth	**7500 mm**
Length	15000mm
Length/Breadth	2
Rise	3750mm
Rise/Span	0.5
Radius of Curvature	3750 mm
Surface Area	176.71455sq. m

5.2.2.8 Vault G-02(7.5m x 15m)

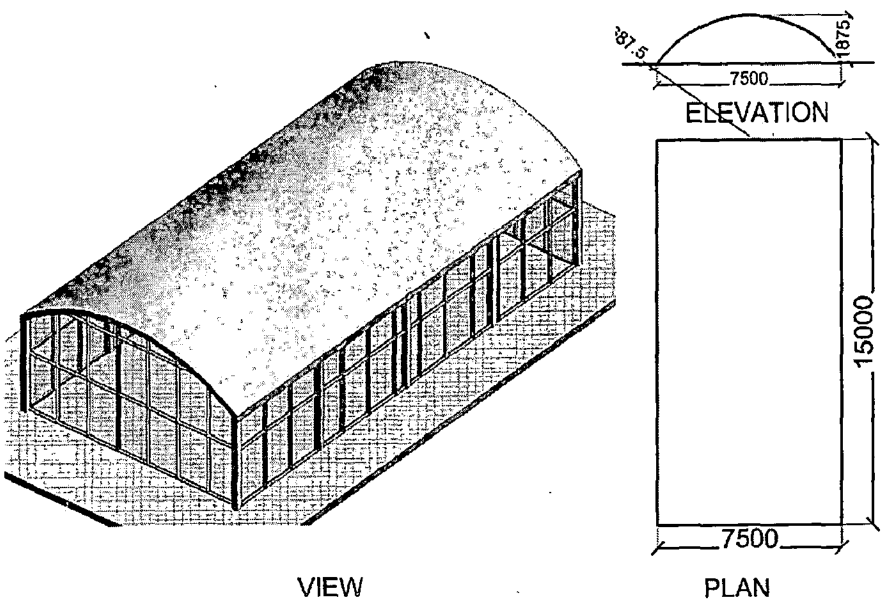


Figure 5-28Vault G-02

Span=Breadth	7500 mm
Length	15000 mm
Length/Breadth	2
Rise	1875 mm
Rise/Span	0.25
Radius of Curvature	4687.5mm
Surface Area	130.40085sq. m

5.2.2.9 Vault G-03(7.5m x 15m)

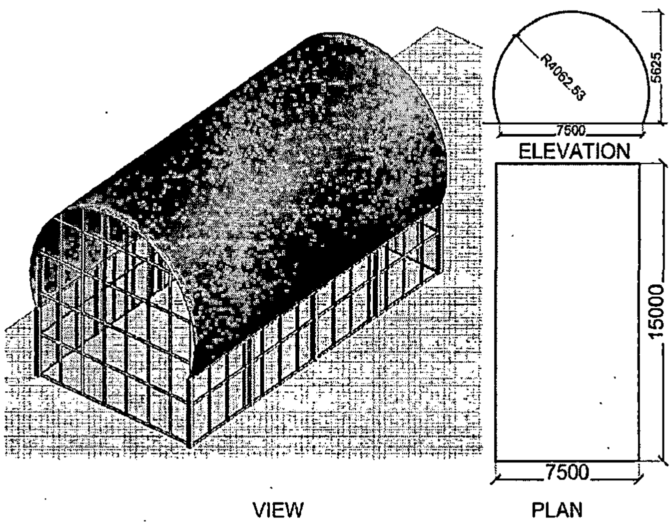


Figure 5-29Vault G-03

Span=Breadth	7500mm
Length	15000mm
Length/Breadth	2
Rise	5625mm
Rise/Span	0.75
Radius of Curvature	4062.53mm
Surface Area	239.56005sq. m

5.2.2.10 Vault H-01(7.5m x 22.5m)

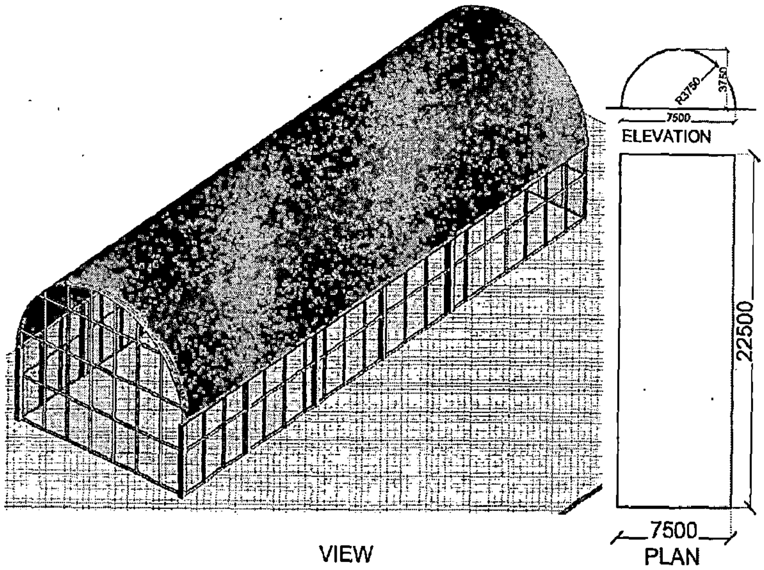


Figure 5-30Vault H-01

Span=Breadth	**7500 mm**
Length	22500 mm
Length/Breadth	3
Rise	3750 mm
Rise/Span	**0.5**
Radius of Curvature	3750 mm
Surface Area	265.071825sq. m

5.2.2.11 Vault H-02 (7.5m x 22.5m)

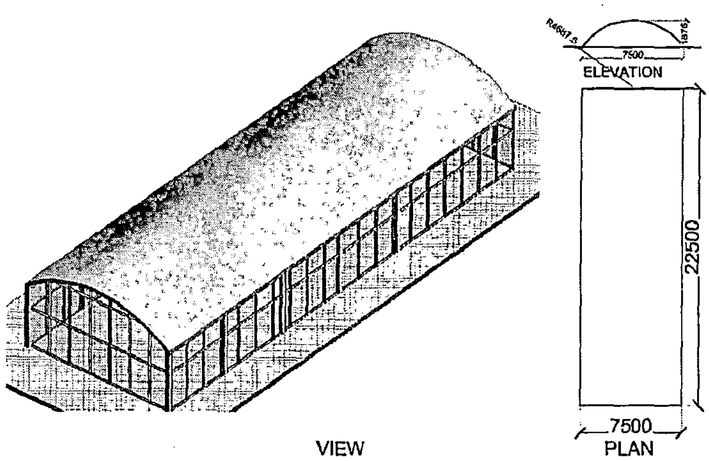


Figure 5-31Vault H-02

Span=Breadth	**7500 mm**
Length	22500mm

Length/Breadth	3
Rise	18750mm
Rise/Span	0.25
Radius of Curvature	4687.5 mm
Surface Area	195.601275 sq.m.

5.2.2.12 Vault H-03 (7.5m x 22.5m)

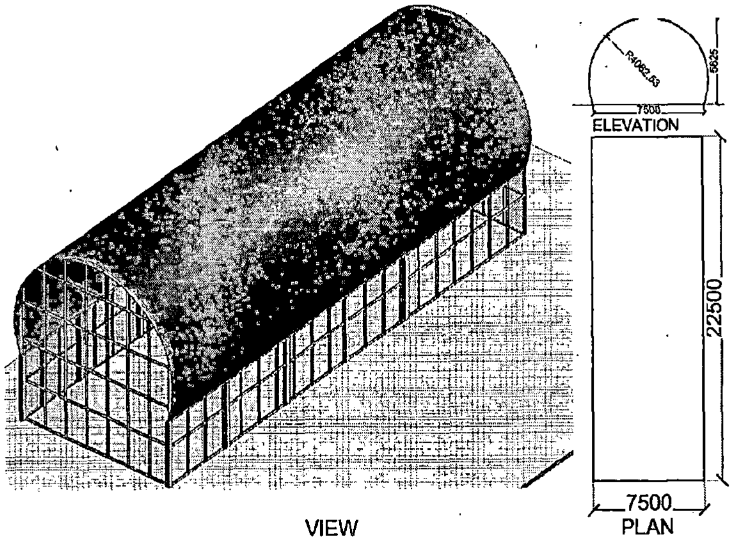


Figure 5-32Vault H-03

Span=Breadth	7500 mm
Length	22500 mm
Length/Breadth	3
Rise	5625 mm
Rise/Span	0.75
Radius of Curvature	4062.53 mm
Surface Area	359.340075sq. m

5.2.2.13 Vault I-01 (10m x 20m)

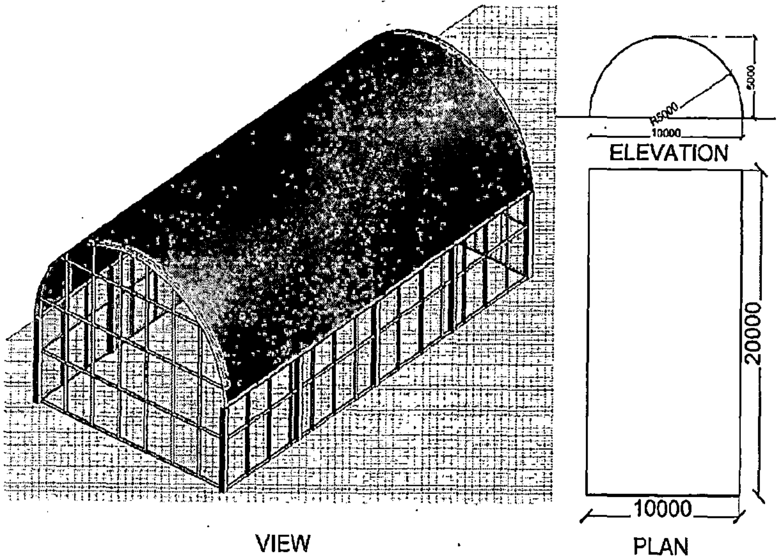


Figure 5-33Vault I-01

Span=Breadth	**10000 mm**
Length	20000 mm
Length/Breadth	2
Rise	5000 mm
Rise/Span	0.5
Radius of Curvature	5000 mm
Surface Area	314.1592sq. m

5.2.2.14 Vault I-02 (10m x 20m)

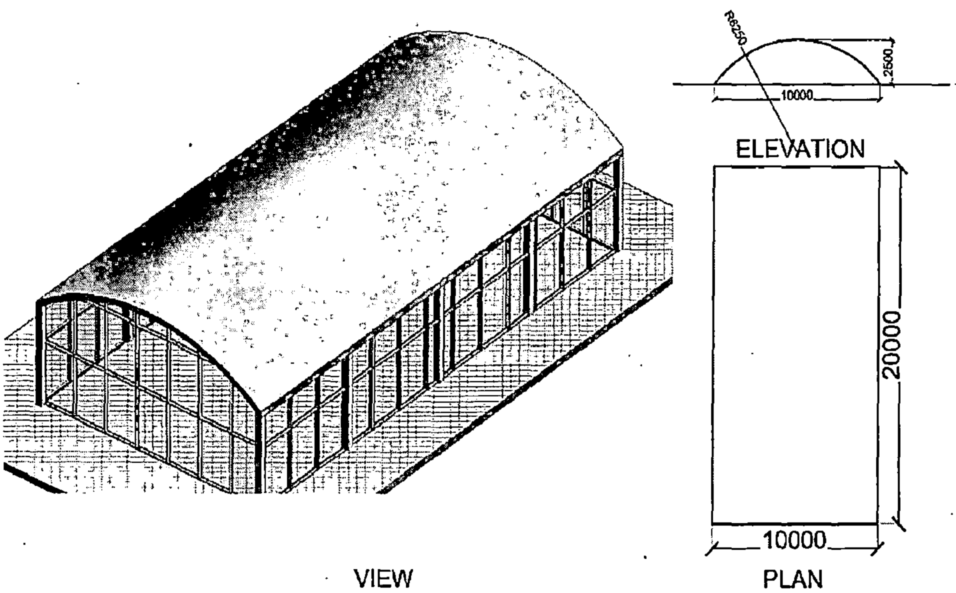


Figure 5-34Vault I-02

Span=Breadth	**10000 mm**

Length	20000 mm
Length/Breadth	2
Rise	2500 mm
Rise/Span	0.25
Radius of Curvature	6250 mm
Surface Area	231.8238sq. m

5.2.2.15 Vault I-03 (10m x 20m)

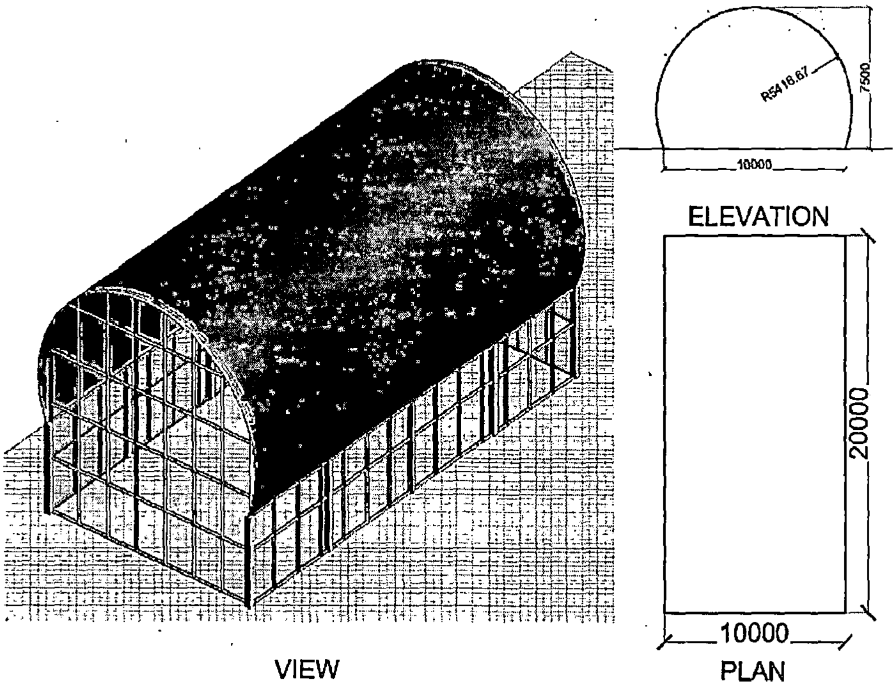


Figure 5-35Vault I-03

Span=Breadth	10000 mm
Length	20000 mm
Length/Breadth	2
Rise	7500 mm
Rise/Span	0.75
Radius of Curvature	mm
Surface Area	5416.67sq. m

5.2.2.16 Vault J-01 (10m x 30m)

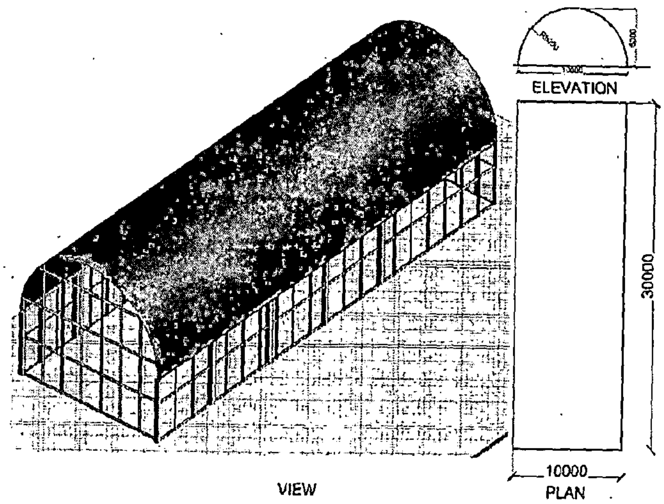


Figure 5-36Vault J-01

Span=Breadth	10000 mm
Length	30000 mm
Length/Breadth	3
Rise	5000 mm
Rise/Span	0.5
Radius of Curvature	5000 mm
Surface Area	471.2388sq. m

5.2.2.17 Vault J-02 (10m x 30m)

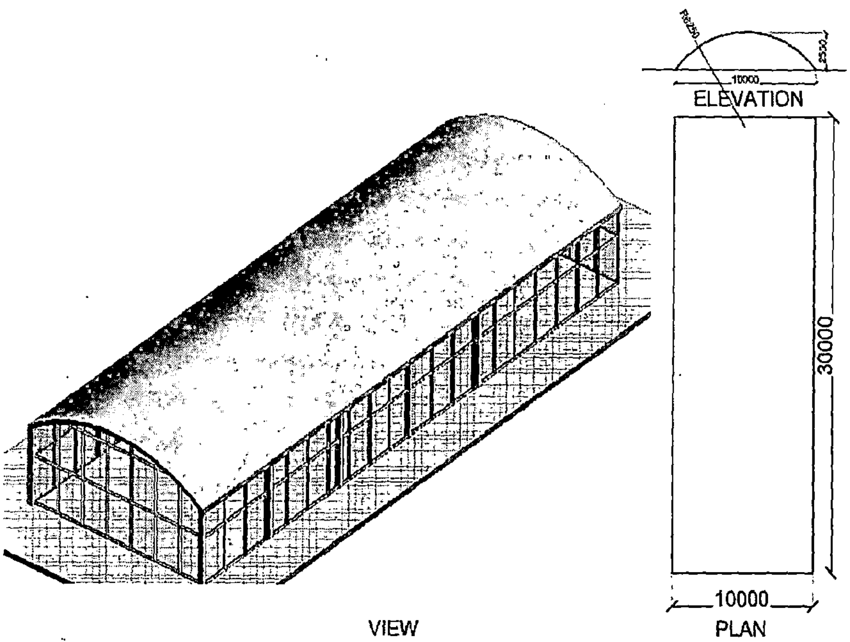


Figure 5-37Vault J-02

Span=Breadth	10000 mm

Length	30000 mm
Length/Breadth	3
Rise	2500 mm
Rise/Span	0.25
Radius of Curvature	6250mm
Surface Area	347.7357sq. m

5.2.2.18 Vault J-03 (10m x 30m)

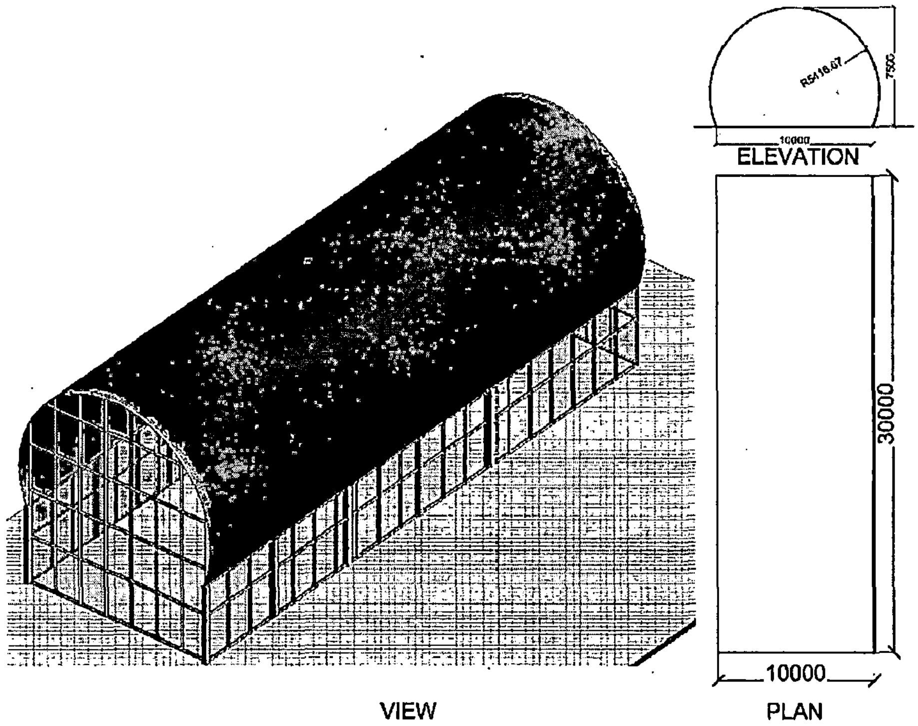


Figure 5-38Vault J-03

Span=Breadth	**10000 mm**
Length	30000 mm
Length/Breadth	3
Rise	7500 mm
Rise/Span	0.75
Radius of Curvature	5416.67 mm
Surface Area	638.8158sq. m

5.2.2.19 Vault K-01 (15m x 30m)

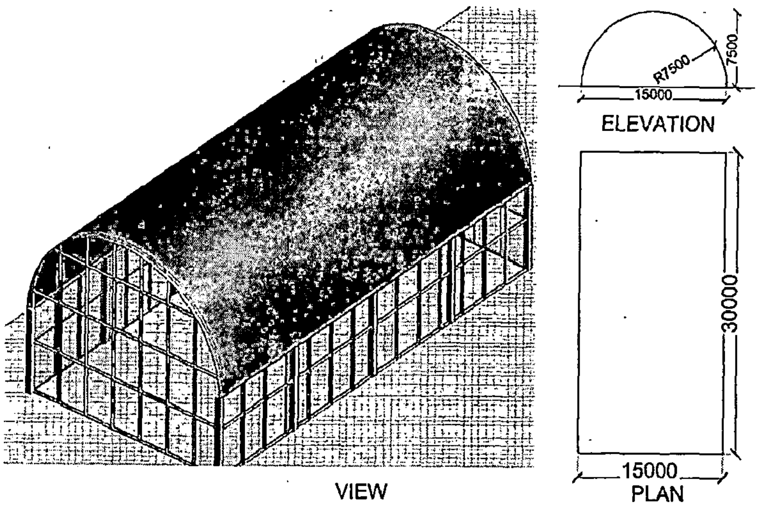


Figure 5-39Vault K-01

Span=Breadth	**15000 mm**
Length	30000 mm
Length/Breadth	2
Rise	7500 mm
Rise/Span	0.5
Radius of Curvature	7500 mm
Surface Area	706.8582sq. m

5.2.2.20 Vault K-02 (15m x 30m)

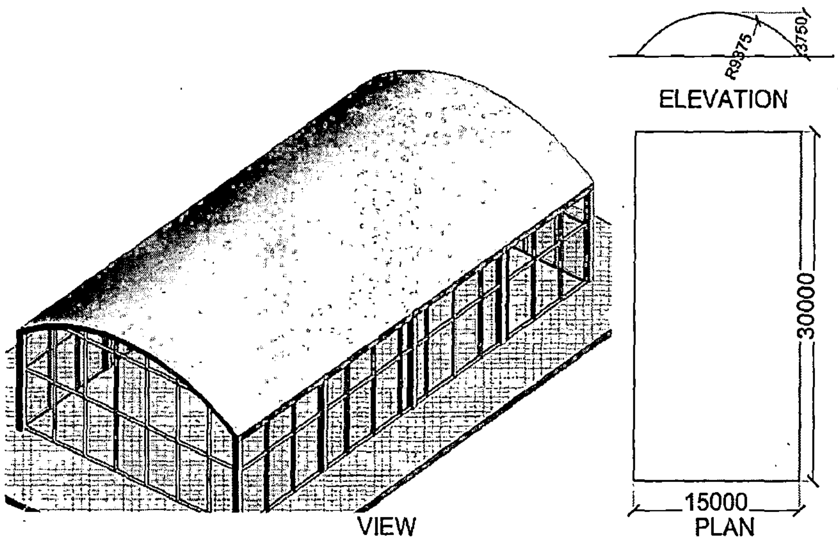


Figure 5-40Vault K-02

Span=Breadth	**15000 mm**
Length	30000 mm

Length/Breadth	2
Rise	3750 mm
Rise/Span	0.25
Radius of Curvature	9375 mm
Surface Area	521.6037sq. m

5.2.2.21 Vault K-03 (15m x 30m)

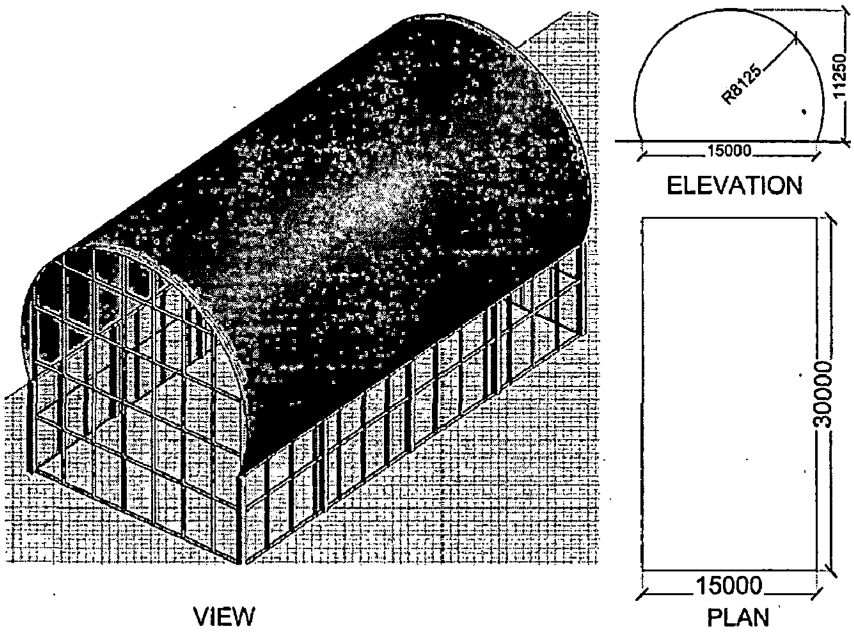


Figure 5-41Vault K-03

Span=Breadth	**15000 mm**
Length	30000 mm
Length/Breadth	2
Rise	11250 mm
Rise/Span	0.75
Radius of Curvature	8125mm
Surface Area	958.224 sq. m

5.2.2.22 Vault L-01 (15m x 45m)

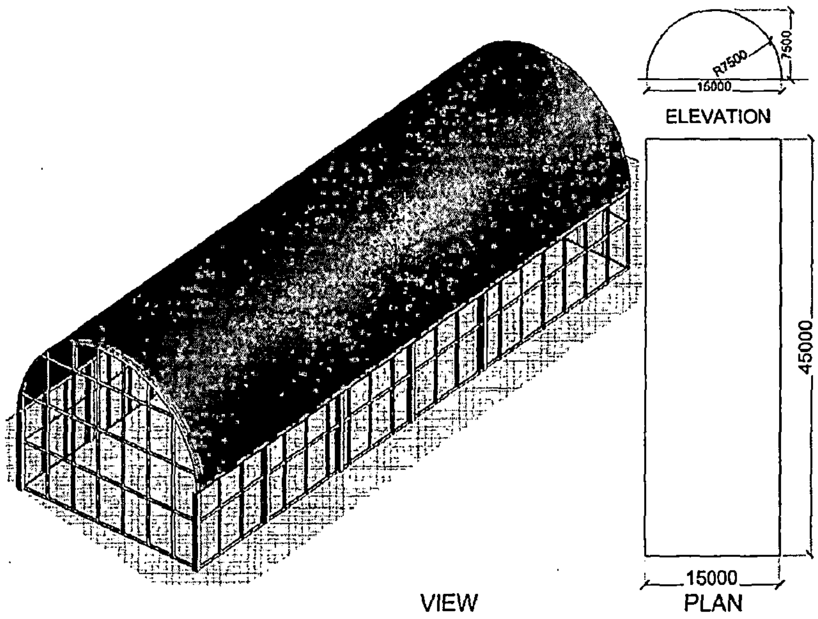


Figure 5-42Vault L-01

Span=Breadth	**15000 mm**
Length	45000 mm
Length/Breadth	3
Rise	7500 mm
Rise/Span	0. 5
Radius of Curvature	7500 mm
Surface Area	1060.2873 sq. m

5.2.2.23 Vault L-02 (15m x 45m)

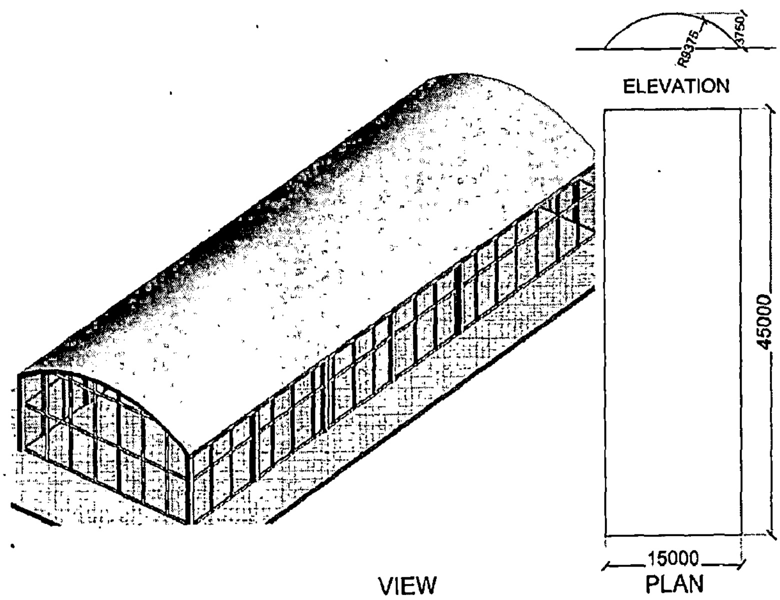


Figure 5-43Vault L-02

Span=Breadth	**15000 mm**
Length	45000 mm
Length/Breadth	3
Rise	3750 mm
Rise/Span	0. 25
Radius of Curvature	9375 mm
Surface Area	782.40555 sq. m

5.2.2.24 Vault L-03 (15m x 45m)

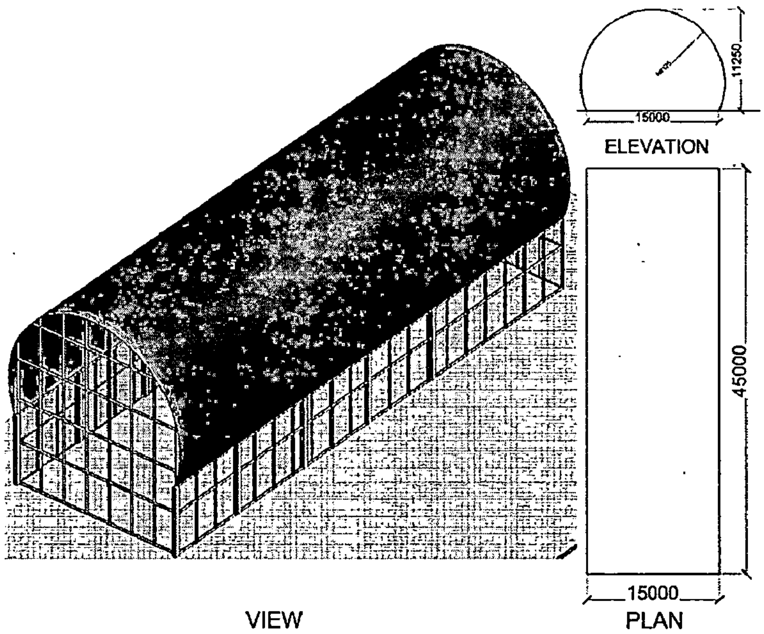


Figure 5-44Vault L-03

Span=Breadth	**15000 mm**
Length	45000 mm
Length/Breadth	3
Rise	11250 mm
Rise/Span	0. 75
Radius of Curvature	8125mm
Surface Area	1437.336 sq. m

5.2.3 HYPERBOLIC PARABOLOID

5.2.3.1 Hyperbolic Paraboloid M-01 (7.5m x7.5m)

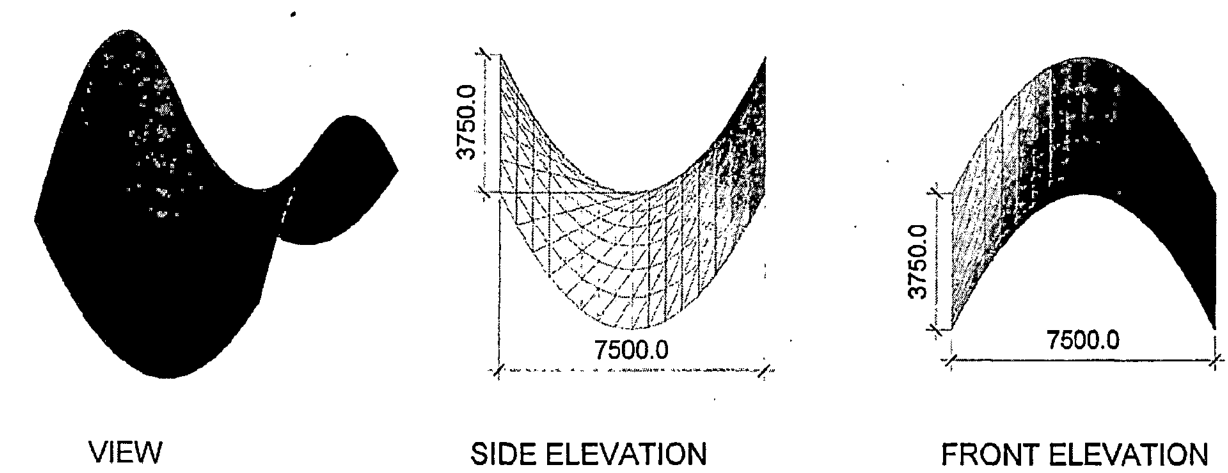


Figure 5-45 Hyperbolic Paraboloid M-01

Span=Breadth	**7500 mm**
Length	7500 mm
Length/Breadth	1
Rise	3750mm
Rise/Span	0.5
Function	Z=3750(x^2/3750^2-y^2/3750^2)

5.2.3.2 Hyperbolic Paraboloid M-02 (7.5m x7.5m)

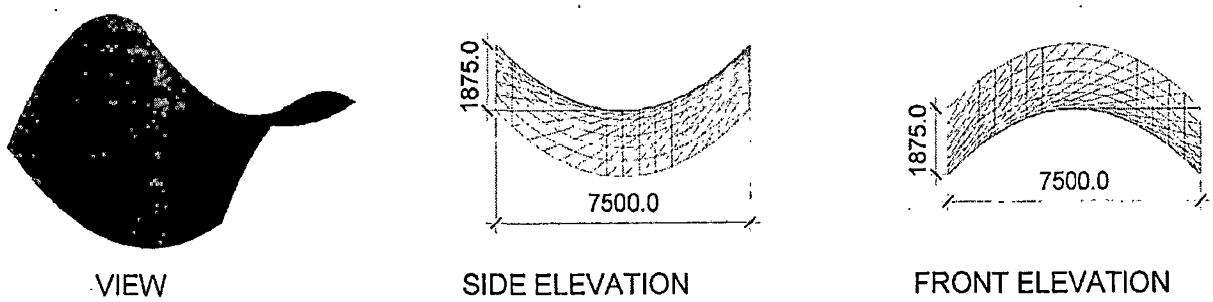


Figure 5-46Hyperbolic Paraboloid M-02

Span=Breadth	**7500 mm**
Length	7500 mm
Length/Breadth	1
Rise	1875mm
Rise/Span	0.25
Function	Z=1875(x^2/3750^2-y^2/3750^2)

5.2.3.3 Hyperbolic Paraboloid M-03 (7.5m x 7.5m)

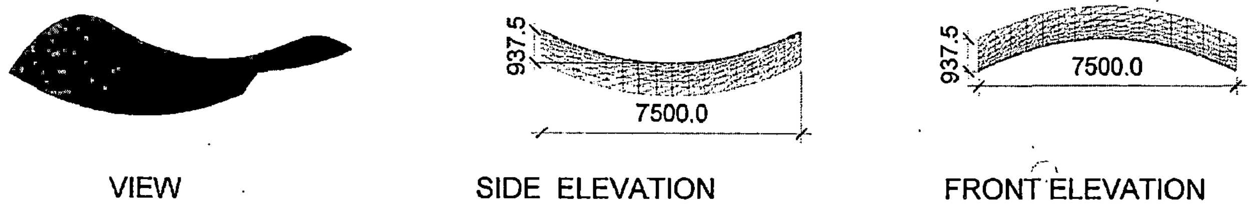


Figure 5-47Hyperbolic Paraboloid M-03

Span=Breadth	**7500 mm**
Length	7500 mm
Length/Breadth	1
Rise	937.5 mm
Rise/Span	0.125
Function	Z=937.5 (x^2/3750^2-y^2/3750^2)

5.2.3.4 Hyperbolic Paraboloid N-01 (7.5m x 20m)

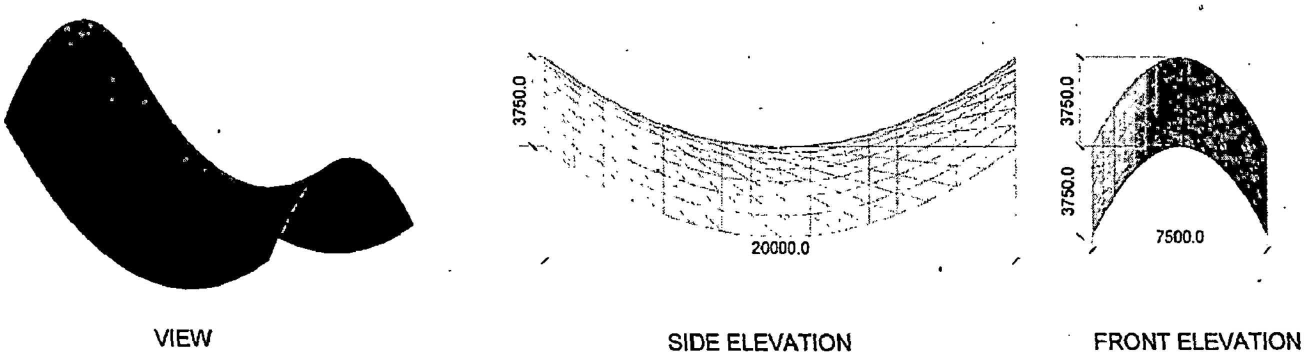


Figure 5-48Hyperbolic Paraboloid N-01

Span=Breadth	**7500 mm**
Length	20000 mm
Length/Breadth	2.67
Rise	3750 mm
Rise/Span	0.5
Function	Z=3750 (x^2/3750^2-y^2/10000^2)

5.2.3.5 Hyperbolic Paraboloid N-02 (7.5m x 20m)

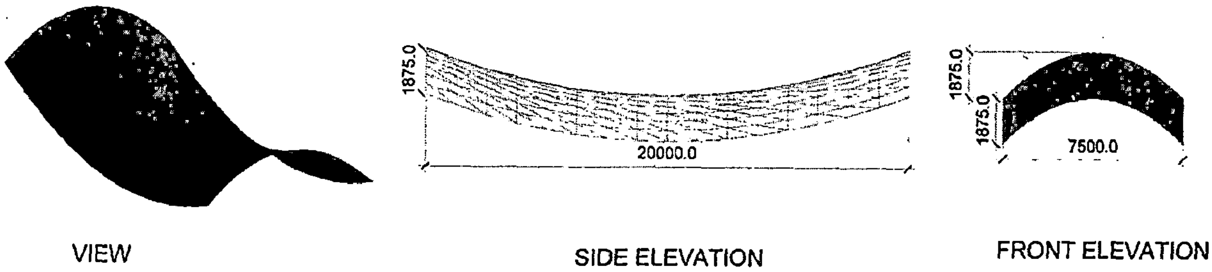


Figure 5-49Hyperbolic Paraboloid N-02

Span=Breadth	**7500 mm**
Length	20000 mm
Length/Breadth	2.67
Rise	1875 mm
Rise/Span	**0.25**
Function	Z=1875 (x^2/3750^2-y^2/10000^2)

5.2.3.6 Hyperbolic Paraboloid N-03 (7.5m x 20m)

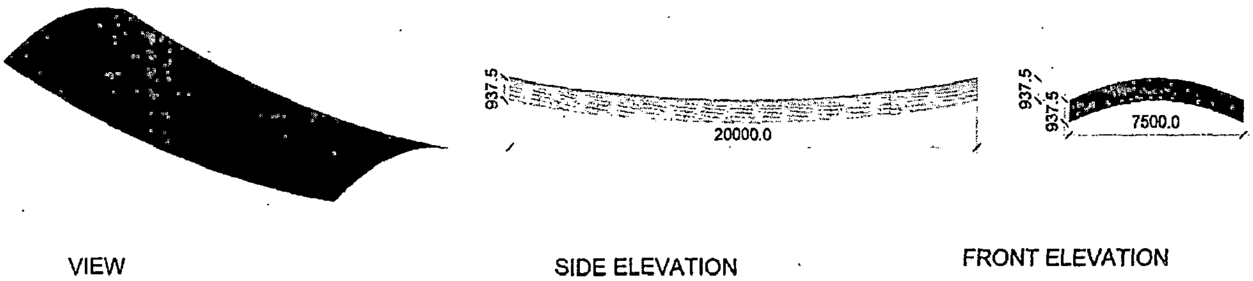


Figure 5-50Hyperbolic Paraboloid N-02

Span=Breadth	**7500 mm**
Length	20000 mm
Length/Breadth	2.67
Rise	937.5 mm
Rise/Span	**0.125**
Function	Z=937.5 (x^2/3750^2-y^2/10000^2)

5.2.3.7 Hyperbolic Paraboloid O-01 (10m x 10m)

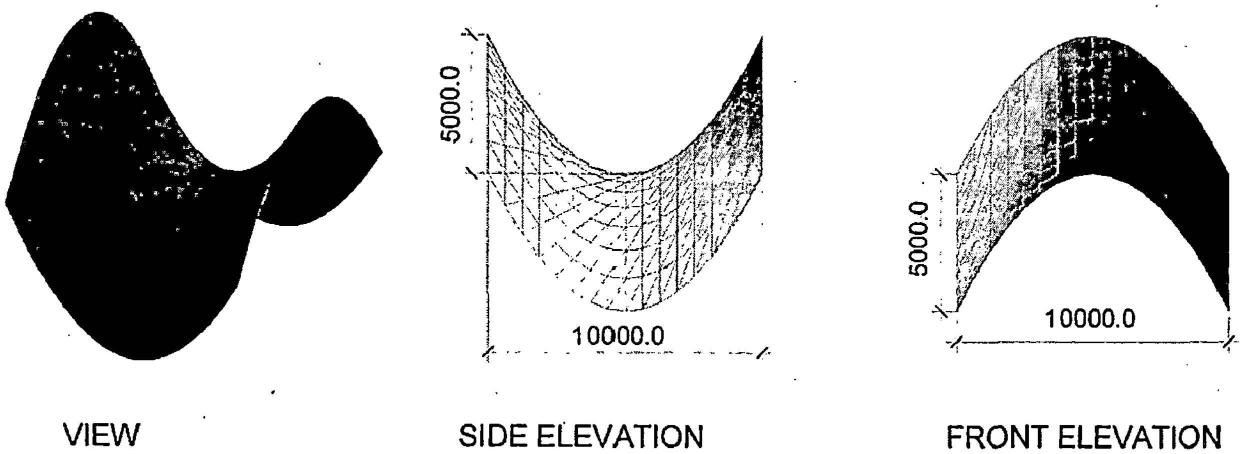


Figure 5-51Hyperbolic Paraboloid O-01

Span=Breadth	**10000 mm**
Length	10000 mm
Length/Breadth	1
Rise	5000 mm
Rise/Span	**0.5**
Function	Z=5000 (x^2/5000^2-y^2/5000^2)

5.2.3.8 Hyperbolic Paraboloid O-02 (10m x 10m)

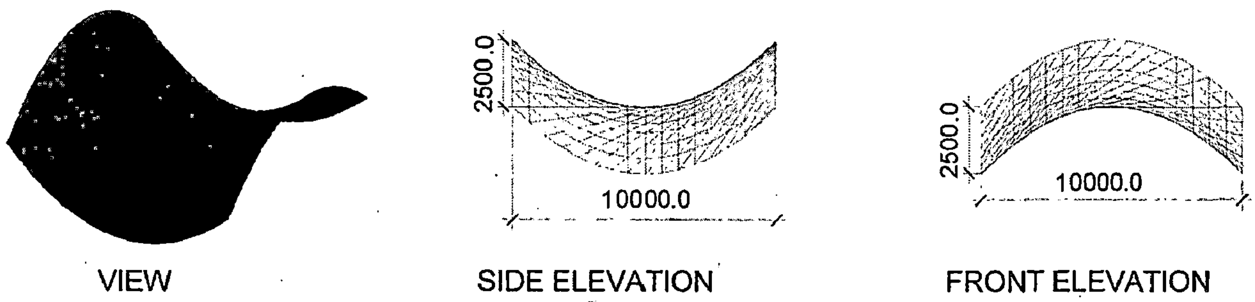


Figure 5-52 Hyperbolic Paraboloid O-02

Span=Breadth	**10000 mm**
Length	10000 mm
Length/Breadth	1
Rise	2500 mm
Rise/Span	**0.25**
Function	Z=2500 (x^2/5000^2-y^2/5000^2)

5.2.3.9 Hyperbolic Paraboloid O-03 (10m x 10m)

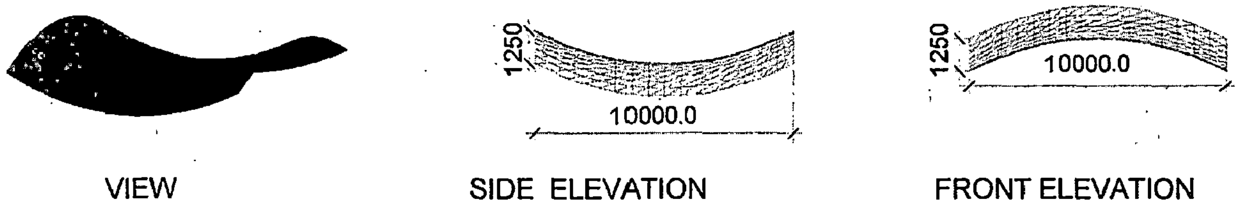


Figure 5-53 Hyperbolic Paraboloid O-03

Span=Breadth	**10000 mm**
Length	10000 mm
Length/Breadth	1
Rise	1250 mm
Rise/Span	0.125
Function	Z=1250 (x^2/5000^2-y^2/5000^2)

5.2.3.10 Hyperbolic Paraboloid P-01 (10m x 25m)

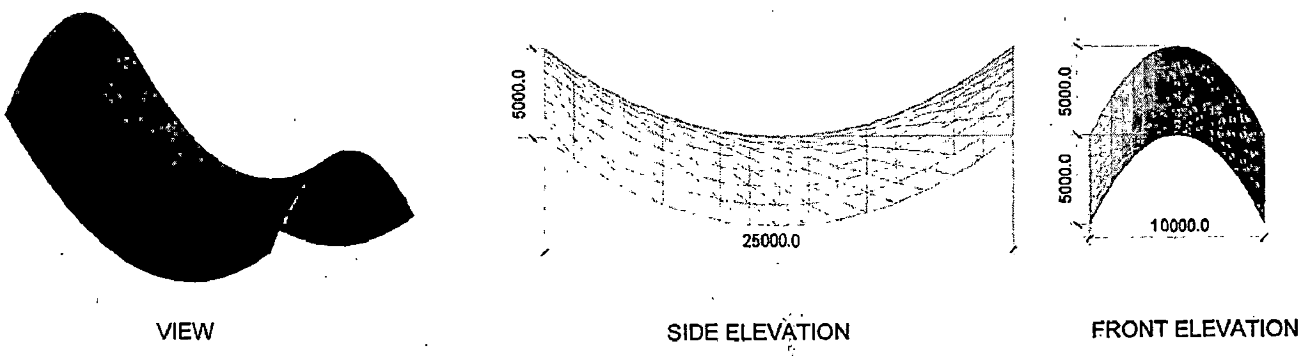


Figure 5-54 Hyperbolic Paraboloid P-01

Span=Breadth	**10000 mm**
Length	25000 mm
Length/Breadth	2.5
Rise	5000 mm
Rise/Span	0.5
Function	Z=5000 (x^2/5000^2-y^2/12500^2)

5.2.3.11 Hyperbolic Paraboloid P-02 (10m x 25m)

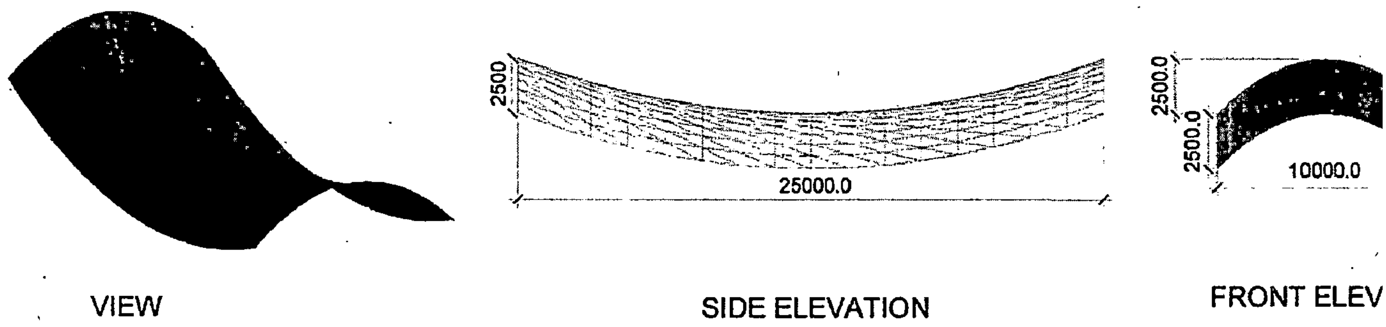


Figure 5-55Hyperbolic Paraboloid P-02

Span=Breadth	**10000 mm**
Length	25000 mm
Length/Breadth	2.5
Rise	2500 mm
Rise/Span	0.25
Function	Z=2500 (x^2/5000^2-y^2/12500^2)

5.2.3.12 Hyperbolic Paraboloid P-03 (10m x 25m)

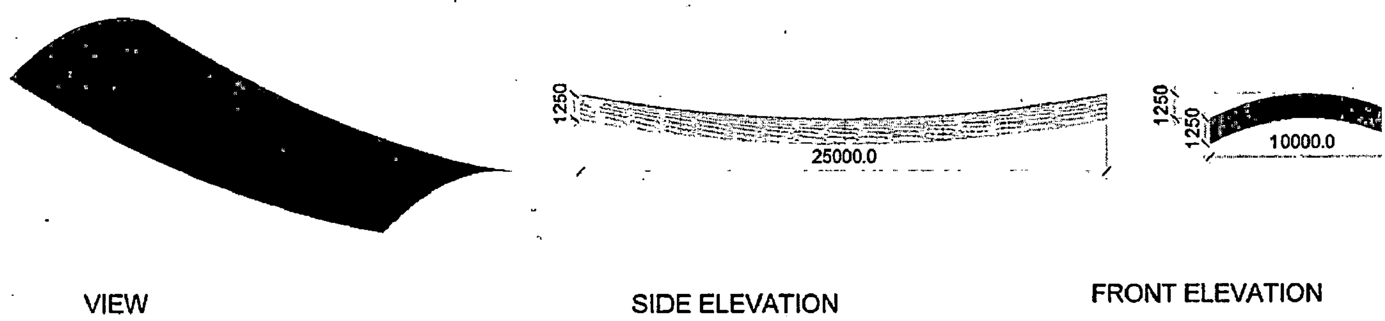


Figure 5-56Hyperbolic Paraboloid P-03

Span=Breadth	**10000 mm**
Length	25000 mm
Length/Breadth	2.5
Rise	1250 mm
Rise/Span	0.125
Function	Z=1250 (x^2/5000^2-y^2/12500^2)

5.2.4 FLAT ROOF

For flat roof analysis a 10m x 10m area is taken.

5.3 MATERIAL SPECIFICATIONS AND CONSIDERATIONS

5.3.1 FRP (FROM STANDARDS/ISBN PUBLISHED PAPERS/MANUFACTURERS

5.3.1.1 Type of Construction

Various types of construction practices are prevalent like Single skin construction, Corrugated/ Ribbed Construction, Sandwich Construction etc. Among these Sandwich construction is the strongest and is being used in high end buildings. However it is expensive. Single skin construction is the cheapest among these; however it is weak w.r.t. deflection criteria. Single skin construction gives economical solution for funicular forms.

So the Type of Construction taken for the analysis and design is **Single Skin FRP Self Supporting Structures (No MS Structure Required).**

5.3.1.2 Material Properties

Source: (AMJAD, Aref J. and Sreenivas, Alampalli, 2001)

Material		Glass fibers in advanced polyester resin with Class 1 Fire Retardant as Described by ASTM E-84
Lamination Type		0°/90°/0° (it is the superior case, referenced from *(PRADYUMNA, S and Bandyopadhyay, J. N., 2007)*
Density		1440 Kg/m^3
Elastic Properties	E_1	25000 N/mm^2
	E_2	1000 N/mm^2
	$G_{12}=G_{31}$	500 N/mm^2
	G_{23}	250 N/mm^2
	υ_1	0.25
	υ_2	0.01

5.3.1.3 Loads

Self-Weight	Density X Volume = Self-Weight = 0.00001413xh N/mm^2 (h= Thickness of the Panel/sheet)
Access Provided Load	1.5 KN/m^2= 0.0015 N/mm^2
Finish Load	0.0005 N/mm^2
Wind Load	1 KN/m^2= 0.001 N/mm^2

5.3.1.4 Cost

Source: (MP POLYMERS) http://www.mppolymers.com/pricelist.html)

Cost (for 5mm Thickness) per SQM of Surface Area in INR	2534.43

Fixing Charges per SQM Area of Plan	161

5.3.2 RCC (FROM STANDARDS)

5.3.2.1 Construction type

Shell Structure, as we are considering large span structures with curvilinear sections it is best for RCC.

5.3.2.2 Material Properties*(Source: IS 456)*

Concrete Grade		M-25, f_{ck}= 25N/mm^2
Steel Grade		Fe 415, f_y= 415N/mm^2
RCC Density		25 KN/m^3
Elastic Properties	$E_1 = E_2$	25000 N/mm^2
	$G_{12}=G_{31}=G_{23}$	9615.38 N/mm^2
	$\upsilon_1 = \upsilon_2$	0.3

5.3.2.3 Cost (in INR)

(Source: CPWD ANALYSIS FOR RATES IN DELHI 2010 http://cpwd.gov.in/deputation/ar1-final.pdf)

Cost of RCC Shell in M 20 excluding Centering and Shuttering per CuM	3773.15
Additional Cost per CuMfor richer mix Of M25 instead of M 20	109.1
Centering and Shuttering upto 6m Span per SqMof Surface Area	514.7
Extra for C&S exceeding 6m Span per SqMof Surface Area	259.6
Reinforcement for RCC work including straightening, cutting, bending, palcing in position and binding all complete - Cost of 1 Kg (Mild Steel & Medium/Tensile Steel Bars)	41.5
Cost of RCCsupporting structure and footing M 25 excluding C&S and Reinforcement per CuM	5201.5
M25 grade concrete work for RCC footing cum	4841.15
Cost of CC Supporting structure and footing C&S per SqM of Surface Area	119.25

5.3.3 COST OF STEEL WORK

(Source: CPWD ANALYSIS FOR RATES IN DELHI 2010 http://cpwd.gov.in/deputation/ar1-final.pdf)

Density of steel = 7850 kg/m^3

Steel Work in Built-up Tubular Trusses = Rs 79.8 per Kg

5.4 DESIGN AND CALCULATIONS

This section describes the process of analysis and structural design of the above chosen cases. The inherent property of FRP makes it very strong w.r.t. stresses (high specific strength and stiffness) but is weak w.r.t. deflection. So for determining thickness of the section of FRP panel to be used for roof structure we have to find out the maximum deflection which should be less than the permissible deflection. Whereas for designing Concrete structure stresses play the role.

5.4.1 STRUCTURAL ANALYSIS

The structural analysis is carried out by using a finite element based software code developed by FORTRAN programming language.

The composite shell structure has been modeled as a two dimensional structure by using higher order shear deformation theory.

This program is used because

- The available structural design and analysis softwares are based upon Ist order theory whereas the program used is based upon higher order theory.
- User friendly, easy to learn.
- The present program is being validated by the results of the following papers:
  - REDDY J.N., LIU C.F. , A Higher order Shear Deformation Theory of Laminated Elastic Shells, 1985 (0020-7225/85)
  - BHASKAR K., VARADAN T.K., A higher -order Theory for Bending Analysis of Laminated shells of Revolution (0045-7949/90)
  - WUNG P.M., Laminated Composite Structures by Continuum-based shell elements with transverse deformation, 1992 , Computers and Structures Vol. 62, Elsevier Science Ltd.
  - PRADYUMNA S, BANDYOPADHYAY J.N., Static and Free Vibration Analysis of Laminated Shells using Higher – order theory, Journal of Reinforced Plastics and Composites, 2007

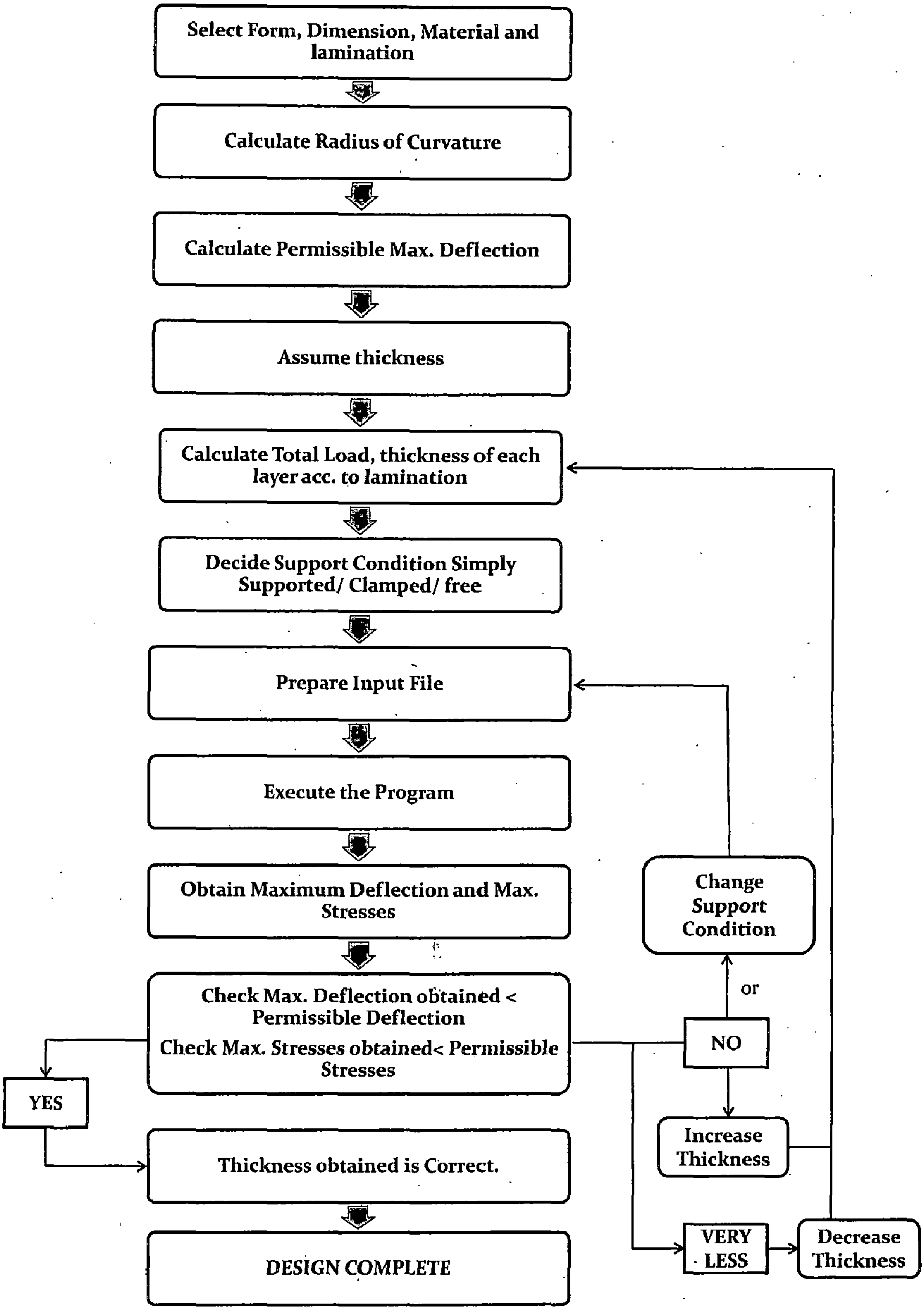


Figure 5-57 Design Process

1 -0.0004 0.0 0.0	CC Inverse Radius of Curvature in X- axes(XR) YR XYR
5000 10000 0	Span (XL) Length (YL) Angle with XY plane
16 16	No. of Elements in each direction (Division of whole into small elements)
1 1 1 1	Support boundary condition (SS=1 Clamped=2 etc.)
0 0.003070632	No. of Point loads, Total U.D.L.
1	No. of Materials
25000 1000 0.25 0.01 500 500 200	$E_1\ E_1\ \nu_1\ \nu_2\ G_{12}\ G_{31}\ G_{23}$ (Elastic Properties of Material).
2,2	No. of Layers above mid plane, No. of Layers below mid plane
0.833,90,1	Thickness of layer, orientation, material no.
1.667,0,1	-do-
0.833,90,1	-do-
1.667,0,1	-do-
0	No. of Stress Points

Figure 5-58 Input File Format for FRP FEA

5.4.2 STRUCTURAL DESIGN OF SUPPORTING STRUCTURE

- In this section problems of hemi spherical dome and semicircular vault made of both RCC and FRP materials are solved with the help of FE model. Supporting RCC structures are designed by limit state method using IS 456.
- Cost analysis is done on the basis of rates obtained from CPWD – analysis of Rates Delhi 2010 and FRP rates are based upon present market rate.

5.4.2.1 Hemi Spherical Dome - FRP

➢ ***Design of FRP Roof shell***

To design a FRP spherical shell above mentioned procedure is followed:

1. **Specifications:**

- Material : FRP (Lamination Scheme-0°/90°/0°)
- Span of the shell :30 m
- Diameter of shell (d) :15 m
- Rise of shell (h) :15 m
- Assumed thickness of shell :5 mm
- Loads : As Mentioned in *Section 5.3*

2. **Design Load**

Total working load = [(0.00001413 x 5) + 0.003] N/mm^2=0.00307065 N/mm^2

3. **Check thickness for maximum deflection criteria**

Maximum Deflection of shell = 11.09 mm (Obtained from FE model)

Maximum permissible deflection = (Span / 800) = (30000/800) = 37.5 mm

4. **Check thickness for maximum stresses criteria**

The allowable and maximum stresses are as follows:

Stress (N/mm^2)	Stress	In-plane normal stress σ_x	In-plane normal stress σ_y	In-plane shear stress τ_{xy}
Location (x,y,z)	Location (x,y,z)	(0,15,0.0025)	(0,15, 0.00083)	(0.1,0.1,0.0025)
Maximum Stress (N/mm^2)	Maximum Stress	15.625	0.153	0.025
Allowable stress (N/mm^2)	Allowable stress	483	331	179

➢ ***Design of column***

1. **Considerations**

- Effective length of column : 3 m
- Materials : M25 and Fe415
- Design philosophy : Limit state method conforming to IS 456 : 2000

2. **Loading**

Surface area of shell = $\pi\left[(d/2)^2+h^2\right]$= 1413.717 x $10^6 mm^2$

Total weight of shell superstructure = 0.00307065 x 1413.717 x 10^6 = 4341.03 kN

Provide 16 columns @ 5.89 m c/c along the periphery of shell

Load on one column = 4341.03/ 16 = 271.314 kN

Design load on a column (P_u) = 1.5 x 271.314 = 406.97 kN≈410 kN

3. **Determination of size of column**

Assume percentage of steel reinforcement = 1.5 %

$$P_u = 0.4 f_{ck} A_g + 0.67 f_y A_{sc}$$

$$A_{g_{reqd.}} = \frac{P_u}{0.4 f_{ck} + (0.67 f_y 0.015)} = 28932.837 mm^2$$

Required size of square column = $\sqrt{28932.837}$ =170.09 mm

Provide square column of size 250 mm x 250 mm.

Provided area of concrete ($A_{g_{provided}}$) = 62500 mm²

4. **Longitudinal reinforcement**

Required $A_{sc reqd.} = 0.015 A_{g.reqd.}$ = 433.99mm²

Required Nos. of 12 mm ϕ bars = $433.99/(\pi \times 6^2)$ = 3.837

Use 6 Nos. 12 mm ϕ bars, area provided = 678.584mm²

5. **Lateral ties**

Minimum diameter = 12/4 =3 mm or 5 mm whichever is greater

Pitch $\leq$ (250 mm or (16 x 12=192 mm) or 300 mm)

Provide 6 mm ϕ bars @ 180 mm c/c

➢ ***Design of footing***

1. **Considerations:**

• Type of footing	: Isolated pad footing
• Size of column	: 250 mm x 250 mm
• Axial load of column	: 410 kN
• Bearing capacity of soil	: 100 kN/m²
• Material	: M25 and Fe415
• Effective cover for bottom steel	:60 mm
• Design philosophy	: Limit state method conforming to IS 456 : 2000

2. **Design Constants:**

$R_{umax} = 0.138 f_{ck}$= 3.45 N/mm²

3. **Proportioning of base size**

Load transferred from column (P_u) = 410 kN

Self-Weight of Column (P_c) =250x250x3000x25x10⁻⁹=4.6875 kN

Self-weight of footing (at 10% of $P=P_u+P_c$) = 41.468 kN

Total load = 456.156 kN

Area of footing required = A_f= (495.724/100) =4.957m²

Required size of square footing = $\sqrt{A_{f_{reqd.}}}$ = 2.226 m

Provide square footing of size 2.3 m x 2.3 m

Area of footing provided = A_f= 5.29 m²>2.226 m²

Length of the footing (L) = = 2.3 m

Projection of the footing from the face of column (C) = (2.3-0.25)/2 = 1.025 m

Upward factored soil pressure = wu = (1.5 x 450.622 /5.29) = 127.776 kN/m2

4. **Depth of the footing from bending moment consideration**

= 154.381 kN.m.

Required effective depth for bending

= 139.484 mm

Assume total depth of 300 mm

Effective depth ( ) = 320-60 = 260 mm

5. **Check for two way shear**

Critical section is at distance from the column periphery.

Perimeter at critical section = 4[250 + 260] = 2040 mm

Area resisting shear = 2040 x 260 = 530400 mm2

= 1.25 N/mm2

Shear resisted by concrete = Vuc2 = (1.25 x 530400)/1000 = 663 kN

Design Shear = VuD2 = = 653.318 kN

Vuc2 (=663 kN) > VuD2 (= 653.318 kN)......Safe.

6. **Area of steel and check for development length**

Required area of steel for bending

=1728.314 mm2

Ast. min = (0.85 x 2300 x260 /415)= 1224.819 mm2 > Ast

Provide 16 No. #12 mm dia bars, Area provided ( ) = 1809.557 mm2>

Provide 16 No. #12 mm dia. bars in both directions,

Total area of steel provided = 1809.557 x 2 = 3619.115 mm2

Required development length (Ld) = = 472.433 mm

Available development length = C-50 = 975 mm > 472.333 mm ....Safe.

5.4.2.2 .Hemi Spherical Dome - RCC

- ***Design of Roof Shell***

To design a RCC spherical shell following steps is followed:

1. **Considerations:**

- Span of the shell :30 m
- Diameter of shell (d) :15 m
- Rise of shell (h) :15 m
- Assumed thickness of shell :70 mm

(Minimum thickness is 40 mm as per IS 2210:1988 Clause 7.1)

- Materials : M25 and Fe415
- Design philosophy : IS 2210 : 1988

2. **Loading data**

- Self weight : 25 kN/m3 (IS 456:2000 Cl.19.2.1)
- Access Load : 1.5 kN/m2 (IS 875 Part II)
- Wind Load : 1 kN/m2 (IS 875 Part III)
- Finish Load : 0.75 kN/m2 (IS 875 Part I)

3. **Design Load**

Self weight of shell = 0.025 x 70 = 1.75 N/mm2

Total working load = 1.75 + 1.5 + 1 + 0.75 = 0.005 N/mm2

Design Load = 0.005 x 1.5 = 0.0075 N/mm2

4. **Check thickness for maximum deflection criteria**

Maximum Deflection of shell = 0.936 mm (Obtained from Proposed FE model)

Maximum permissible deflection = (Span / 250) (IS 456:2000 Cl.23.2)

= (30000/250) = 120 mm

5. **Check thickness for maximum stresses criteria**

Allowable stresses in Tension in Concrete = 3.2 N/mm2 (IS 456:2000 Cl.B-2.1.1)

Allowable stresses in Compression in Concrete = 8.5 N/mm2(IS 456:2000 Cl.B-2.1)

Maximum stresses:

- In-plane normal stresses

= 1.018 N/mm2 (Obtained from Proposed FE model)

= 0.212 N/mm2 (Obtained from Proposed FE model)

- In-plane shear stress

= 0 N/mm2 (Obtained from Proposed FE model)

6. **Steel Reinforcement**

As the stresses are within permissible limit, provide minimum reinforcement.

Minimum reinforcement = (0.12 x 1000 x 70 /100) (IS 456:2000 Cl.26.5.2.1)

= 84 mm2/m

Provide 6 mm bars @ 150 mm c/c

- ***Design of column for RCC roof***

1. **Considerations**

- Effective length of column : 3 m
- Materials : M25 and Fe415
- Design philosophy : Limit state method conforming to IS 456 : 2000

2. **Loading**

Surface area of shell = = 1413.717 x 106 mm2

Total weight of shell superstructure = 0.005 x 1413.717 x 106 = 7068.584 kN

Provide 16 columns @ 5.89 m c/c along the periphery of shell

Load on one column = 7068.584/ 16 = 441.787 kN

Design load on a column (Pu) = 1.5 x 441.787 = 662.679 kN

3. **Determination of size of column**

Assume percentage of steel reinforcement = 1.5

(IS 456:2000 Cl.39.3)

= 46763.862 mm2

Required size of a side of square column = =216.249 mm

Provide square column of size 250 mm x 250 mm.

Provided area of concrete ( ) = 62500 mm2

4. **Longitudinal reinforcement**

Required = 701.458 mm2

Required No. of 12 mm bars = = 6.202

Use 8 Nos. 12 mm bars, area provided = 904.779 mm2

5. **Lateral ties**

Minimum diameter = 12/4 =3 mm or 5 mm whichever is greater.

Pitch (250 mm or (16 x 12=192 mm) or 300 mm)

Provide 6 mm bars @ 180 mm c/c

- ***Design of footing for RCC roof***

1. **Considerations:**

- Type of footing : Isolated pad footing
- Size of column : 250 mm x 250 mm
- Axial load of column : 662.679 kN
- Bearing capacity of soil : 100 kN/mm2
- Material : M25 and Fe415
- Effective cover for bottom steel :60 mm
- Design philosophy : Limit state method conforming to IS 456 : 2000

2. **Design Constants:**

Rumax = 0.138 fck = 3.45 N/mm2

3. **Proportioning of base size**

Load transferred from column (P) = 662.679 kN

Self weight of footing (at 10% of P) = 66.268 kN

Total load = 728.947 kN

Area of footing required = = (728.947/100) = 7.28947 m2

Required size of square footing = = 2.699 m

Provide square footing of size 3 m x 3 m

Area of footing provided = = 9 m2 > (7.28947 m2)

Length of the footing (L) = 3 m

Projection of the footing from the face of column (C) = (3-0.25)/2 = 1.375 m

Upward factored soil pressure = wu = (1.5 x 662.679 /9) = 110.447 kN/m2

4. **Depth of the footing from bending moment consideration**

= 313.221 kN.m

Required effective depth for bending

= 173.962 mm

Assume total depth of 400 mm

Effective depth ( ) = 400-60 = 340 mm

5. **Check for two way shear**

Critical section is at distance from the column periphery.

Perimeter at critical section = 4[250 + 340] = 2360 mm

Area resisting shear = 2360 x 340 = 8024400 mm2

= 1.25 N/mm2

Shear resisted by concrete = Vuc2 = (1.25 x 802400)/1000 = 1003 kN

Design Shear = VuD2 = = 880.888 kN

Vuc2 (=1003 kN) > VuD2 (= 880.888 kN)......Safe.

6. **Area of steel and check for development length**

Required area of steel for bending

= 2688.739 mm2

Ast. min = (0.85 x 3000 x340 /415)= 2089.156 mm2 > Ast

Provide 26 No. #12 mm dia. bars, Area provided ( ) = 2940.531 mm2 >

Provide 26 No. #12 mm dia. bars in both directions,

Total area of steel provided = 2941 x 2 = 5882mm2

Required development length (Ld) = (IS 456:200 Cl.26.2.1)

= 472.433 mm

Available development length = C-50 = 1.325 mm > 472.433 mm ....Safe.

5.4.2.3 Semi-Circular Barrel Vault - FRP

- ***Design of FRP Roof shell***

To design a FRP spherical shell above mentioned procedure is followed:

5. **Specifications:**

- Material : FRP (Lamination Scheme-0°/90°/0°)
- Span of the shell :15 m
- Length :45 m
- Rise of shell (h) :7.5 m
- Assumed thickness of shell :5 mm (calculation based upon section 5.4.1)
- Loads : As Mentioned in *Section 5.3*

6. **Design Load**

Total working load = 1.5x0.005x1060.2873x10^6 = 7952.15 kN

7. **Check thickness for maximum deflection criteria**

Maximum Deflection of shell = 11.09 mm (Obtained from FE model)

Maximum permissible deflection = (Span / 800) = (30000/800) = 37.5 mm

8. **Check thickness for maximum stresses criteria**

The allowable and maximum stresses are as follows:

Stress (N/mm²)	Stress	In-plane normal stress σ_x	In-plane normal stress σ_y	In-plane shear stress τ_{xy}
Location (x,y,z)	Location (x,y,z)	(0,15,0.0025)	(0,15, 0.00083)	(0.1,0.1,0.0025)
Maximum Stress (N/mm²)	Maximum Stress	15.625	0.153	0.025
Allowable stress (N/mm²)	Allowable stress	483	331	179

- ***Design of column***

6. **Considerations**

- Effective length of column : 3 m

- Materials : M25 and Fe415
- Design philosophy : Limit state method conforming to IS 456 : 2000

7. **Loading**

Surface area of shell = 1060.2873 x $10^6 mm^2$

Total weight of shell superstructure =[0.00001413x5+0.003]x1060.2873 x 10^6 = 3255.77 kN

Provide 16 columns @ 6.42 m c/c along the periphery of shell

Load on one column = 3255.77/ 16 = 203.485 kN

Design load on a column (P_u) = 1.5 x 203.485 = 305.22 kN≈310 kN

8. **Determination of size of column**

Assume percentage of steel reinforcement = 1.5 %

$$P_u = 0.4 f_{ck} A_g + 0.67 f_y A_{sc}$$

$$A_{g_{reqd.}} = \frac{P_u}{0.4 f_{ck} + (0.67 f_y 0.015)} = 28932.837 mm^2$$

Required size of square column = $\sqrt{28932.837}$ =170.09 mm

Provide square column of size 250 mm x 250 mm.

Provided area of concrete ($A_{g_{provided}}$) = 62500 mm^2

9. **Longitudinal reinforcement**

Required $A_{sc_{reqd.}} = 0.015 A_{g.reqd.}$ = 433.99mm^2

Required Nos. of 12 mm ϕ bars = $433.99/(\pi \times 6^2) = 3.837$

Use 6 Nos. 12 mm ϕ bars, area provided = 678.584mm^2

10. **Lateral ties**

Minimum diameter = 12/4 =3 mm or 5 mm whichever is greater

Pitch $\leq$ (250 mm or (16 x 12=192 mm) or 300 mm)

Provide 6 mm ϕ bars @ 180 mm c/c

➢ ***Design of footing***

4. **Considerations:**

- Type of footing : Isolated pad footing
- Size of column : 250 mm x 250 mm
- Axial load of column : 410 kN
- Bearing capacity of soil : 100 kN/m^2
- Material : M25 and Fe415
- Effective cover for :60 mm

bottom steel

- Design philosophy : Limit state method conforming to IS 456 : 2000

5. **Design Constants:**

R_{umax} = 0.138 f_{ck}= 3.45 N/mm²

6. **Proportioning of base size**

Load transferred from column (P_u) = 310 kN

Self-Weight of Column (P_c) =250x250x3000x25x10^{-9}=4.6875 kN

Self-weight of footing (at 10% of $P=P_u+P_c$) = 31.468 kN

Total load = 346.148 kN

Area of footing required = A_f= (346.148/100) =3.46m²

Required size of square footing = $\sqrt{A_{f_{reqd.}}}$ = 1.86 m

Provide square footing of size 2.0 m x 2.0 m

Area of footing provided = A_f= 4 m²>3.46 m²

Length of the footing (L) = 2.0 m

Projection of the footing from the face of column (C) = (2.0-0.25)/2 = 0.875 m

Upward factored soil pressure = W_u = (1.5 x 314.68 /4.0) = 118 kN/m2

4. **Depth of the footing from bending moment consideration**

$M_u = w_u L C^2 / 2$ = 90.34kN.m.

Required effective depth for bending

$d = \sqrt{M_{ux} / (R_{u\max} \times L)}$ = 114.4 mm

Assume total depth of 260 mm

Effective depth ( ) = 260-60 = 200 mm

5. **Check for two way shear**

Critical section is at distance from the column periphery.

Perimeter at critical section = 4[250 + 200] = 1800 mm

Area resisting shear = 1800 x 200 = 360000 mm2

$\tau_{uc} = 0.25\sqrt{f_{ck}}$ = = 1.25 N/mm2

Shear resisted by concrete = Vuc2 = (1.25 x 360000)/1000 = 450 kN

Design Shear = VuD2 = $w_u \left[L^2 - (250 + 200)^2 \right]$ = 448 kN

Vuc2 > VuD2 ......Safe.

6. **Area of steel and check for development length**

Required area of steel for bending

$$A_{st} = \frac{0.5 f_{ck} L d}{f_y}\left(1-\sqrt{1-\frac{4.6 M_u}{f_{ck} L d^2}}\right)$$ =1705.8 mm2

Ast. min = (0.85 x 2000 x200 /415)=819 mm2 < Ast

Provide 16 No. #12 mm dia bars, Area provided ( ) = 1809.557 mm2>

Provide 16 No. #12 mm dia. bars in both directions,

Total area of steel provided = 1809.557 x 2 = 3619.115 mm2

Required development length (Ld) = = 472.433 mm

Available development length = C-50 = 875 mm > 472.333 mm ....Safe.

5.4.2.4 Semi Circular Vault – RCC

- ***Design of Roof Shell***

To design a RCC spherical shell following steps is followed:

1. **Considerations:**

•	Span of the shell	:30 m
•	Diameter of shell (d)	:15 m
•	Rise of shell (h)	:15 m
•	Assumed thickness of shell	:70 mm

(Minimum thickness is 40 mm as per IS 2210:1988 Clause 7.1)

•	Materials	: M25 and Fe415
•	Design philosophy	: IS 2210 : 1988

2. **Loading data**

•	Self weight	: 25 kN/m3	(IS 456:2000 Cl.19.2.1)
•	Access Load	: 1.5 kN/m2	(IS 875 Part II)
•	Wind Load	: 1 kN/m2	(IS 875 Part III)
•	Finish Load	: 0.75 kN/m2	(IS 875 Part I)

3. **Design Load**

Self weight of shell = 0.025 x 70 = 1.75 N/mm2

Total working load = 1.75 + 1.5 + 1 + 0.75 = 0.005 N/mm2

Design Load = 0.005 x 1.5 = 0.0075 N/mm2

4. **Check thickness for maximum deflection criteria**

Maximum Deflection of shell = 0.936 mm (Obtained from Proposed FE model)

Maximum permissible deflection = (Span / 250) (IS 456:2000 Cl.23.2)

= (30000/250) = 120 mm

5. **Check thickness for maximum stresses criteria**

Allowable stresses in Tension in Concrete = 3.2 N/mm2 (IS 456:2000 Cl.B-2.1.1)

Allowable stresses in Compression in Concrete = 8.5 N/mm2(IS 456:2000 Cl.B-2.1)

Maximum stresses:

- In-plane normal stresses

= 1.018 N/mm2 (Obtained from Proposed FE model)

= 0.212 N/mm2 (Obtained from Proposed FE model)

- In-plane shear stress

= 0 N/mm2 (Obtained from Proposed FE model)

6. **Steel Reinforcement**

As the stresses are within permissible limit, provide minimum reinforcement.

Minimum reinforcement = (0.12 x 1000 x 70 /100) (IS 456:2000 Cl.26.5.2.1)

= 84 mm2/m

Provide 6 mm bars @ 150 mm c/c

- ***Design of column for RCC roof***

1. **Considerations**

- Effective length of column : 3 m
- Materials : M25 and Fe415
- Design philosophy : Limit state method conforming to IS 456 : 2000

2. **Loading**

Surface area of shell =1060.2873 x 106 mm2

Total weight of shell superstructure = 0.0075 x1060.2873x 10^6 = 7952.15 kN

Provide 16 columns @ 5.89 m c/c along the periphery of shell.

Load on one column = 7952.15/ 16 = 497 kN

Design load on a column (Pu) = 1.5 x 497 =745.5 kN

3. **Proportioning of base size**

Load transferred from column (P) = 745.5 kN

Self weight of footing (at 10% of P) = 74.5 kN

Total load = 820 kN

Area of footing required = = (820/100) = 8.2 m2

Required size of square footing = = 2.699 m

Provide square footing of size 3 m x 3 m

Area of footing provided = = 9 m2 > (8.2 m2)

Length of the footing (L) = 3 m

Projection of the footing from the face of column (C) = (3-0.25)/2 = 1.375 m

Upward factored soil pressure = wu = (1.5 x 745 /9) = 124.16 kN/m2

4. **Depth of the footing from bending moment consideration**

$M_u = w_u LC^2 / 2 = $ = 313.221 kN.m

Required effective depth for bending

= 173.962 mm

Assume total depth of 400 mm

Effective depth ( ) = 400-60 = 340 mm

5. **Check for two way shear**

Critical section is at distance from the column periphery.

Perimeter at critical section = 4[250 + 340] = 2360 mm

Area resisting shear = 2360 x 340 = 8024400 mm2

= 1.25 N/mm2

Shear resisted by concrete = Vuc2 = (1.25 x 802400)/1000 = 1003 kN

Design Shear = VuD2 = = 880.888 kN

Vuc2 (=1003 kN) > VuD2 (= 880.888 kN)......Safe.

6. **Area of steel and check for development length**

Required area of steel for bending

= 2688.739 mm2

Ast. min = (0.85 x 3000 x340 /415)= 2089.156 mm2 > Ast

Provide 26 No. #12 mm dia. bars, Area provided ( ) = 2940.531 mm2 >

Provide 26 No. #12 mm dia. bars in both directions,

Total area of steel provided = 2941 x 2 = 5882mm2

Required development length (Ld) = (IS 456:200 Cl.26.2.1)

= 472.433 mm

Available development length = C-50 = 1.325 mm > 472.433 mm ....Safe.

5.4.3 COST ANALYSIS

Cost Analysis of Roof shell is calculated for each of the cases, however for whole structure it is calculated for the above two cases described in detail. Below is the cost analysis for the detailed two cases mentioned in section 5.4.2.

5.4.3.1 Hemi-spherical Dome – FRP

FRP shell	No.	Description	Unit	Quantity	Rate	Amount

Shell Roof	i	Details of cost of FRP shell	sq.m	1413.717	2534.43	35,82,966.78
	ii	Details of cost of Fixing charges	sq.m	706.858	161	1,13,804.19
		Total				**36,96,770.97**
Columns	i	Details of cost of concrete Volume of column = 0.25 x 0.25 x 3 x 16 = 3 cum	cum	3	5201.5	15604.5
	ii	Details of cost of Centering and shuttering Contact surface area = 4 x 0.25 x 3 x 16 = 48	sq.m	48	238.4	11443.2
	iii	Details of cost of Reinforcement Volume of steel in one column = 0.00067854 x 3 + [(3/0.18)+1] x 28.274 x 10^-6=0.002544684 cum Total weight of steel = 0.002544684 x7850 x 16 = 320 kg	Kg	320	42.70	13664
		Total				40711.2
Footing	i	Details of cost of concrete Volume of Concrete = 2.3 x 2.3 x 0.3 x 16 = 25.392 cum	cum	25.392	4841.15	1,22,926.48
	ii	Details of cost of centering and shuttering Contact surface area = 4 x 2.3 x 0.3 x 16 = 44.16 sq.m	sq.m	44.16	119.25	5266.08
	iii	Details of cost of reinforcement Volume of steel in one footing = 0.003620 x 2.3 = 0.008326 cum Total weight of steel = 0.008326 x 7850 x 16 = 1045.746 kg	Kg	1045.746	42.70	44,653.34
		Total				1,72,845.89
Total Cost of Supporting Structure						**Rs.2,13,556.2**

5.4.3.2 Hemi Spherical Dome- RCC

RCC Shell	No.	Description	Unit	Quantity	Rate	Amount
RCC Roof Shell	i	Details of cost of Concrete Rate for M25 concrete = (3773.15 + 109.1) = Rs. 3882.25 Volume of concrete = Surface area x Thickness = 1413.717 x 0.07 = 98.960 cum	cum	98.960	3882.25	3,84,188.19
	ii	Details of cost of Centering and shuttering Rate for 30m span shell = (514.7 +259.6)= Rs. 774.3 per sq.m of surface area	Sqm	1413.717	774.3	10,94,641.07
	iii	Details of cost of Reinforcement Volume of steel = 1.4844 cum Weight of steel = 1.4844 x 7850 = 11652.54 kg	Kg	11652.54	42.70	4,97,563.45
		Total				**Rs. 19,76,392**
Columns	i	Details of cost of concrete Volume of columns = 0.25 x 0.25x 3 x 16 = 9 cum	cum	3	5201.5	15604.5
	ii	Details of cost of Centering and shuttering Contact surface area = 4 x 0.2 5 x 3 x16 = 144	Sq.m	48	238.4	11443.2
	iii	Details of cost of Reinforcement Volume of steel in one column = 0.000904779x3+[(3/0.18)+1]x28.274x10-	Kg	404.848	42.70	17287.00

		6=0.003223269 cum Total weight of steel = 0.003223269 x7850 x 16 = 404.848 kg				
		Total				Rs. 44334
Footing	i	Details of cost of concrete Volume of Concrete =3 x 3 x 0.4 x 16 = 57.6 cum	cum	57.6	4841.15	2,78,850.24
	ii	Details of cost of centering and shuttering Contact surface area = 4 x 3 x 0.4 x 16 = 76.8 sq.m	Sq.m	76.8	119.25	9158.4
	iii	Details of cost of reinforcement Volume of steel in one footing = 0.005882 x 3 = 0.017646 cum Total weight of steel = 0.017646 x 7850 x 16 = 2216.338 kg	Kg	2216.338	42.70	94,637.62
		Total				Rs. 3,82,646
Total cost of supporting structure						**Rs. 4,26,980**

5.4.3.3 Semi Circular Vault- FRP

FRP shell	No.	Description	Unit	Quantity	Rate	Amount
Shell Roof	i	Details of cost of FRP shell	sq.m	1060.28	2534.43	2687205.44
	ii	Details of cost of Fixing charges	sq.m	675	161	108675
		Total				**Rs.2695880**
Columns	i	Details of cost of concrete Volume of column = 0.25 x 0.25 x 3 x 16 = 3 cum	cum	3	5201.5	15604.5
	ii	Details of cost of Centering and shuttering Contact surface area = 4 x 0.25 x 3 x 16 = 48	sq.m	48	238.4	11443.2
	iii	Details of cost of Reinforcement Volume of steel in one column = 0.00067854 x 3 + [(3/0.18)+1] x 28.274 x 10^-6=0.002544684 cum Total weight of steel = 0.002544684 x7850 x 16 = 320 kg	Kg	320	42.70	13664
		Total				40711.2
Footing	i	Details of cost of concrete Volume of Concrete = 2.0 x 2.0 x 0.26 x 16 = 16.64 cum	cum	16.64	4841.15	80556.736
	ii	Details of cost of centering and shuttering Contact surface area = 4 x 2.0 x 0.26 x 16 = 33.28 sq.m	sq.m	33.28	119.25	39686.64
	iii	Details of cost of reinforcement Volume of steel in one footing = 3619.115x10^-6 x 2.0 = 0.007238 cum Total weight of steel = 0.007238 x 7850 x 16 = 909.12 kg	Kg	909.12	42.70	38819.49
		Total				1,59,062.897
Total Cost of Supporting Structure						**Rs.1,99,774.07**

5.4.3.4 Semi-Circular Vault- RCC

RCC Shell	No.	Description	Unit	Quantity	Rate	Amount
RCC Roof Shell	i	Details of cost of Concrete Rate for M25 concrete = (3773.15 + 109.1) = Rs. 3882.25 Volume of concrete = Surface area x Thickness = 1060.2873x 0.07 = 74.22 cum	cum	74.22	3882.25	288140.94

	ii	Details of cost of Centering and shuttering Rate for 30m span shell = (514.7 +259.6)= Rs. 774.3 per sq.m of surface area	Sqm	1060.2873	774.3	820980.45
	iii	Details of cost of Reinforcement Volume of steel = 1.4844 cum Weight of steel = 1.4844 x 7850 = 11652.54 kg	Kg	11652.54	42.70	4,97,563.45
		Total				**Rs. 1,706,683**
Columns	i	Details of cost of concrete Volume of columns = 0.25 x 0.25x 3 x 16 = 9 cum	cum	3	5201.5	15604.5
	ii	Details of cost of Centering and shuttering Contact surface area = 4 x 0.2 5 x 3 x16 = 144	Sq.m	48	238.4	11443.2
	iii	Details of cost of Reinforcement Volume of steel in one column = 0.000904779x3+[(3/0.18)+1]x28.274 x10-6=0.003223269 cum Total weight of steel = 0.003223269 x7850 x 16 = 404.848 kg	Kg	404.848	42.70	17287.00
		Total				Rs. 44334
Footing	i	Details of cost of concrete Volume of Concrete =3 x 3 x 0.4 x 16 = 57.6 cum	cum	57.6	4841.15	2,78,850.24
	ii	Details of cost of centering and shuttering Contact surface area = 4 x 3 x 0.4 x 16 = 76.8 sq.m	Sq.m	76.8	119.25	9158.4
	iii	Details of cost of reinforcement Volume of steel in one footing = 0.005882 x 3 = 0.017646 cum Total weight of steel = 0.017646 x 7850 x 16 = 2216.338 kg	Kg	2216.338	42.70	94,637.62
		Total				Rs. 3,82,646
Total Cost of Supporting Structure						**Rs. 4,26,980**

5.4.3.5 Comparative Cost Analysis

Roof	ITEM	Cost of FRP	Cost of RCC	Saving in FRP	Saving in RCC
Dome	Roof Shell	Rs. 36,96,770	Rs. 19,76,392	-	46.5%
Dome	Support Structure	Rs. 2,13,556	Rs. 4,26,980	49.98%	-
Dome	Total cost	Rs. 3,910,326	Rs. 2,403,372	-	38.5%
Vault	Roof Shell	Rs.2695880	Rs. 1,706,683	-	36.6%
Vault	Support Structure	Rs.1,99,774	Rs. 4,26,980	53.2%	-
Vault	Total Cost	Rs. 2,895,654	Rs.2,133,663	-	26%

5.4.4 COMPARISON WITH STEEL

The following analysis is based upon existing design of a well-known building Plaza Valle Shopping Center in Monterey, Mexico. Specifications are taken referred from http://geometrica.com

Dimensions	17m x 25m
Rise	4.5m
Form	Elliptical Dome
Weight of Steel structure	0.053 kN/m^2
Thickness of FRP structure (based upon section 5.4.1)	5mm
Calculated FRP weight (based upon section 5.4.1)	0.0072kN/m^2
Reduction in Weight/m^2	45.8%

5.4.4.1 Cost analysis

Cost of Steel Structure (Section 5.3.3)	=0.053 x 0.101972 x 7850 x 79.5	= Rs. 3372 per sqm
Cost of FRP Structure of 5mm thickness (Section 5.4.1)		= Rs. 2695.43 per sqm
Saving in Cost		= 20%

5.5 FINDINGS AND RESULTS

5.5.1 DOME

5.5.1.1 Structural Analysis of Simply Supported Dome

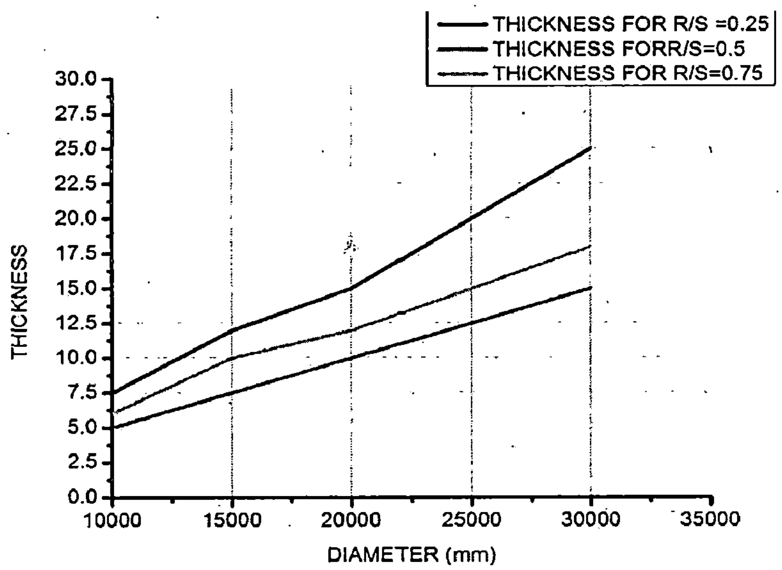
The results obtained by design procedure described in section5.4.1 with specification as given in section 5.3 and support condition as Simply Supported on all boundaries is given in the following table.

Table 11 Result sheet - Dome with Simply supported boundary condition

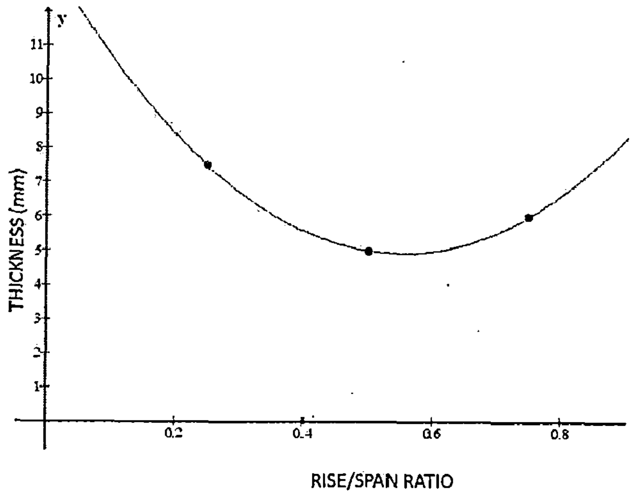
TYPE	ID	RISE (H) (mm)	THICKNESS (h) (mm)	TOTAL UDL (N/mm sq.)	PERMISSIBLE DEFLECTION (mm)	MAX. DEFLECTION (mm)
DOME -- A (10m diameter)	A-01-01	5000	10	0.003141264	12.5	5.525
	A-01-02	5000	5	0.003070632	12.5	10.8011
	A-01-03	5000	7.5	0.003105948	12.5	8.7987
	A-02-01	2500	10	0.003141264	12.5	8.7101
	A-02-02	2500	7.5	0.003105948	12.5	11.48
	A-03-01	7500	10	0.003141264	12.5	6.508
	A-03-02	7500	7.5	0.003105948	12.5	8.677
	A-03-03	7500	5	0.003070632	12.5	12.72
	A-03-04	7500	6	0.003084758	12.5	10.651
DOME-- B (15m diameter)	B-01-01	7500	10	0.003141264	18.75	12.4373
	B-01-02	7500	25	0.00335316	18.75	5.3113
	B-01-03	7500	7.5	0.003105948	18.75	16.396
	B-02-01	1875	15	0.003211896	18.75	13.35
	B-02-02	1875	10	0.003141264	18.75	19.59
	B-02-03	1875	12	0.003169517	18.75	16.477
	B-03-01	11250	15	0.003211896	18.75	9.982

	B-03-02	11250	10	0.003141264	18.75	14.644
	B-03-03	11250	7.5	0.003105948	18.75	19.3
DOME-- C (20m diameter)	C-01-01	10000	15	0.003211896	25	15.06
	C-01-02	10000	12	0.003169517	25	18.58
	C-01-03	10000	10	0.003141264	25	22.099
	C-02-01	5000	15	0.003211896	25	23.74
	C-02-02	5000	18	0.003254275	25	20.0522
	C-02-03	5000	20	0.003282528	25	18.204
	C-03-01	15000	15	0.003211896	25	17.74
	C-03-02	15000	12	0.003169517	25	21.89
DOME --D (30m diameter)	D-01-01	15000	25	0.00335316	37.5	21.745
	D-01-02	15000	20	0.003282528	37.5	25.9012
	D-01-03	15000	15	0.003211896	37.5	33.7909
	D-01-04	15000	18	0.003254275	37.5	28.531
	D-02	7500	25	0.00335316	37.5	34.05
	D-03-01	22500	25	0.00335316	37.5	25.578
	D-03-02	22500	22	0.003310781	37.5	28.0471
	D-03-03	22500	15	0.003211896	37.5	39.9
	D-03-04	22500	18	0.003254275	37.5	33.69

Based on the above results the graphs below are plotted to find out the relationship between diameter of the plan and thickness of the shell roof, and how Rise/Span ratio plays role in deciding thickness.



GRAPH 5-1 Diameter vs. Thickness of FRP Dome with Simply supported boundary condition



GRAPH 5-2 Relationship between Rise/Span ratio and Thickness for Dome A

The above results show that:

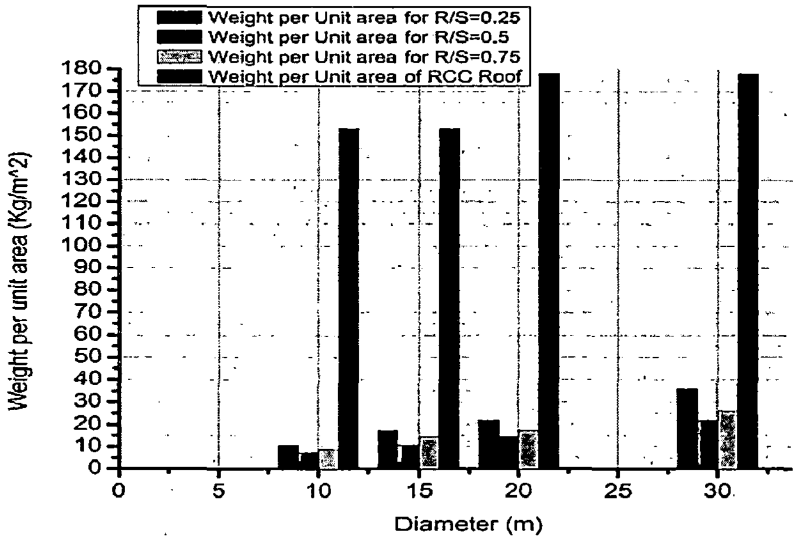
- Thickness increases with increasing span (diameter).
- R/S=0.5 (Hemi-spherical dome) gives the thinnest design thus most economical solution.
- As we decrease or increase the R/S value beyond 0.5 thickness increases.

5.5.1.2 Comparative Analysis of FRP simply supported Dome with RCC Dome

Table 12 Dome SS Comparison of Weight per unit area FRP & RCC

			FRP		RCC		
TYPE	ID	RISE (H) (mm)	THICKNESS (h) (mm)	Weight Per Unit Area	THICKNESS (h) (mm)	Weigth Per Unit Area	Percentage Reduction in Weight Per Unit Area
DOME -- A	A-01-02	5000	5	0.0000072	60	0.000153	95.29%
(10m	A-02-02	2500	7.5	0.0000108	60	0.000153	92.94%
diameter)	A-03-04	7500	6	0.00000864	60	0.000153	94.35%
DOME-- B	B-01-03	7500	7.5	0.0000108	60	0.000153	92.94%
(15m	B-02-03	1875	12	0.00001728	60	0.000153	88.70%
diameter)	B-03-02	11250	10	0.0000144	60	0.000153	90.58%
DOME-- C	C-01-03	10000	10	0.0000144	60	0.000153	90.58%
(20m	C-02-01	5000	15	0.0000216	70	0.000178	87.89%
diameter)	C-03-02	15000	12	0.00001728	70	0.000178	90.31%
DOME --D	D-01-03	15000	15	0.0000216	70	0.000178	87.89%
(30m	D-02	7500	25	0.000036	70	0.000178	79.82%
diameter)	D-03-04	22500	18	0.00002592	70	0.000178	85.47%

Based on the above results the graph below is plotted to find out the relationship between diameter of the plan and Weight per unit area of the shell roof for each Rise/Span ratio and for RCC roof.



GRAPH 5-3 Diameter Vs. Weight Per unit Area of FRP and RCC

The above results shows that

- The domical roof made with FRP will be much lighter than that with RCC.
- Percentage reduction in weight achieved by FRP roof ranges from 79.82% to 95.29%.
- Weight per unit area of R/S=0.25 is the maximum than the other two, but due to less surface area total weight is least among the three.

5.5.1.3 Cost Analysis of FRP Simply Supported Dome

Table 13 Cost of FRP Simply Supported Dome ***(Section 5.3.1.4)***

TYPE	ID	RISE (H) (mm)	THICKNESS (h) (mm)	TOTAL COST FRP ROOF	COST OF FRP ROOF PER SQM AREA PLAN
DOME -- A (10m diameter)	A-01-02	5000	5	Rs. 4,10,912.48	Rs. 5,234.55
	A-02-02	2500	7.5	Rs. 3,86,020.76	Rs. 4,917.46
	A-03-04	7500	6	Rs. 4,78,617.97	Rs. 6,097.04
DOME-- B (15m diameter)	B-01-03	7500	7.5	Rs. 10,36,565.84	Rs. 5,868.74
	B-02-03	1875	12	Rs. 8,85,348.62	Rs. 5,012.59
	B-03-02	11250	10	Rs. 17,75,850.02	Rs. 10,054.35
DOME-- C (20m diameter)	C-01-03	10000	10	Rs. 19,62,263.98	Rs. 6,249.25
	C-02-01	5000	15	Rs. 18,42,783.71	Rs. 5,868.74
	C-03-02	15000	12	Rs. 37,78,364.11	Rs. 12,033.01
DOME --D (30m diameter)	D-01-03	15000	15	Rs. 65,65,738.85	Rs. 9,293.33
	D-02	7500	25	Rs. 68,34,569.46	Rs. 9,673.84
	D-03-04	22500	18	Rs. 1,26,95,076.78	Rs. 17,968.97

It can be seen that as span increases cost of FRP roof per unit area plan increases, also the results are quite expensive.

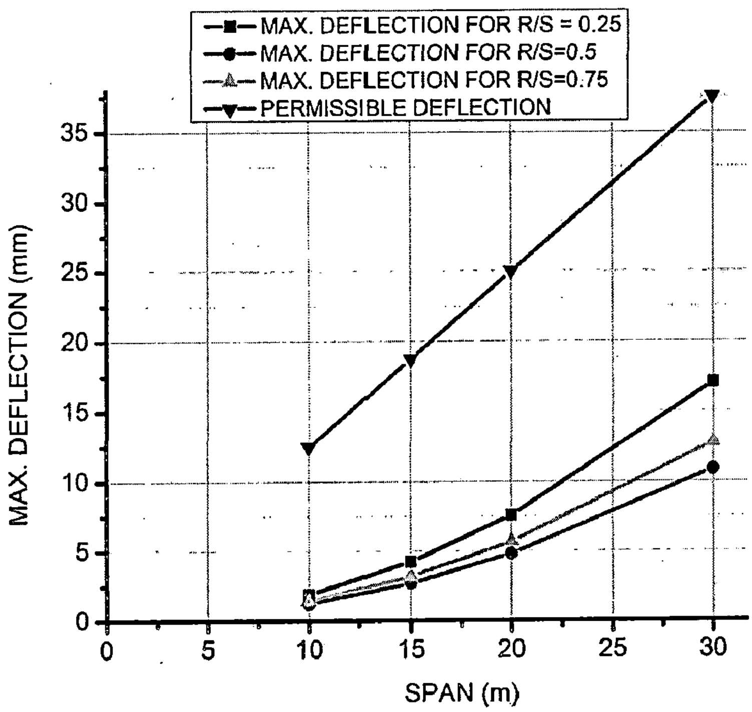
5.5.1.4 Structural Analysis of FRP Dome (Clamped)

For cost saving we can change the boundary condition from Simply Supported to Clamped (fixed s). This will dramatically reduce the maximum deflection onto which thickness depends which will eventually decrease the cost.

Table 14 Dome- Clamped Max. Deflection

TYPE	ID	Rise H (mm)	THICKNESS (h) (mm)	PERMISSIBLE DEFLECTION (mm)	MAX. DEFLECTION (mm)
TYPE A (10M DIAMETER)	A-01	5000	5	12.5	1.211
	A-02	2500	5	12.5	1.89
	A-03	7500	5	12.5	1.42
TYPE B (15M DIAMETER)	B-01	7500	5	18.75	2.72
	B-02	1875	5	18.75	4.26
	B-03	11250	5	18.75	3.199
TYPE C (20M DIAMETER)	C-01	10000	5	25	4.84
	C-02	5000	5	25	7.576
	C-03	15000	5	25	5.688
TYPE D (30M DIAMETER)	D-01	15000	5	37.5	10.881
	D-02	7500	5	37.5	17.06
	D-03	22500	5	37.5	12.806

Based on the above results the graph below is plotted to find out the relationship between diameter of the plan , maximum deflection for each R/S ratio and permissible deflection.



GRAPH 5-4Span vs. Max. Deflection for Dome with Clamped Supports

The above results show that:

- If we change the boundary condition for the dome roof from simply supported to Clamped connection maximum deflection decreases many fold.
- The max. Deflection obtained is very less than permissible deflection due to which minimum thickness of 5mm[8] has to be provided for all the cases.
- Dome with Rise/Span =0.5 is the most stable form.

5.5.1.5 Comparative Analysis and Cost analysis of Dome (Clamped)

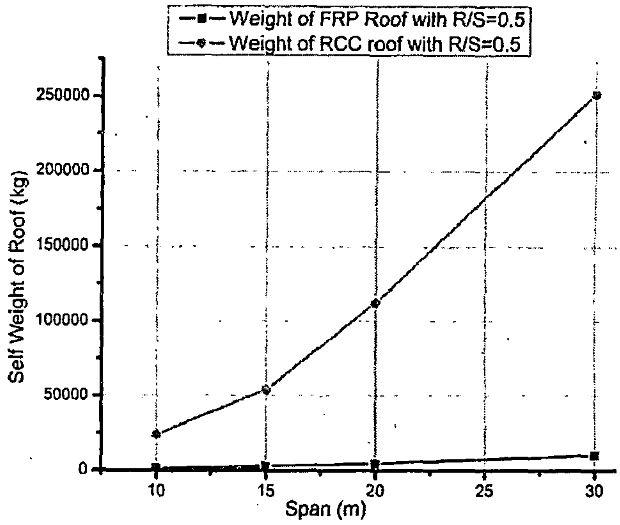
Table 15Comparison of FRP and RCC dome with Clamped boundary condition

		FRP			RCC				
TYPE	ID	THICKNESS (h) (mm)	WEIGHT (kg)	COST	h	WEIGHT	COST	% age Reduction in Weight	%age Increase in Cost
TYPE A (10M DIAMETER)	A-01	5	1131.4	Rs. 4,10,918	60	24027.8	Rs. 2,04,354	95.3%	50.3%
	A-02	5	707.1	Rs. 2,61,567	60	15017.4	Rs. 1,27,721	95.3%	51.2%
	A-03	5	1838.6	Rs. 6,59,835	60	39045.1	Rs. 3,32,075	95.3%	49.7%
TYPE B (15M DIAMETER)	B-01	5	2545.7	Rs. 9,24,565	60	54062.5	Rs. 4,59,796	95.3%	50.3%
	B-02	5	795.5	Rs. 5,04,517	60	28720.7	Rs. 2,44,267	95.3%	51.6%
	B-03	5	4136.8	Rs. 14,84,628	60	87851.5	Rs. 7,47,168	95.3%	49.7%
TYPE C (20M DIAMETER)	C-01	5	4525.7	Rs. 16,43,670	70	112129.6	Rs. 8,72,533	96.0%	46.9%
	C-02	5	2828.6	Rs. 10,46,269	70	70081.0	Rs. 5,45,333	96.0%	47.9%
	C-03	5	7354.3	Rs. 26,39,339	70	182210.6	Rs. 14,17,867	96.0%	46.3%
TYPE D (30M DIAMETER)	D-01	5	10182.9	Rs. 36,98,258	70	252291.6	Rs. 19,76,392	96.0%	46.9%
	D-02	5	6364.3	Rs. 23,54,105	70	157682.3	Rs. 12,27,000	96.0%	47.9%
	D-03	5	16547.1	Rs. 59,38,513	70	409973.9	Rs. 31,90,200	96.0%	46.3%

Based on the above results the graph below is plotted to find out the relationship between diameter of the plan and weight of the shell roof; the comparison of costs for each Rise /span ratio and comparison of cost of FRP roof and RCC roof.

[8] Thickness of upto 3mm is provided for span equal or less than 3m , above 3m span minimum thickness is 5mm.

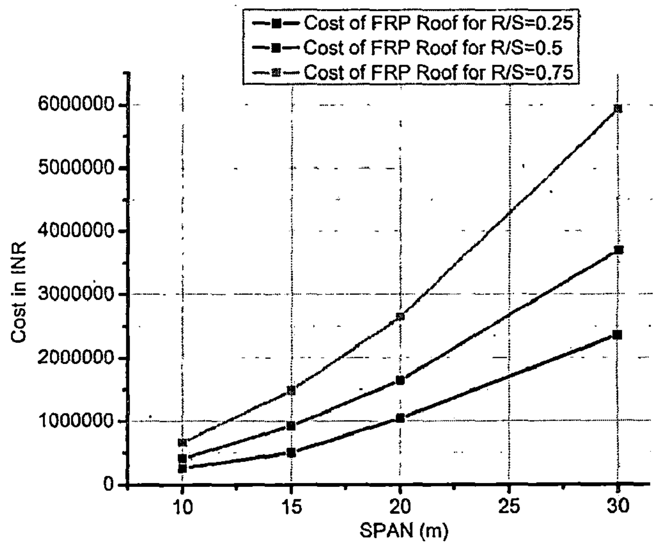
This graph shows that FRP roof is much lighter than RCC roof, percentage reduction in self-weight of roof with FRP w.r.t. RCC is about 95-96%



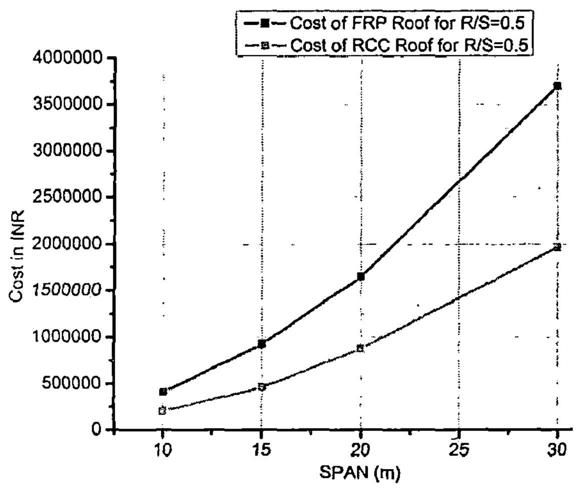
GRAPH 5-5 Span vs Self Weight of Dome (Clamped) with R/S=0.5

- ***Cost Analysis of Shell Roof***

This graph shows that FRP roof with R/S =0.25 is the most cost effective, while that of R/S=0.75 is the most expensive by virtue of their surface areas.



GRAPH 5-6 Span vs Cost for Dome (Clamped)



GRAPH 5-7 Span vs Cost of FRP roof and RCC roof for R/S=0.5

This graph shows FRP roof costs about 44-48% more than that of RCC.

➢ ***Comparative Cost Analysis of supporting structures***

As derived from section ⍰

Percentage reduction of cost of supporting structure for FRP roof with that of RCC roof is 48%

5.5.2 VAULT

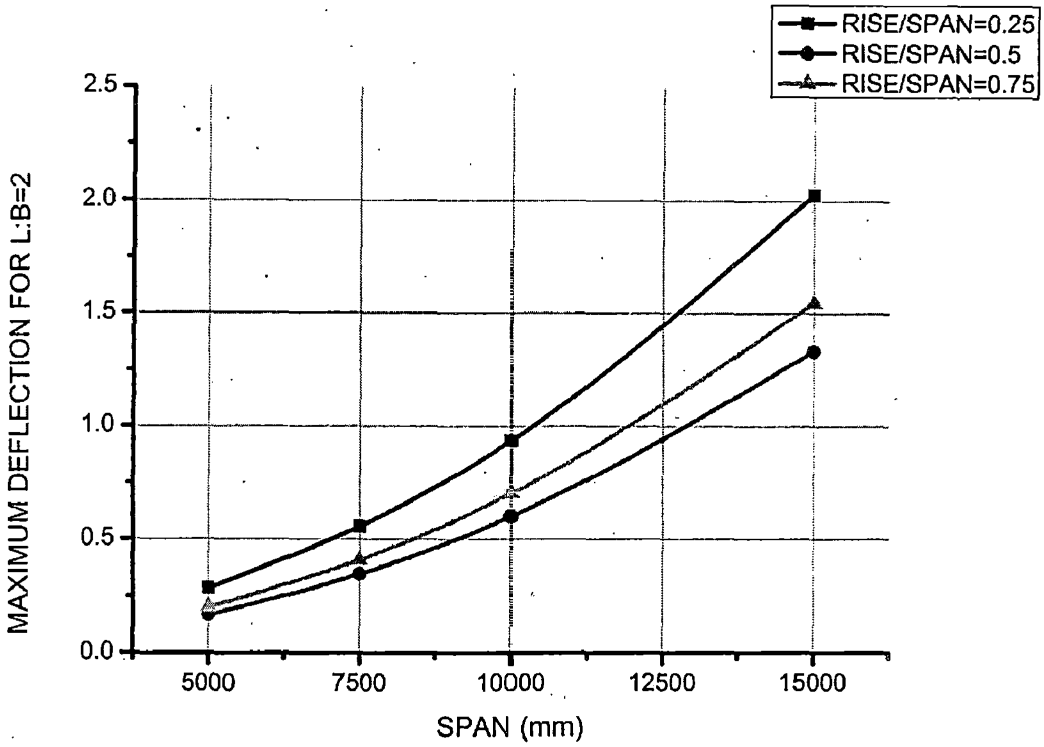
5.5.2.1 Structural Analysis

The results obtained by design procedure described in section 5.5.1 with specification as given in section 5.4 and support condition as clampeda is given in the following table.

Table 16 Vault Structural Analysis Results

TYPE	ID	H (mm)	THICKNESS (h) (mm)	PERMISSIBLE DEFLECTION (mm)	MAX. DEFLECTION (mm)
VAULT--E (5mX10m)	E-01	2500	5	6.25	0.1676
	E-02	1250	5	6.25	0.286
	E-03	3750	5	6.25	0.2019
VAULT--F (5mX15m)	F-01	2500	5	6.25	0.18386
	F-02	1250	5	6.25	0.3283
	F-03	2500	5	6.25	0.225
VAULT--G (7.5mx15m)	G-01	3750	5	9.375	0.3468
	G-02	1875	5	9.375	0.557
	G-03	5625	5	9.375	0.409
VAULT--H (7.5mX22.5m)	H-01	3750	5	9.375	0.35895
	H-02	1875	5	9.375	0.60117
	H-03	5625	5	9.375	0.42883
VAULT--I (10mX20m)	I-01	5000	5	12.5	0.6009
	I-02	2500	5	12.5	0.93599
	I-03	7500	5	12.5	0.70188
VAULT--J (10mX30m)	J-01	5000	5	12.5	0.60038
	J-02	2500	5	12.5	0.9582
	J-03	7500	5	12.5	0.70553
VAULT--K (15mX30m)	K-01	7500	5	18.75	1.3336
	K-02	3750	5	18.75	2.0298
	K-03	11250	5	18.75	1.5469
VAULT--L (15mX45m)	L-01	7500	5	18.75	1.2891
	L-02	3750	5	18.75	1.9587
	L-03	11250	5	18.75	1.4917

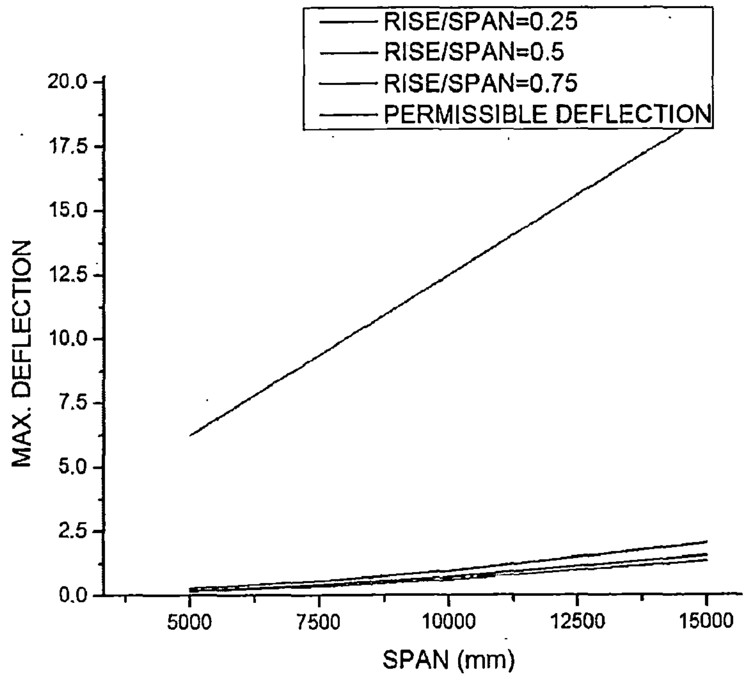
Based on the above results the graph below is plotted to find out the relationship between span , maximum deflection for each R/S ratio and permissible deflection.



GRAPH 5-8 Span vs Max. Deflection for Vault with L:B=2

The above relationship shows that Rise/span ratio =0.5 (i.e. semicircular cross section) is the most stable form.

5.5.2.2 Comparative Analysis with RCC



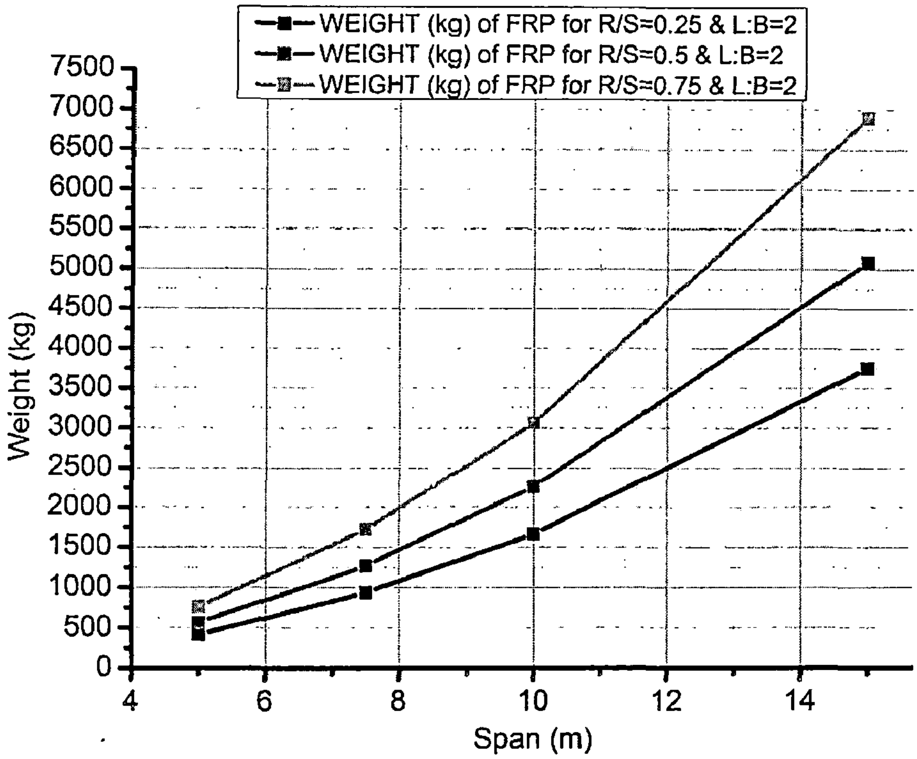
GRAPH 5-9 Span vs Max. deflection - a comparison of max. deflection with permissible deflection of Vault

The above graph shows that maximum deflection is very less than permissible deflection for that span of vault, hence structures are safe with minimum thickness of cross section of 5mm.

Table 17 Vault Weight and Cost Analysis

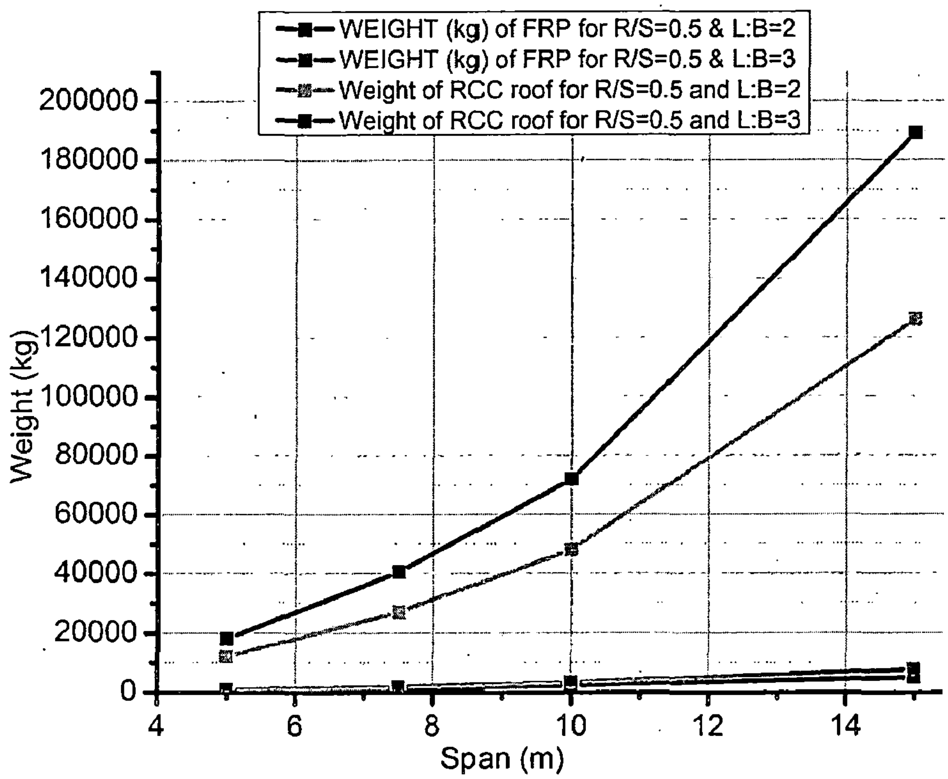
TYPE	ID	Total Weight of FRP roof (kg)	Total Weight of RCC roof (kg)	Total cost of FRP roof	Total Cost of RCC Roof	Percentage Increase in Cost
VAULT-- E (5mX10m)	E-01	565.49	12,009.05	Rs. 2,07,103.63	Rs. 1,32,839.31	35.86%
	E-02	417.28	8,861.70	Rs. 1,54,935.43	Rs. 98,024.63	36.73%
	E-03	766.58	16,279.58	Rs. 2,77,888.99	Rs. 1,80,078.23	35.20%
VAULT-- F (5mX15m)	F-01	848.23	18,013.57	Rs. 3,10,655.44	Rs. 1,99,258.97	35.86%
	F-02	625.92	13,292.56	Rs. 2,32,403.14	Rs. 1,47,036.95	36.73%
	F-03	1,149.87	24,419.37	Rs. 4,16,833.48	Rs. 2,70,117.35	35.20%
VAULT-- G (7.5mx15m)	G-01	1,272.34	27,020.36	Rs. 4,65,983.16	Rs. 2,98,888.45	35.86%
	G-02	938.89	19,938.81	Rs. 3,48,604.33	Rs. 2,20,555.17	36.73%
	G-03	1,724.83	36,629.69	Rs. 6,25,260.68	Rs. 4,05,183.00	35.20%
VAULT --H (7.5mX22.5m)	H-01	1,908.52	40,530.54	Rs. 6,98,974.74	Rs. 4,48,332.68	35.86%
	H-02	1,408.33	29,908.22	Rs. 5,22,906.49	Rs. 3,30,832.76	36.73%
	H-03	2,587.25	54,944.53	Rs. 9,37,891.02	Rs. 6,07,774.51	35.20%
VAULT--I (10mX20m)	I-01	2,261.95	48,036.20	Rs. 8,28,414.50	Rs. 5,31,357.25	35.86%
	I-02	1,669.13	35,446.79	Rs. 6,19,741.19	Rs. 3,92,098.20	36.73%
	I-03	3,066.32	65,118.33	Rs. 11,11,555.95	Rs. 7,20,312.94	35.20%
VAULT--J (10mX30m)	J-01	3,392.92	72,054.30	Rs. 12,42,621.75	Rs. 7,97,035.87	35.86%
	J-02	2,503.70	53,170.18	Rs. 9,29,611.79	Rs. 5,88,147.30	36.73%
	J-03	4,599.47	97,677.49	Rs. 16,67,333.93	Rs. 10,80,469.41	35.20%
VAULT--K (15mX30m)	K-01	5,089.38	1,26,095.02	Rs. 18,63,932.63	Rs. 11,95,553.81	35.86%
	K-02	3,755.55	93,047.84	Rs. 13,94,418.07	Rs. 8,82,221.20	36.73%
	K-03	6,899.21	1,70,935.66	Rs. 25,01,001.65	Rs. 16,20,704.62	35.20%
VAULT--L (15mX45m)	L-01	7,634.07	1,89,142.53	Rs. 27,95,898.94	Rs. 17,93,330.71	35.86%
	L-02	5,633.32	1,39,571.76	Rs. 20,91,627.10	Rs. 13,23,331.80	36.73%
	L-03	10,348.82	2,56,403.49	Rs. 37,51,502.48	Rs. 24,31,056.93	35.20%

Based on the above results following inferences can be drawn:



GRAPH 5-10 Span vs Weight of the FRP Vault structure

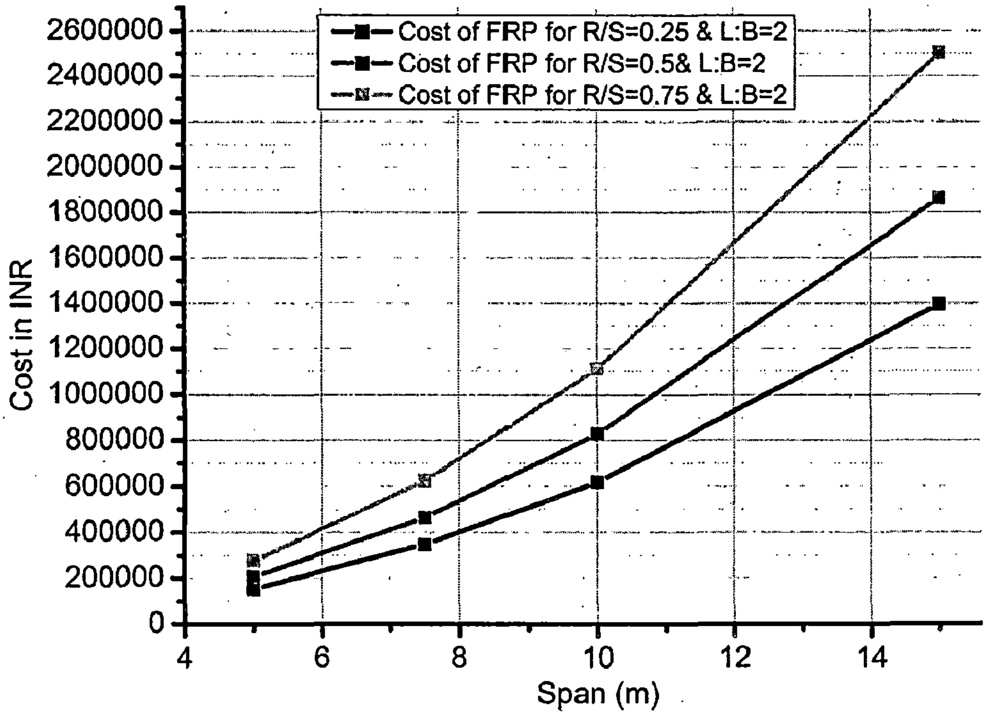
The above graph shows that for R/S=0.25 we get the most light structure by virtue of its less surface area, as we increase R/S ratio the weight increases.



GRAPH 5-11 Span vs Weight of FRP and RCC Vault structures

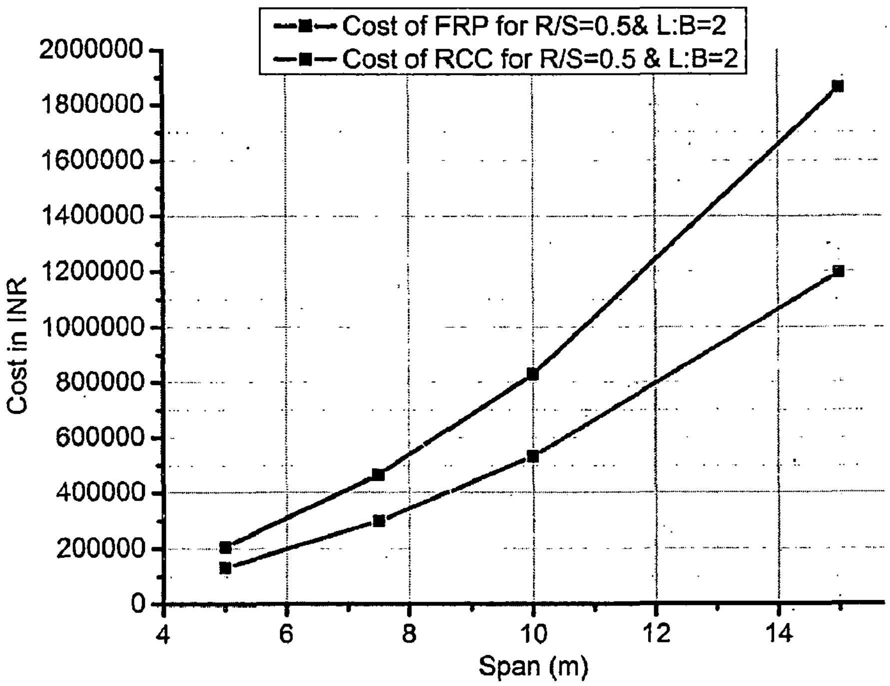
The above graph shows that FRP roof is 95-96% lighter than RCC roof.

5.5.2.3 Cost Analysis



GRAPH 5-12 Span vs Cost of FRP Vault

The above graph shows that for R/S=0.25 we get the most economical structure by virtue of its less surface area, as we increase R/S ratio the cost increases.



GRAPH 5-13 Span vs Cost of FRP and RCC roof

The above graph shows that initial cost of FRP roof is 36-37% more than that of RCC.

But as we have already derived in section 5.4.2 in supporting structure for FRP roof we **save 53.2%** than that of RCC.

5.5.3 HYPERBOLIC PARABOLOID

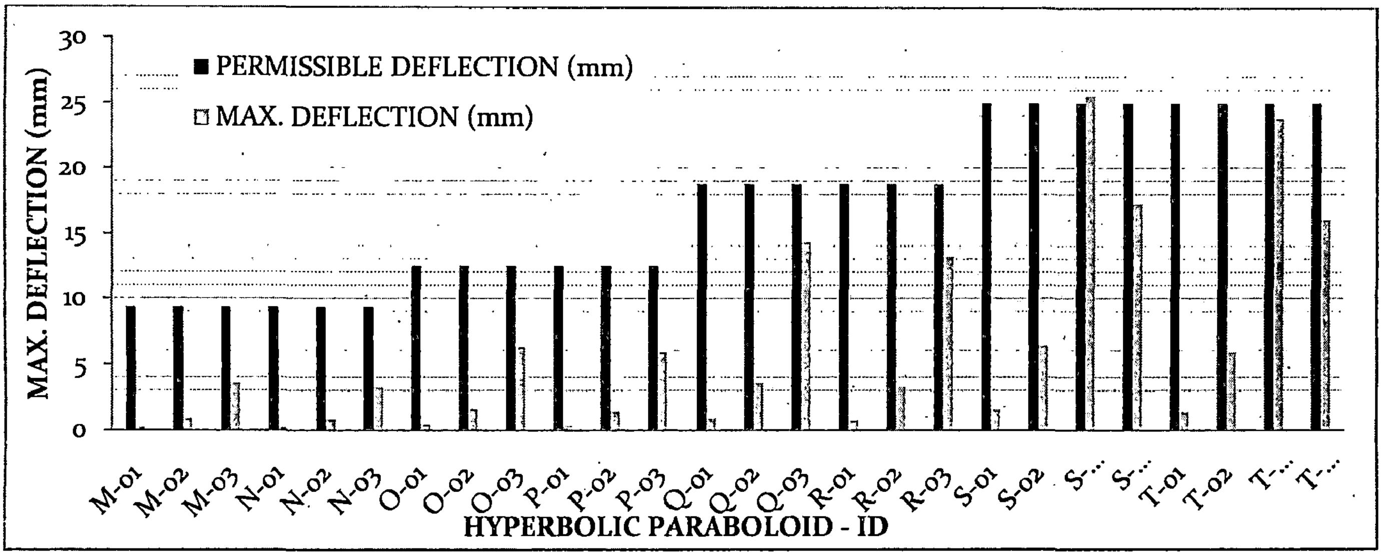
5.5.3.1 Structural Analysis

The results obtained by design procedure described in section 5.5.1 with specification as given in section 5.4 and support condition as clamped along the length is given in the following table.

TYPE	ID	C (RISE)	XR[9]	YR	h	PERMISSIBLE DEFLECTION (mm)	MAX. DEFLECTION (mm)
HP--M (7.5mX7.5m)	M-01	3750	-0.0005333	0.0005333	5	9.375	0.2211
	M-02	1875	-0.0002667	0.0002667	5	9.375	0.8928
	M-03	937.5	-0.0001333	0.0001333	5	9.375	3.536
HP--N (7.5mX20m)	N-01	3750	-0.0005333	0.000075	5	9.375	0.18995
	N-02	1875	-0.0002667	0.0000375	5	9.375	0.8093
	N-03	937.5	-0.0001333	1.875E-05	5	9.375	3.255
HP--O (10mX10m)	O-01	5000	-0.0004	0.0004	5	12.5	0.3935
	O-02	2500	-0.0002	0.0002	5	12.5	1.5923
	O-03	1250	-0.0001	0.0001	5	12.5	6.328
HP--P (10mX25m)	P-01	5000	-0.0004	0.000064	5	12.5	0.3468
	P-02	2500	-0.0002	0.000032	5	12.5	1.46399
	P-03	1250	-0.0001	0.000016	5	12.5	5.8909
HP--Q (15mX15m)	Q-01	7500	-0.0002667	0.0002667	5	18.75	0.88601
	Q-02	3750	-0.0001333	0.0001333	5	18.75	3.5921
	Q-03	1875	-6.667E-05	6.667E-05	5	18.75	14.338
HP--R (15mX40m)	R-01	7500	-0.0002667	0.0000375	5	18.75	0.76029
	R-02	3750	-0.0001333	1.875E-05	5	18.75	3.2515
	R-03	1875	-6.667E-05	9.375E-06	5	18.75	13.1939
HP--S (20mX20m)	S-01	10000	-0.0002	0.0002	5	25	1.5755
	S-02	5000	-0.0001	0.0001	5	25	6.3926
	S-03-01	2500	-0.00005	0.00005	5	25	25.57223
	S-03-02	2500	-0.00005	0.00005	7.5	25	17.209
HP--T (20mX50m)	T-01	10000	-0.0002	0.000032	5	25	1.3878
	T-02	5000	-0.0001	0.000016	5	25	5.8728
	T-03-01	2500	-0.00005	0.000008	5	25	23.785
	T-03-02	2500	-0.00005	0.000008	7.5	25	15.97149

[9] XR= $-1/(2c/a^2)$,YR=$-1(2c/b^2)$, where a= Span/2, b=Length/2, c= Rise

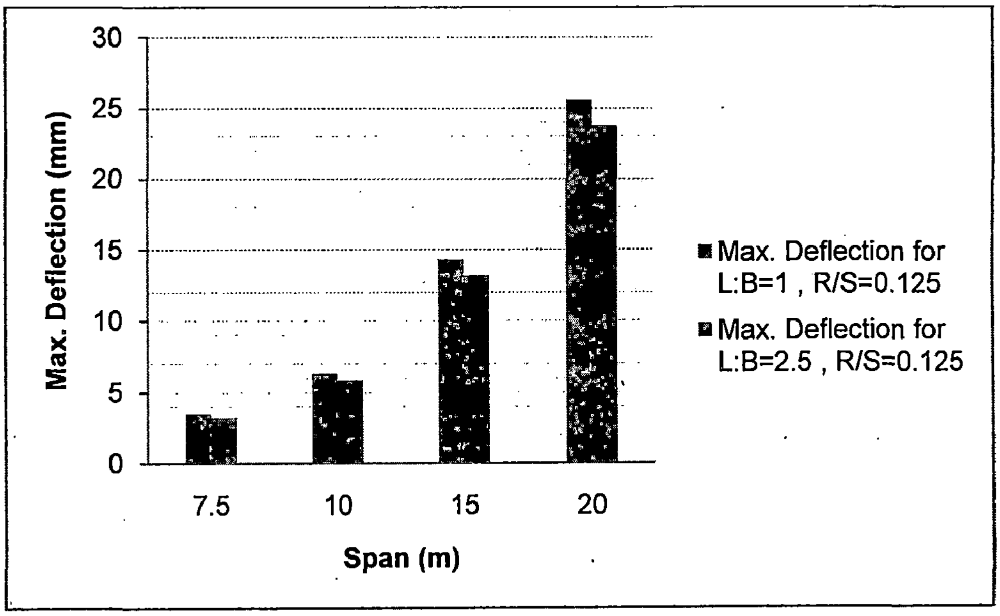
Based on the results the graphs below are plotted to find out the relationship between various parameters.



GRAPH 5-14 Relationship between Max. Deflection and Permissible Deflection for Hyperbolic Paraboloid

The above relationship shows that for smaller span permissible deflection is very high than maximum deflection of the structure, hence minimum thickness of 5mm is safe for these structure. Whereas for larger spans (more than 15m) max. deflection is more.

For 20m span or more and for lower R/S ratio thickness of cross section is increased (see S-03)



GRAPH 5-15 Max. Deflection for L/B =1 and L:B=2.5

We can observe from the above result that hyperbolic Paraboloid roof is more stable with rectangular plan than with the square plan.

5.5.3.2 Comparative Analysis with RCC

Table 18 Weight per unit area of FRP and RCC hyperbolic Paraboloid roof

TYPE	ID	C (RISE)	Weight of FRP per sq. m of surface area	Weight of RCC per sq. m of surface area	Percentage reduction in Weight
HP--M (7.5mX7.5m)	M-01	3750	7.2	152.904	95.29%
	M-02	1875	7.2	152.904	95.29%
	M-03	937.5	7.2	152.904	95.29%
HP--N (7.5mX20m)	N-01	3750	7.2	152.904	95.29%
	N-02	1875	7.2	152.904	95.29%
	N-03	937.5	7.2	152.904	95.29%
HP--O (10mX10m)	O-01	5000	7.2	152.904	95.29%
	O-02	2500	7.2	152.904	95.29%
	O-03	1250	7.2	152.904	95.29%
HP--P (10mX25m)	P-01	5000	7.2	152.904	95.29%
	P-02	2500	7.2	152.904	95.29%
	P-03	1250	7.2	152.904	95.29%
HP--Q (15mX15m)	Q-01	7500	7.2	152.904	95.29%
	Q-02	3750	7.2	152.904	95.29%
	Q-03	1875	7.2	152.904	95.29%
HP--R (15mX40m)	R-01	7500	7.2	152.904	95.29%
	R-02	3750	7.2	152.904	95.29%
	R-03	1875	7.2	152.904	95.29%
HP--S (20mX20m)	S-01	10000	7.2	152.904	95.29%
	S-02	5000	7.2	152.904	95.29%
	S-03-02	2500	10.8	152.904	92.94%
HP--T (20mX50m)	T-01	10000	7.2	152.904	95.29%
	T-02	5000	7.2	152.904	95.29%
	T-03-01	2500	7.2	203.872	96.47%

The above results show that FRP hyperbolic Paraboloid roof is about 92-95% lighter than that of RCC.

5.5.4 FLAT

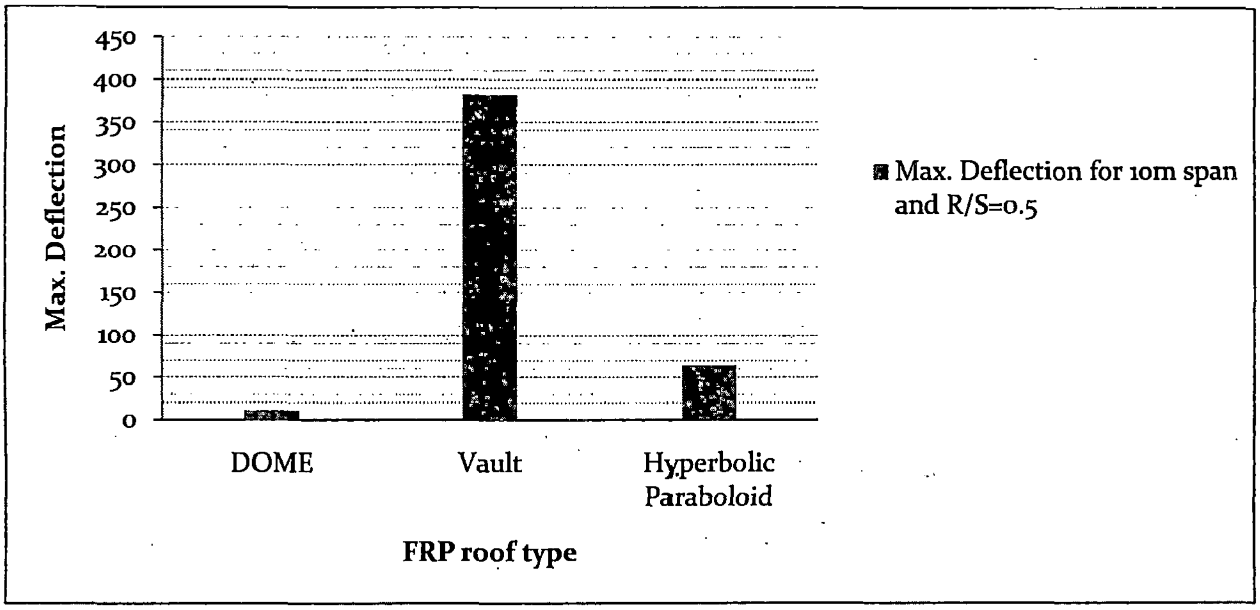
ID	Width	Length	Thickness (h) (mm)	PERMISSIBLE DEFLECTION (mm)	MAX. DEFLECTION (mm)
FLAT-01	10000	10000	15	12.5	43.02
FLAT -02	10000	10000	30	12.5	23.345

The above results show that even with 30mm thickness the structure is not safe. The safe structure thus can be designed either by increasing the thickness or by using sandwich construction. If we increase the thickness, the roof will be very expensive.

Sandwich construction is more suited for Flat roof structure rather than single skin construction.

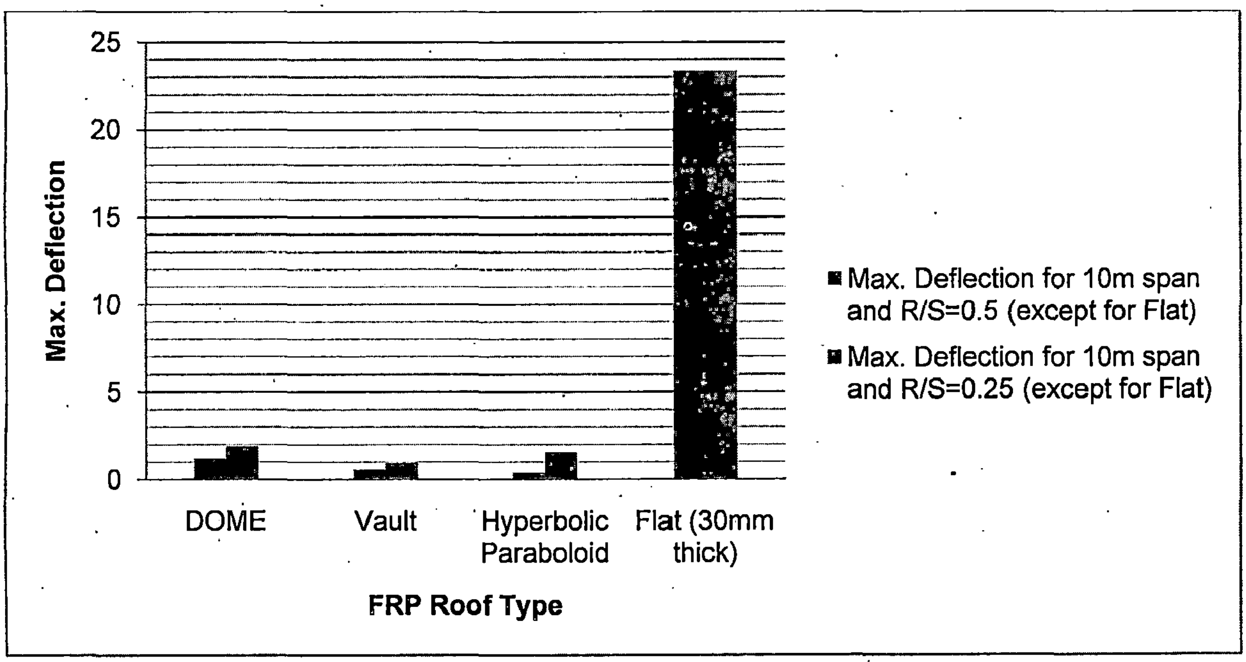
5.5.5 COMPARATIVE ANALYSIS – ALL FORMS

- ***Stability***



GRAPH 5-16 Max. Deflection for Simply supported Roof (thickness=5mm)

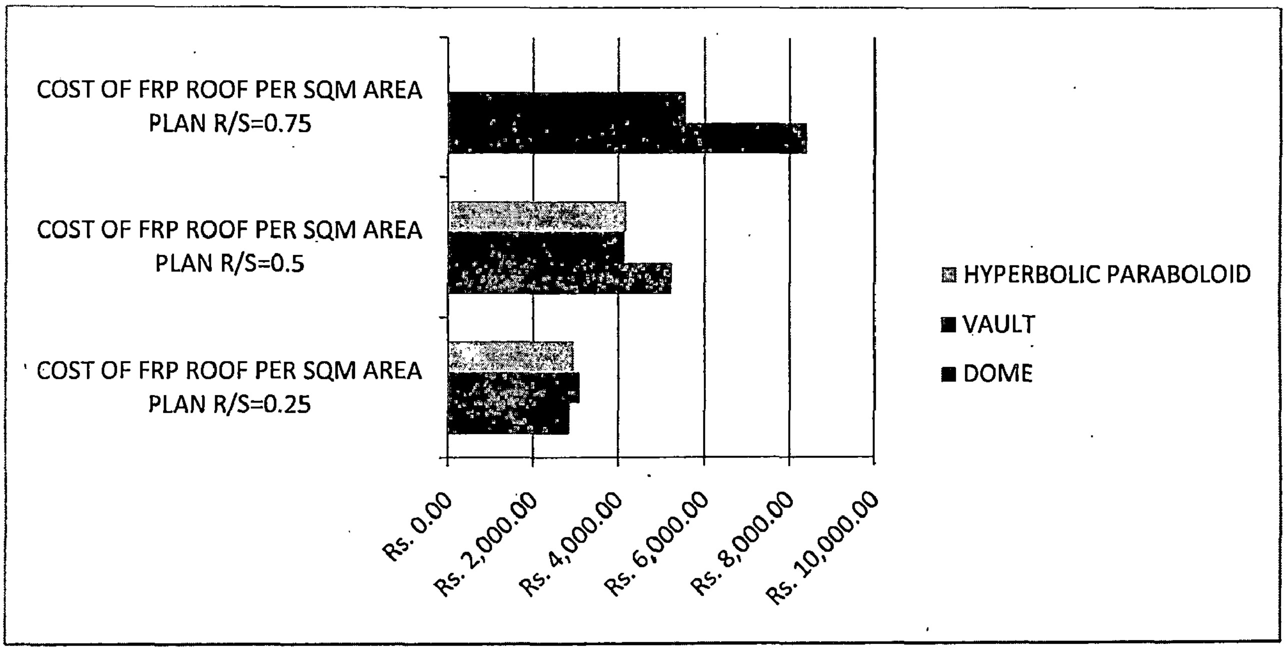
For simply supported roof dome is the most stable form because of its doubly curved form, while vault is the most vulnerable because of its singly curved form.



GRAPH 5-17 Max. Deflection for Clamped FRP roof with 5mm thickness (except for Flat)

For roof with clamped boundary condition Vault is the most stable form, while Flat is the most unstable form.

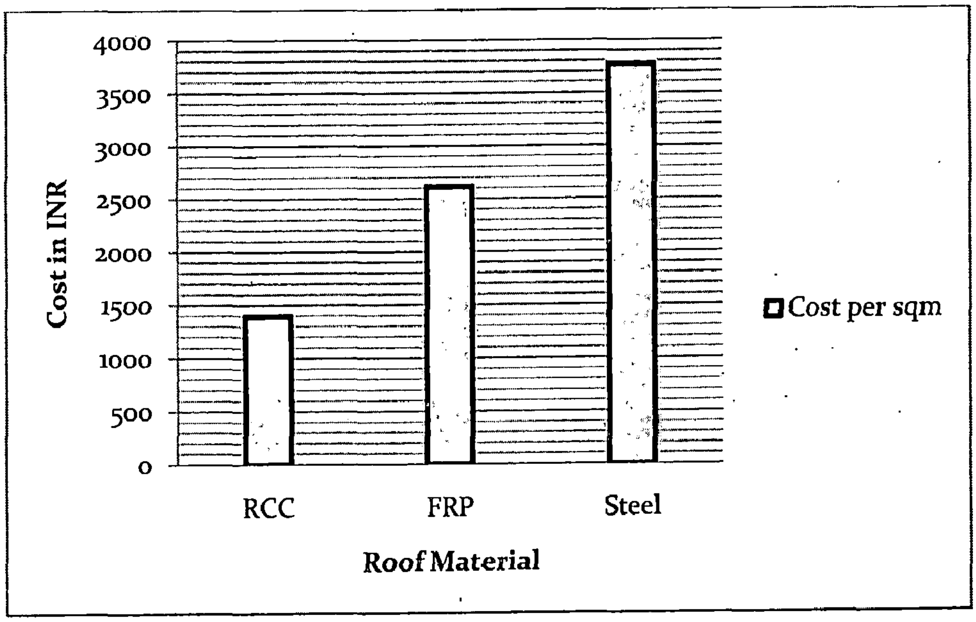
- ***Cost***



GRAPH 5-18 Comparison of cost of types of roofs w.r.t. R/S ratio for Clamped support condition

From the above graph, following inferences are derived:

- As we decrease R/S ratio cost of roof decreases.
- For smaller values of R/S , all three forms costs are similar, vault being the most costly
- As we increase R/S ratio, Dome is costlier than Hyperbolic paraboloid and Vault both.
- Vault is most cost effective for higher R/S ratio.



GRAPH 5-19 Comparative Cost analysis of Roof per sq.m. made of FRP, RCC and Steel (Base upon Section 5.4.3 and 5.4.4)

The above graph shows that there is 20% cost reduction for FRP structure when compared with steel. Whereas there is 44% cost reduction for RCC shell structure when compared with FRP. However we can save in support structure by 49% for FRP roof because of its light weight.

CHAPTER 6. CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

In the previous chapter three basic geometrical roof forms viz. Dome, Vault and Hyperbolic Paraboloid have been analyzed in terms of structural safety and cost and other properties of FRP have already been described in the Literature study. Based on Properties of FRP, its applications, Construction practices, Case studies, Structural and Cost analysis the following conclusionsare drawn:

- **Form**

  For a Particular span among the studied forms- dome, vault, hyperbolic Paraboloid:

  - Supporting boundary condition affects the stability and hence cost of the structure. Clamped boundary condition gives more stability than simply supported condition.
  - For simply supported roof doubly curved synclastic shells like dome is the most stable form, while singly curved shells like vault is the most vulnerable.
  - For simply supported structure dome, or domical structures can be design with thickness 5mm-7mm up to 15m span, above that we have to increase the thickness.
  - For roof with clamped boundary condition Vault is the most stable form, while Flat is the most unstable form.
  - For span ranging from 5m to 30m we can design any FRP roof form with thickness 5mm-7.5mm for clamped support condition.
  - Flat roof is very expensive for single skin construction. Sandwich construction is the best option for flat roofs of large span areas.
  - Rise/Span=0.5 is the most stable ratio, increasing or decreasing this value results in increase of max. Deflection.
  - As we change Rise/Span ratio expenditure on roof changes as follows:
    - R/S drives the surface area of the form hence the more R/S ratio more is the cost and vice versa.
    - For smaller values of R/S, Dome is the most cost effective, vault being the most costly.
    - As we increase R/S ratio, Dome is costlier than Hyperbolic Paraboloid and Vault both.
    - Vault is most cost effective for higher R/S ratio.
  - Hyperbolic Paraboloid roof is more stable with rectangular plan rather than square plan.

- For a rectangular large span requirement vault roof form is a good option. For circular area like atrium of a building (Malls, Hospitals, Library etc.) dome is the best option.

- **Unit Size:**
  - FRP roof have to be molded in various parts for ease of manufacturing, transportation and construction.
  - Size of the unit should be optimized. It should not be too large for ease of transportation and lifting, and not be too small for saving time.
- **Light Weight and High Strength**
  - For the same span FRP structure is much thinner than that of RCC, it shows that FRP is stronger than RCC for same thickness.
  - FRP structures are much lighter than that made with conventional materials. For instance above analysis shows that FRP roofs are 90-96% lighter than the roofs made with RCC.
  - Thus FRP can be used as roof material where large span is required like stadiums, auditoriums, warehouses, Industrial sheds etc.
  - Since FRP roof structures are lightweight the panels can be easily transported from factory to the site saving money.
  - Light weight also facilitates easy lifting with small cranes, whereas for any RCC or Steel Pre-engineered building (PEB) due to very heavy unit's transportation requires large no. of trucks and lifting requires huge cranes.
  - High strength makes it suitable for shelter for hurricane prone areas. FRP buildings sustain while others fall in hurricanes.
  - Suitable for earthquake prone areas
- **High Durability**
  - The inherent properties of FRP make it a highly durable material.
  - Resistance to corrosion and environmental degradation
  - No or minimal maintenance required.
  - A lifetime investment.
- **Aesthetics**
  - Any architectural form can be achieved with FRP.
  - No painting is required.
  - We can provide any of the surface rendering, colors, design, textures while molding the FRP unit, thus no need to provide painting/tiling or any decorative treatment.

- Cost on providing decorative treatment is reduced.

- **Cost**[10]
    - FRP roof structure when compared with steel tubular lattice structure, saves about 20% in cost, and 45 % in weight, which will further reduce the cost in the supporting structure.
    - Initial Cost of FRP roof is 35-45% more than that of RCC.
    - Since the structure is lightweight we save in supporting structure and foundation about 44-53%.
    - As described above due to light weight structures we can save in transportation expenses.
    - Construction of FRP requires small cranes for lifting light weight FRP panels, thus lot of money can be saved.
    - All Dry Construction saves TIME, thus money spent for machinery rental, labor charges, staff charges etc.
    - If mass produced initial cost can be reduced.
- **Prefabrication**
    - As the FRP units are prefabricated, on-site just assembling of the units is required for construction to complete which is very less (ranging from a few hours to a week depending upon scale of the project) in comparison to RCC construction wet construction.
    - Accuracy can be maintained with the units hence no or minimal wastage.
    - Any shape or Form can be built thus allows freedom of creativity which is restricted in other materials due to constraints.
    - FRP structure can be disassembled and shifted
    - Prefabrication makes it suitable for disaster relief shelters, army shelters, low cost mass housing, etc. as it can be shifted from 1 place to another and rapid construction is possible.
- **Climate**

  It is suitable for all climates including
    - Cold and dry climate, High altitude cold regions like ladakh and other upper Himalayan regions where RCC or Steel structures may become brittle; moreover

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[10]The rates taken for FRP are market rates, while rates for RCC are taken from CPWD Analysis of rates for Delhi Zone.

construction on these high mountains is much easier with FRP. No extra insulation is required for keeping inside of the FRP building warm.

  - Coastal regions where high level of humidity and salt may corrode the steel structures and reinforcement of RCC.
  - Warm and humid climate, heavy rainfall prone areas, as it is hydrophobic material, reduced dampness inside the building.

- So whenever we have a requirement of
  - Limited Time
  - Large span
  - Light weight structure
  - Challenging Form
  - Adverse climates
  - Portability

  FRP is a good option.

6.2 SCOPE FOR FUTURE RESEARCH

FRP has a promising future in building industry as it is suitable for challenging building forms which are quite difficult to construct in the conventional materials.

As knowledge and understanding of FRP increases in Designers community efficient structures and construction practices would be evolved.

The following are some of the possible areas of research where the present investigation can be extended in future:

- The present study covers three major types for geometrical forms dome, vault and hyperbolic Paraboloid. The study on other forms of roof like Folded plate structures, stressed skin structures is a potential area of research.
- Single skin construction is considered in this study, this can be extended to sandwich construction.

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ANNEXURE: LIST OF FRP MANUFACTURERS AND CONSULTANTS

INTERNATIONAL MANUFACTURERS AND CONSULTANTS

Gurit International

- Development and manufacture of advanced composite, composite process equipment and tools for the global Wind Energy, Tooling, Transportation and Marine markets.
- Website: www.gurit.com
- Gurit Headquarters
  Gurit Services AG
  Schaffhauserstrasse 339
  CH-8050,Zurich

Optima Projects

- U.K. based Consultancy (led by David Kendall) undertaking large engineering projects, particularly those involving advanced structures and FRP composite materials.
- Contact
  David Kendall, Managing Director
  Email: info@optima-projects.com
  Website: http://www.optima-projects.com/

NGCC – **Network group of Composites (U.K.)**

- NGCC develops and promotes best practice in the application of fiber reinforced polymer composites in construction.
- Website : http://www.ngcc.org.uk

Fiberline Composites:

- Works in building structures, wind power, windows, doors and facades
- Address:
  Fiberline Composites A/S,
  Barmstedt Allé 5
  DK-5500, Denmark
- Website: http://www.fiberline.com

AOC – **Resins**

- Global supplier of resins, gel coats, colorants and synergistic systems for composites and cast polymers.
- AOC Corporate Headquarters
  955 Highway 57 East
  Collierville TN, USA
- Website: http://www.aoc-resins.com

Composites UK

- Enhance and promote the safe and effective use of composites, representative body of the UK composites industry.
- Address:
  Composites Processing Association Sarum Lodge
  St Anne's Court Talygarn Pontyclun CF72 9HH UK
- Website: http://compositesuk.co.uk/

National Composites Network

- The National Composites Network is a unique Knowledge Transfer Network jointly funded by government and industry that embraces the entire UK Composites industry and its supply chain.
- Address:
  Granta Park, Great Abington
  Cambridge, United Kingdom
- Website: http://www.ncn-uk.co.uk

A to Z in GRP Ltd.

- A to Z in GRP Ltd design and manufacture glass reinforced plastic (GRP Fiberglass) mouldings to suit a wide range of uses and applications, including architectural mouldings for the building industry, swimming pools, roofing, cabins and kiosks as well as bespoke projects such as cars and boats.
- Address:
  Blacklands Farm, Wheatsheaf Road, Henfield, West Sussex, BN5 9AT
  Tel: (01273) 493528 Fax: (01273) 495985
- Website: http://www.sussexgrp.co.uk/

NATIONAL MANUFACTURERS AND CONSULTANTS

Sintex Plastics

- Manufacturing of Thermoplastic, thermoset, FRP products, sandwich panels etc. Building and construction products – tanks, piping systems, doors,, windows, panels, prefabricated housing etc.
- Address:
  Sintex Industries Limited
  Plastic Division
  KALOL (N. GUJARAT) 382 721. INDIA
  Email: plastic@sintex.co.in
- Website: http://sintex-plastics.com

Devi Polymers Pvt. Ltd.

- Pioneers in manufacturing Polyester Moulding Compound (PMC), Sheet Moulding Compound (SMC) and Dough Moulding Compound (DMC) in India.
- Address:
  S.Ram Mohan, Manager - Marketing & Devpt.
  (Marketing Division, Unit 'C')
  Devi Polymers Private Limited
  NP 23 & 24, Developed Plot,
  Ekkattuthangal, Chennai - 600 097, INDIA
- Website: http://www.devipolymers.com

Kemrock India

- Manufactures and exports FRP/GRP (Composite) Products for major industrial sectors such as aerospace, defense, renewable energy, wind energy, railways, chemical processing, oil and gas, water and waste water management, infrastructure, construction, electrical and electronics, marine, telecommunications etc.
- Address:
  Village Asoj,
  Vadodara-Halol Express Way,
  Dist. Vadodara - 391 510,
  Gujarat, India

- Website: http://www.kemrock.com

Fyfe Asia

- Specialists in composite strengthening (TYFO Systems, TYFO Architectural Systems)
- Address:
  FYFE (India) Pvt Ltd
  226 Hammersmith Industrial Estate
  Narayan Pathare Marg
  Mahim (West), Mumbai 400016
  India
  Email: fyfeindia@vsnl.net
- Website: http://fyfeasia.com

Meena Fiberglass Industries

- Meena Fiberglass Industries make FRP custom-made FRP products
- Address:
  R.S.No. 151/3, Cuddalore-Pondy Main road
  Kattukuppam, Pondicherry-607 402
  Phone: Off: (0413)-2611009; Telefax: 2615421
  Mobile: 94432-36562
  e-mail: admin@meenaFibers.com
- Website: http://meenaFibers.com/index.html

Shrivastava Fibers

- Manufacturer, exporter, trader, supplier and service provider of Roof Air Wind Ventilator, Fiber Canopies For Silent Generator, Fiber Sheet, Domes, Poly Carbonate Sheet, etc.
- Address:
  4842, St. No. 2, Dharampura, Kulfi wali gali, Shingar Cinema Road, Near shagun Marriage Palace, Ludhiana - 141008, Punjab, India
  Phone:91-161-5036487
- Website: http://shrivastavafiber.tradeindia.com/