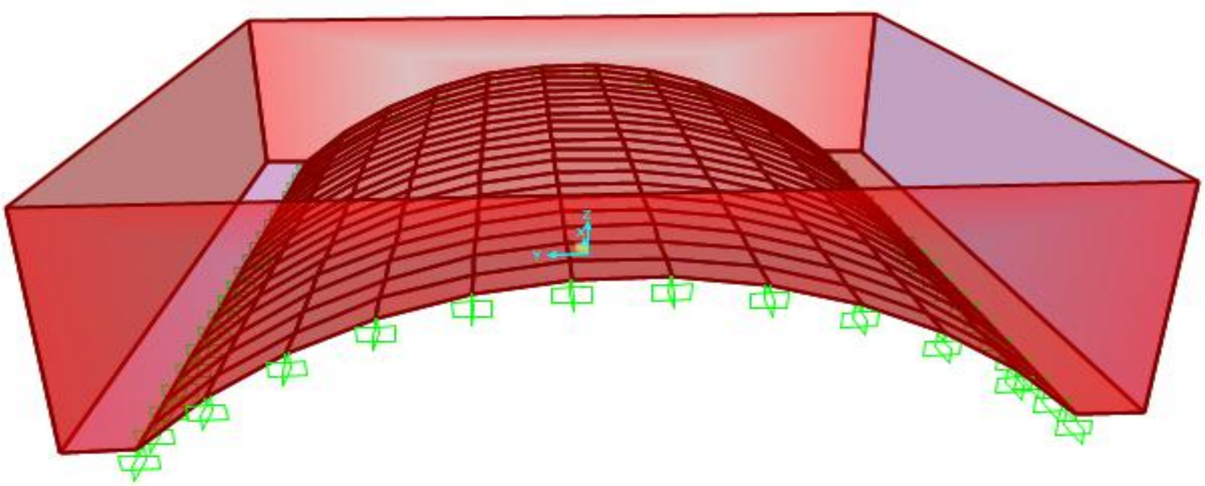
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES
INSTITUTE OF THECNOLOGY
DEPARTMENT OF CIVIL ENGINEERING

COMPUTERIZED ANALYSIS AND DESIGN OF UNDERWATER CYLINDRICAL SHELL STRUCTURES USING FIBER GLASS



By
Finot Mezgebu Wubete

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Approved by Board of Examiners

Dr. -Ing Bedilu Habte	______________	______________
Advisor	Signature	Date
Dr. Asnake Adamu	______________	______________
External Examiner	Signature	Date
Dr. Shifferaw Taye	______________	______________
Internal Examiner	Signature	Date
	______________	______________
Chair man	Signature	Date

Declaration

I declare that this thesis is my original work. This thesis has not been presented for any other university and is not concurrently submitted in candidature of any other degree, and that all sources of material used for the thesis have been duly acknowledged.

Name: Finot Mezgebu

Signature: ___________

Place: Addis Ababa University

Institute of Technology

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Abstract

The computerized design of underwater cylindrical shell will be addressed in this research by using different mechanisms. Since it should be done more accurately and approximately the combination of different programs will be needed. The design will include both analytical and finite element design method. The design will be done for different dimension of the cylindrical shell which can support the load applied. The most applicable and time saving way will be chosen for the design. There will be some exposure to see the behavior of the cylindrical shell with respect to its structural behavior.

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NOMENCLATURE

R-Radius (m)

L-Length (m)

Ψ_k-Angle of the shell (radian)

t-Thickness of the shell (mm)

E-Young's modulus of concrete (kN/m^2)

ν -Poisson's ratio of fiber glass

Ψ-Generic angle in shell (radian)

Υ-Specific weight (KN/m^3)

M_x-Bending moment in plane x-z

M_Ψ-Bending moment in plane r-Ψ

$M_{X\Psi}$-Torque moment in plane x-z

$M_{\Psi x}$-Torque moment in plane r-Ψ

N_x -Axial force in x-direction (KN/m)

$N_\Psi(N_h)$-Axial force in Ψ-direction (KN/m)

$N_{\Psi x}$-Shear force in x –direction(KN/m)

Q_x -Shear force in radial direction along longitudinal edges

Q_Ψ-Shear force in radial direction along transversal edges

ε_x-Normal strain in x-direction

ε_Ψ-Normal strain in Ψ -direction

$\gamma_{X\Psi}$-Shear strain in plane x-Ψ

Ψ_x-Curvature in plane x-z

Ψ_φ-Curvature in plane r-Ψ

$\Psi_{\varphi x}$-Curvature in plane x-z

Pu-Factored distributed surface load (KN/m^2)

p_x-Surface load on the shell in x-direction (KN/m^2)

p_Ψ-Surface load in Ψ-direction (KN/m^2)

p_r-Surface load on the shell in radial direction (KN/m^2)

p_z-Surface load on the shell in z-direction (KN/m^2)

u_x-Displacement component in x-direction (mm)

u_Ψ(u_h)-Displacement component in Ψ-direction(mm)

u_r(u_v)-Displacement component in radial direction(mm)

u_z-Displacement component in z- direction(mm)

R_{ck}-Compressive cube strength of concrete (KN/m^2)

Lr-Roof load

R-Rain load

F-Loads due to weight and pressures of fluids with well-defined densities and controllable maximum heights, or related interval moments and forces

T-Cumulative effect of temperature, creep, shrinkage, differential settlement, shrinkage-compensating concrete

CHAPTER1 INTRODUCTION

1.1 GENERAL BACKGROUND OF THE PROBLEM

In this world there are different structures, which are built to make the life of a human being more easy and comfortable. Even though there are different structures all of them have different purposes. Man is building a structure on the ground, in the ground, on the water and even in the water. As the science of engineering grows the type and the location of the structure also changes.

Engineering is a big and wide field. As the name implies it is a work of creativity. At the end of any engineering field there is always a need of creativity and the means to introduce new technological development. Structural engineering is one of those fields which accommodates one of the basic need of human being that is shelter and additional recreational structures, water structures, bridges, etc.

In Ethiopia there are different kind of structures built. The thesis is an attribute to adding to the structurescurrently existing. Every civilization has its own mark. For Ethiopia the old civilization in century of the civilization of Axum left us a mark by building those three sculpture from one stone. And in king Lalibela ruling time those eleven structurally amazing and detailed structures were built. So from the century we are living now there are different new findings and new technology. Based on that this will be a step forward.

One of the problems found in Ethiopia is introducing new materials. It is almost taken asunreliable way to construct a structure. Most people think the stability and durability of the structure depends on its being constructed with stone or not. But if this material is used practically since it would be a large structure and carry the load of the water it will be a stepping stone for the society and helps us to be open for changes that are scientifically proven.

1.2 OBJECTIVES

The main objective is to do computerized design of underwater cylindrical shell structure using fiber glass.There are many options of dimensions and also fiber glass type for the design. But as the structure is being designed and redesigned the final stable design can be mate. Stability is checked based on ultimate limit state design for compressive and tensile stress of fiber glass. Serviceability limit state design for the deflection limitation of cylindrical shell.

1.3 METHODOLOGY

1.3.1 Procedure

A three step methodology can be used for this study:

i) Study about under water cylindrical shell structure, the analysis, the load and the material that is going to be used.

ii) Analytical Modeling:

   a) Modeling the design problem by differentiating the constraint and taking in to consideration the limitation of stress and deflection.
   b) Design of the cylindrical shell structure using the above constraints by developing appropriate software program.
   c) Verification of the design using structural analysis program (SAP).

iii) Conclusion ,recommendation and limitation

1.4 Limitation

This thesis covers computerized design of underwater cylindrical shell structure. It is specifically limited to:

- The function of the design is for qua zoo so it considers only minimum volume per usable area.
- Basic design formula for thin and thick cylindrical shell.
- The place of construction is not taken in to consideration.
- Doesn’t consider the arrangement of fiber glass layers and the diameter of fiber glass is not also considered.

1.5 Scope

The scope of the thesis is deign of cylindrical shell structure using a C++ programing language. Formulas for design of thin and thick cylindrical shell structure are used for the analytical design. Structural analysis program is used for the finite element analysis. The design considers ultimate limit state design for the type of fiber glass used, serviceability limit state design for the deflection of the cylindrical shell structure and local stability of the structure is taken in to consideration.

CHAPTER 2 LITERATURE REVIEW

2.1SHELL STRUCTURES FUNDAMENTALS

2.1.1 INTRODUCTION

Structural shells are curved-surface systems that are usually capable of transmitting loads in more than two directions to supporting elements. They exhibit structural efficiency when they are so shaped, proportionedand supported that they provided resistance to and transmit the loads without little bending or twisting. They constitute among the most common and most efficient structural elements in nature and technology. They are used whenever high strength, large pans and minimum material content are required. Shells of double curvature, for example, are among the most efficient of known structural forms.[7]

2.2HISTORY OF DESIGN AND CONSTRUCTION OF SHELLS

The theory and practice of shell design goes back to the 1920's when Dyckerhoff and Widmann contractors from Munich, Germany, together with water Bauersfeld and Franz Discharger, developed the famous Cupoia for the Zeiss-Planetarium in Germany. [7]

Anton Tadesko' summarizes his experience with concrete shells as follows.There are three important points which the success of shells depends on. [7]

1. Designers learn from having experience with full-scale structures.
2. Engineers should visualize the actual construction during the design stage ,the economy of shells depends on the close collaboration of design and builder
3. Even in working with architects of prestige, the engineer must stand firm, making it clear as to what can be done and what should not be done.

The thin reinforced-concrete shell, as we know it today, had its beginning in Germany in the 1920s. Most of the early shells built were cylindrical barrels. In 1924, the first concrete shell roof was designed by Carl Zeiss and built in the Zeiss work in Jena, Germany. [1]

Shell structures have found wide applications in practice. These include, among others roof of various types, water tanks and reservoirs as well as liquid contains and storage facilities, foundations, egg-shaped sewage digesters cooling towers at thermal power stations, one of the major structural elements of nuclear power plants,boilers, pressure vessels, bodies of transportation structures including aircrafts, spacecraft, motor vehicles and ships.[7]

2.3HISTORY OF ANALYSIS METHODS

The first analytical approach to the design of shells was presented G. Lame' and E. Clapeyron, who in 1826 produced the "membrane analogy" in which a shell was considered capable of resisting external loads by direct stresses unaccompanied by any bending .The next important contribution in this field was made in 1892 by A.E.H. Love, who developed mathematical conceptions which made possible a more accurate analysis than could be achieved by membrane analogy. Around the year 1923 u. Finsterwalder and F. Dischinger were the first to develop a theoretical analysis applicable to reinforced concrete cylindrical shells. In the united State, H. Schorer further simplified the derivation of Finsterwalder (1936). Until about 1940, the cylindrical shell more or less dominated the scene. The beam theory for shell analysis was developed by H. Lundgren of Denmark in 1949.This consists of separate analyses in which the shell is considered first as a beam and secondly as an arch. The load balancing method, which was developed by T. Y. Lin, for prestressed concrete member offers a new approach and greatly simplifies the design of prestressed shells. [1]

2.4CLASSIFICATION OF SHELLS

Shell structures can be classified into number of categories based on several factors.

2.4.1 CLASSIFICATION BASED ON THICKNESS

The thickness of a shell is important parameter upon which the behavioral response of a shell depends in its ability to resist and transmit the effects loads. The use of shells as structural systems is motivated primarily for two reasons- economy and aesthetics. In either case, however, the cost factors for shells may vary considerably with parameters such as shape and support conditions. In concrete roof-shell structures for example, the high cost of formwork and scaffolding can noticeably restrict the size of spans that are considered economical. On the other hand, form reuse many significantly lower the cost for the shell. [7]

Shells are then classified as membrane, thin and thick shells depending on the ratio of their thickness to respective radius of curvature. Criteria for thinness vary, depending on the magnitude of errors that can be tolerated in regarding a particular shell as thin, and hence suited to study by thin-shell theories rather than by the more general (but less convenient) thick-shell theories which, by their nature are closer to general theory of elasticity. A precise classification may not be possible as many shell structures could be classified either way; thenumerical values presented earlier are only indicative values for the classification. A thin shell is a curved surface structure whose thickness is generally much, much smaller than the other dimensions and in which the geometry activates axial internal stress result to become significant load-resisting stress systems. The effort in planning and design of thin shells to make the shell as thin as practical requirements permit so that the own weight is reduced and the structure functions as a member free from large bending stress. This implies that a minimum material volume is used to maximum structural advantage.[7]

1. Membrane shells : thickness to radius of curvature is

$$\frac{t}{r_{\min}} \le \frac{1}{1000} \quad \text{Eq.1.1}$$

2. Thin shell: thickness to radius of curvature is

$$\frac{1}{1000} \le \frac{t}{r_{\min}} \le \frac{1}{50} \quad \text{Eq.1.2}$$

3. Thick shell: thickness to radius of curvature is

$$\frac{t}{r_{\min}} \ge \frac{1}{50} \quad \text{Eq.1.3}$$

2.4.2 CLASSIFICATION ACCORDING TO GAUSSIAN CURVATURE

Gauss curvature, the product of two principal radii of curvature at any point on the surface of the Shell. Based on this method of classification, thin shells fall into three distinct groups. [7]

i. Synclastic surface: A surface for which Gauss curvature is positive.
ii. Developable surface: A surface for which Gauss curvature is zero.

iii. Anticlastic surface: A surface for which Gauss curvature is negative

2.4.3 CLASSIFICATION BASED ON SURFACE OF GEOMETRIC BEHAVIOR

Shells are classified based on this method, whether the surfaces are ruled or not.

I. Shells with ruled surface: Surfaces that can be obtained entirely by straight lines. The surfaceis said to be singly ruled if at every point on the surface a single straight line can be ruledand doubly ruled when at every point on the surface two straight lines can be ruled.[7]

II. Shells with no ruled surface: are those that fall outside the above category of shells. SomeCommon examples are dome, ellipsoid and elliptic paraboloid.[7]

2.4.4 CLASSIFICATION ACCORDING TO MANNER OF GENERATION

Shells are generally classified based on their mode of formation.

I. **SHELL OF REVOLUTION**: shell that are obtained when a plane curve is rotated about an axis of symmetry.[4]

II. **SHELLS OF TRANSLATION**: shells that are generated when one curve moves parallel to itself alonganother curve, the plane of the two curves being at right angle to each other.[4]

III. **CYLINDRICAL SHELLS**: Singly curved shell in which the generatrix (or directrix) is a straight line. The surface generated by moving the straight line against a plane curve.[4]

2.5ADVANTAGE AND DISADVANTAGE OF SHELL STRUCTURES

2.5.1 ADVANTAGES

1. The efficiency in its load carrying behavior(being treated as a membrane)
2. High degree of reserved strength and structural integritY

3. High strength: weight ratio(which is the main criteria in measuring a structure efficiency)
4. Very high stiffness
5. Containment of space
6. High aesthetic value

2.5.2 DISADVANTAGE

1. It's impossible to build a story above the story that has a shell roof, thus shells are always used as a "terminating" roof.

2.6CYLINDRICAL SHELL

A cylindrical shell surface is generated by translating a straight line generatorover a plane curve directrix. An arc of a circle, semi ellipse, parabola, cycloid, and catenary are some ofthe most common directrices to form cylindrical surface. Shells for which the plane curve is arc of acircle are called circular cylindrical shells. All other which have their generating plane curves otherthan circular arc are collectively referred to as non-circular cylindrical shells. [7]

Cylindrical shells are developable surfaces, a property that influences both their structural and architectural aspects .Accordingly, large transverse moments occur in cylindrical shells when the span becomes large, their performance calls for special attention by the way of increasing reinforcement and thickness in region adjacent to springing in reinforced concrete systems or provide sufficient stiffeners for other materials such as steel shells. [7]

Open cylindrical shells are mostly used for the construction of roof for industrial building, sport andexhibition halls, garages and hangars etc...[7]

2.6.1 CLASSIFICATION OF CYLINDRICAL SHELL

Cylindrical shells can be classified as long, short, and sometimes intermediate shells. The object ofthis classification, principally, is to help the designer to determine whether a shell of particulardimension is susceptible for an approximate method of analysis. There are three classificationmethods.

2.6.1.1 CLASSIFICATION BASED ON RADIUS AND LONGITUDINAL LENGTH

A cylindrical shell are usually described as either long or short depending upon the ratio of thelength (L) and radius (R). If the ratio [7]

i. $\frac{r}{l} \leq 0.2$ without edge beam

ii. $\frac{r}{l} \leq 0.33$ with edge beam

& it is called short shell if the ratio $\frac{r}{l} \leq 0.2$

2.6.1.2 CLASSIFICATIONBASED ON THE MAGNITUDE OF EDGE DISTURBANCE

Based on the extent to which the disturbances arising from the springing edges penetrate into thebody of the shell itself. Based on this consideration, once again the radius (r) and the longitudinallength (*l*) of the shell are indicative parameter. [7]

i. $\frac{r}{l} < 0.63$; Long shell

ii. $\frac{r}{l} > 0.63$; Short shell

2.6.1.3 CLASSIFICATION BASED ON GEOMETRIC DIMENSION AND THICKNESS

This method is based on the numerical value of the parameter $\phi = \frac{b}{0.25(12rt)}$ such that

i. Φ < 3; Long shell
ii. 3< Φ < 5; Intermediate shell
iii. Φ < 5; Short shell[7]

2.7FIBER GLASS

Fiber glass is the common name for glass-reinforced plastic or alternatively glass-fiber reinforced. Fiberglass is also known as GFK, for German: Glasfaserverstärkter Kunststoff [10].Fiberglass is a fiber reinforced polymer made of plastic reinforced by glass fibers, commonly woven into a mat. The plastic may be a thermosetting plastic most often epoxy, polyester- or vinyl ester or a thermoplastic. The glass fibers are made of various types of glass depending upon the fiberglass use. These glasses all contain silica or silicate, with varying amounts of oxides of calcium, magnesium, and sometimes boron. Boron-containing fiber glasses consume half the global production of boron minerals, and are the largest commercial consumer of the element.[16]

Fiberglass is a strong lightweight material and is used for many products. Although it's not as strong and stiff as carbon fiber it is less brittle, and its raw materials are much cheaper. Its bulk strength and weight are also better than many metals, and it can be more readily molded into complex shapes. Applications of fiberglass include aircraft, boats, automobiles, bath tubs and enclosures, hot tubs, septic tanks, water tanks, roofing, pipes, cladding, bridges, outdoor aquatics stage and stair cases.[12]

2.7.1 PROPERTIES

An individual structural glass fiber is both stiff and strong in tension and compression that is, along its axis. Although it might be assumed that the fiber is weak in compression, it is actually only the long aspect ratio of the fiber which makes it seem so; i.e., because a typical fiber is long and narrow, it buckles easily. On the other hand, the glass fiber is weak in shearthat is, across its axis. Therefore, if a collection of fibers can be arranged permanently in a preferred direction within a material, and if they can be prevented from buckling in compression, the material will be preferentially strong in that direction. [12]

Furthermore, by laying multiple layers of fiber on top of one another, with each layer oriented in various preferred directions, the material's overall stiffness and strength can be efficiently controlled. In fiberglass, it is the plastic matrix which permanently constrains the structural glass fibers to directions chosen by the designer. With chopped strand mat, this directionality is essentially an entire two dimensional plane; with woven fabrics or unidirectional layers, directionality of stiffness and strength can be more precisely controlled within the plane. [12]

The most common types of glass fiber used in fiberglass is E-glass, which is alumino-borosilicate glass with less than 1% w/w alkali oxides, mainly used for glass-reinforced plastics. Other types of glass used are A-glass (Alkali-lime glass with little or no boron oxide), E-CR-glass (Electrical/Chemical Resistance; alumino-lime silicate with less than 1% w/w alkali oxides, with high acid resistance), C-glass (alkali-lime glass with high boron oxide content, used for glass staple fibers and insulation), D-glass (borosilicate glass, named for its low Dielectric constant), R-glass (alumino silicate glass without MgO and CaO with high mechanical requirements as Reinforcement), and S-glass (alumino silicate glass without CaO but with high MgO content with high tensile strength).[12]

2.7.2 TYPES OF FIBER GLASS

GRP (glass reinforced plastic) is a composite of tough resilient, durable plastic resin, and glass fibers of remarkable strength. The resin is a thick, treacly substance which when activated by an appropriate catalyst, sets to a hard but brittle solid. It can be used alone for small castings, or with a variety of fillers, but, when reinforced with glass fibers, becomes a material of exceptional strength and versatility. [16]

The Glass used commonly for GRP is a calcium-alumina borosilicate with an alkali content of less than one per cent. It is commonly known as ‘E’ type glass, since it was originally developed for use in electrical insulation systems.[16]

Glassfibres are produced by running molten glass from a direct melt furnace into a platinum alloy bushing containing a large number of small holes, from each of which a glass filament is drawn. Filaments for commercial use are normally between 9 and 15 microns in diameter. The filaments are “dressed” with an emulsion before being gathered into fibers. The fibers are remarkably strong-the tensile strength being particularly high. They also exhibit good chemical and moisture resistance, have excellent electrical properties, are not subject to biological attack and are non-combustible with a melting point around 1500^{o}C all excellent qualities in a plastic reinforcement.[16]

Provided the glass reinforcement has been thoroughly impregnated with resin, the result, after curing, is a cohesive completely integrated matrix of resin and fibers. The matrix can have a surprising range of properties, depending on the type of glass material and the formulation of the resin. In general, the GRP laminate will display excellent tensile and compressive strength, acceptable thermal conductivity, a low coefficient of linear expansion, reasonable chemical resistance and good dielectric properties. Compared to other materials of equivalent strength, it will be light durable, moisture-resistant, non-rusting and economic.[16]

There are different kinds of fiber glass with different compression and tensile strength. This is set by East Coast Fiberglass Supplies Ltd 2013

Material	**Specific**	**Tensile strength**	**Compressive**

	gravity	(Mpa)	strength (Mpa)
Polyester resin (Not reinforced)	1.28	55	140
Polyester and Chopped Strand Mat Laminate 30% E-glass	1.4	100	150
Polyester and Woven Rovings Laminate 45% E-glass	1.6	250	150
Polyester and Satin Weave Cloth Laminate 55% E-glass	1.7	300	250
Polyester and Continuous Rovings Laminate 70% E-glass	1.9	800	350
E-glass	2.58	3445	1080
S-2 glass	2.46	4890	1600

TABLE 2.1Common Fiberglass Types[16**]**

The fibers can be used in a variety of ways-chopped into short lengths(“chopped strands”); gathered together into loosely bound ropes (“rovings”); woven into a variety of fabrics, produced from yarn made by twisting and doubling continuous strands. In the UK, the most widely used glassfibre material is chopped strand mat, which consists of glass strands chopped together in short lengths (approx. 50mm) and held together in mat form by a polyvinyl acetate or polyester binder. The mat is available in a range of weights, from 225gm2 to 1200gm2, and is a useful general purpose reinforcement.[16]

Some experiments have been done about fiber glass and this tensile and compressive behavior of fiber glass shows the capacity of fiber glass to be used as a structural material. The behavior of this carbon fiber composite material is that they are brittle and break at their maximum load capacity even though it is used in different countries. From the tests done it is concluded that the material is not ductile.[16]

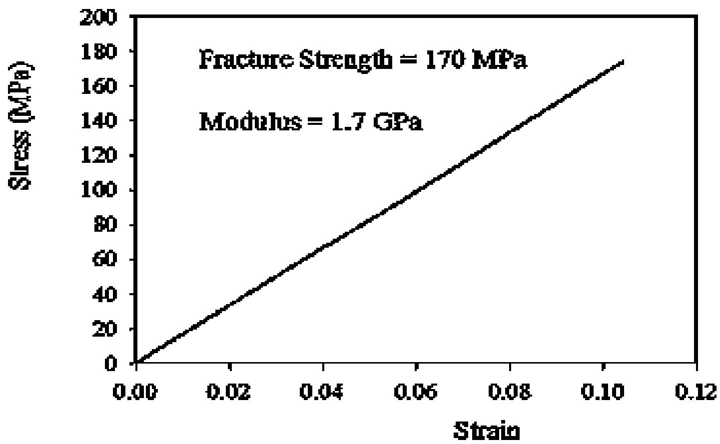

FIGURE 2.1Stress Strain Relation of Fiber Glass in a Tensile Test[16**]**

2.8DESIGN OF SHELL STRUCTURE

2.8.1 LOADING

Loading used in a design of a structure depends on the serviceability and also the ultimate capacity of the structure. If the structure doesn't stand to support these two major divisions of load then it must be revised to do so. There are different kinds of loads this are live load, dead load, wind load and earthquake loading. These loads are the major loads depending on the country snow load and temperature consideration may be added. To know what kind of load that should be considered in the Euro Code check this1990:2002 [13].

2.8.2 LOADING COMBINATION

Required strength, U shall be at least equal to the effects of factored loads in Eq. 2.6.2.1up toEq. 2.6.2.7.The effect of one or more loads not acting simultaneously shall be investigated.

$U = 1.4(D + F)$ ....Eq. 2.6.2.1

$U = 1.2(D + F + T) + 1.6(L + H) + 0.5(LrorSorR)$ ……………………………………Eq. 2.6.2.2

$U = 1.2D + 1.6(LrorSorR) + (1.0Lor0.8W)$ ………………………………………Eq. 2.6.2.3

$U = 1.2D + 1.6W + 1.0L + 0.5(LrorSorR)$ ……………………………………….Eq. 2.6.2.4

$U = 1.2D + 1.0E + 1.0L + 0.2S$ ……………………………………………………Eq. 2.6.2.5

$U = 0.9D + 1.6W + 1.6H$ ………………………………………………………….Eq. 2.6.2.6

$U = 0.9D + 1.0E + 1.6H$ ………………………………………………………….Eq. 2.6.2.7

Except as follows:

- The load factor on the live load L in Eq. (2.6.2.3) to (2.6.2.5) shall be permitted to be reduced to 0.5 except forgarages, areas occupied as places of public assembly, and all areas where L is greater than 488.0408kg/m^2.
- Where wind load W has not been reduced by a directionality factor, it shall be permitted to use 1.3W in place of 1.6W in Eq. (2.6.2.4) and (2.6.2.6).
- Where E, the load effects of earthquake, is based on service-level seismic forces, 1.4E shall be used in place of 1.0E in Eq. (2.6.2.5) and (2.6.2.7).
- The load factor on H, loads due to weight and pressure of soil, water in soil, or other materials, shall be set equal to zero in Eq. (2.6.2.6) and (2.6.2.7) if the structural action due to H counteracts that due to W or E. Where lateral earth pressure provides resistance to structural actions from other forces, it shall not be included in H but shall be included in the design resistance.
- Where Lr is Roof load of the structure. R is rain load, S snow load, F is Loads due to weight and pressures of fluids with well-defined densities and controllable maximum heights, or related interval moments and forces and T is cumulative effective effect of temperature, creep, shrinkage, differential settlement, shrinkage compensating concrete.[13]

If resistance to impact effects is taken into account in design, such effects shall be included with estimations of differential settlement, creep, shrinkage, expansion of shrinkage-compensating concrete, or temperature change shall be based on a realistic assessment of such effects occurring in service.

Generally the factor assigned to each load is influenced by the degree of accuracy to which the load effect usually can be calculated and the variation that might be expected in the load during the lifetime of the structure. Dead loads, because they are more accurately determined and less variable, are assigned a lower load factor than live loads. Load factors also account for variability in the structural analysis used to compute moments and shears.

Consideration should be given to various combinations of loading to determine the most critical design condition. This is particularly true when strength is dependent on more than one load effect, such as strength for combined flexure and axial load or shear strength in members with axial load.

2.8.3 SAFETY FACTOR

Safety factor is used in various design equations were chosen to prevent first deformation. The first deformation is the first visible deformation. The recommended value for this kind of structure is 2.5. [16]

2.8.4 DESIGN CONSIDERATION

While designing different kinds of structure it is a must to know which things should be taken in to consideration. This helps in efficient design of a structure. Therefore the following points should be taken in to consideration while designing cylindrical shell structure.

A. Selection of shell type. For covering very large areas, for hangars, warehouses, etc., short shells are usually economical. The span of the short shell may be chosen as between one-sixth and one – third of the chord width. A practical limit on the span of long reinforced-concrete shells is about 30.48m .For longer shells, prestressing will prove economical.[2]

B. The radius of cylindrical shell has to be chosen keeping acoustic considerations in view. It is desirable to see that the center of curvature does not lie at the working level. [2]

C. Semi central angle

The practice is to keep the semi central angle between 30^0 and 45^0. If the angle exceeds 45^0, concreting becomes difficult without the use of top forms .If the angle is below 40^0, wind load can be ignored, because it causes only a suction on the shell. [2]

D. Thickness

The minimum thickness of reinforced-concrete cylindrical shells is governed by practical considerations such as accommodating reinforcement and providing adequate cover. According to a Dutch report the usual recommended thickness is between 0.07 and 0.08 m .A minimum of 0.04 m is recommended by the institute for the Typification of the German Democratic Republic at Berlin.[2]

E. Width of Edge Beam

A width of two to three times the thickness of shell would usually suffice .A minimum of 0.1524m is demanded by practical considerations. [2]

F. Design of Reinforcement

When fiber glass is used as a construction material

a) Chopped Strands Short (6mm or 12mm) lengths of glassfibre. Can be used to make a resin dough, stronger than that made by mixing resin with filler powder. Chopped Strand Mat a popular and economical form of glass reinforcement for polyester resins. Short strands of glass are bonded with a powder or emulsion into a mat available in a variety of thickness.[16]
b) Filaments for commercial use are normally between 9*10^-6 and 15*10^-6m in diameter. [16]

When reinforced concrete (non prestressed)

a) The ratio of steel to concrete in any portion of the tensile zone should not be less than 0.35% of the cross sectional area of concrete.[2]
b) The minimum temperature and shrinkage steel should not be less than 0.14% of the cross sectional area of concrete.[2]

c) The maximum spacing of bars should not exceed 40 bar diameters nor five times the thickness of the shell. [2]

G. Finishing for fiber glass shell

Glassfibre materials once hardened can be polished, sanded, drilled, sawn or filed. Diamond carborundum or metal finishing tools generally are required. Since the dust produced can be extremely hazardous to eyes and lungs protective goggles and breathing masks should be worn at all times when machining hardened resins, with or without glassfibre reinforcement. [16]

2.8.5 METHOD OF ANALYSIS

2.8.5.1 LOAD BALANCING METHOD

Consider the cylindrical shell without edge beams. The cables can be post-tensioned along the shell surface so that the vertical component of a cable will balance the gravity load. The prestressing forces, and its vertical component of a cable will balance the gravity load. The prestressing forces, and its vertical component W_v and horizontal component W_h are given by [2]

$$H = \frac{Wl^2}{8f_v}\frac{1}{2} \qquad \text{Eq. 2.8.5.1.1}$$

$$W_v = H\frac{8f_v}{l^2} \qquad \text{Eq. 2.8.5.1.2}$$

$$W_h = H\frac{8f_h}{l^2} \qquad \text{Eq. 2.8.5.1.3}$$

In these expression W is the uniform load of the shell per linear feet along the X axis , l is the span of the shell ,f_v is the projected vertical sag of the parabolic cable and $f_h$is the projected horizontal sag of the parabolic cable and f_h is the projected horizontal sag of the parabolic cable.[2]

2.8.5.2 BEAM THEORY

The beam theory involves two analyses:

A) The beam analysis

I. The longitudinal stresses at any cross section of the shell are computed on the basis of the simple flexural theory

$$Nx = \frac{Mc}{I}$$ ……………………………………………………………………Eq. 2.8.5.2.1

Where I is the moment of inertia of the shell cross-section about the axis yy .It may be shown that

$$I = R^3 t\left[\phi_c + \sin\phi_{c(}\left(\cos\phi_c - \frac{2\sin\phi_c}{\phi_c}\right)\right]$$ ………………………………………………Eq. 2.8.5.2.2

The shearing stresses are computed by the corresponding simple expression

$$N_{X\emptyset} = \frac{VQ}{Ib}$$ …………………………………………………………Eq. 2.8.5.2.3

Where Q is the first statically moment of the cross section up to the point under consideration about the axis yy and is [2]

$$Q = 2R^2 t(\sin\phi - \frac{\phi\sin\phi_c}{\phi_c})$$ ……………………………………………..Eq. 2.8.5.2.4

II. For the case of the prestressing force acting on the shell the vertical component of the cable force is equal to some gravity load , therefore , the beam shear force and bending moment are zero for this load .

The longitudinal force is

$$N_x = -\frac{2H}{A}$$ ……………………………………………………………Eq. 2.8.5.2.5

Where A is the cross-sectional area of the shell.

The following equations for transverse forces and moments have been developed by using free body. The force F_v was obtained by summing vertical forces, and M_Φ by taking moments about the intersection of a radial line at angle Φ and the arc of shell.[2]

A. Forces due to Dead Load

$$F_v = gR(\phi_c - \phi) \quad \text{......Eq. 2.8.5.2.6}$$

$$M_\phi = -gR^2[\cos\phi - \cos\phi_c - \sin\phi(\phi_c - \phi)] \quad \text{......Eq. 2.8.5.2.7}$$

$$N_\phi = gR(\phi_c - \phi)\sin\phi \quad \text{......Eq. 2.8.5.2.8}$$

$$Q_\phi = -gR(\phi_c - \phi)\cos\phi \quad \text{......Eq. 2.8.5.2.9}$$

B. Force due to water load

$$P_x = 0 \quad \text{......Eq. 2.8.5.2.10}$$

$$P_n = -\gamma[h + a(1 - \cos\phi)] \quad \text{......Eq. 2.8.5.2.11}$$

$$P_\phi = \gamma(h + a\sin\phi) \quad \text{......Eq. 2.8.5.2.12}$$

Its own stress

$$N_\phi = -\gamma ha\cos\phi \quad \text{......Eq. 2.8.5.2.13}$$

$$N_x = -\frac{\gamma h}{a}\left(\frac{l^2}{4} - x^2\right)\cos\phi \qquad \text{Eq. 2.8.5.2.14}$$

$$N_{x\phi} = N_{\phi x} = -2\gamma h x \sin\phi \qquad \text{Eq. 2.8.5.2.15}$$

2.8.5.3 THE ARCH ANALYSIS

When forces acting on the shell are balanced by prestressing forces, there is no shear flow produced at all, which means no arch action in the shell, but when the acting forces are unbalanced by the prestressing forces, shear flow will appear and the arch action will have an effect on the shell response. The vertical components of the shear flow balance the load on the shell arch; the horizontal components of shear flow which are symmetrically disposed about the crown balance themselves. The resulting internal forces are [2]

$$F_v = \int_{\phi}^{\phi_c} \frac{gR^2\phi_c Q(\theta)}{I}\sin\phi d\phi + gR(\phi_c - \phi) \qquad \text{Eq. 2.8.5.3.1}$$

$$F_h = -\int_{\phi}^{\phi_c} \frac{gR\phi_c Q(\theta)}{I}\cos\phi R d\phi \qquad \text{Eq. 2.8.5.3.2}$$

$$Q_\phi = -F_v\cos\phi + F_h\sin\phi \qquad \text{Eq. 2.8.5.3.3}$$

$$N_\phi = F_v\sin\phi + F_h\cos\phi \qquad \text{Eq. 2.8.5.3.4}$$

$$\begin{aligned} M_\phi = {} & \int_{\phi}^{\phi_c} gR^3\phi_c Q(\theta)\sin\phi(\sin\theta - \sin\phi)d\theta \\ & - \int_{\phi}^{\phi_c} gR^3\phi_c Q(\theta)\cos\phi(\cos\phi - \cos\theta)d\theta - gR^2\left[\cos\phi - \cos\phi_c - \sin\phi(\phi_c - \phi)\right] \end{aligned} \qquad \text{Eq. 2.8.5.3.5}$$

2.8.5.4 MEMBRANE THEORY

The equations of equilibrium for the shell element generally contain ten unknowns: the stress resultants and stress couples – and six equations. The system is therefore statically indeterminate.

As a result, deformation must be considered in order to obtain a solution. The Membrane Theory avoids the complexities involved with solving the statically indeterminate system by reducing the number of unknowns from ten to four. This results in a statically determinate system that can be solved directly. The Membrane Theory accomplishes this by neglecting all normal shears, bending moments, and twisting moments in the shell.[7]

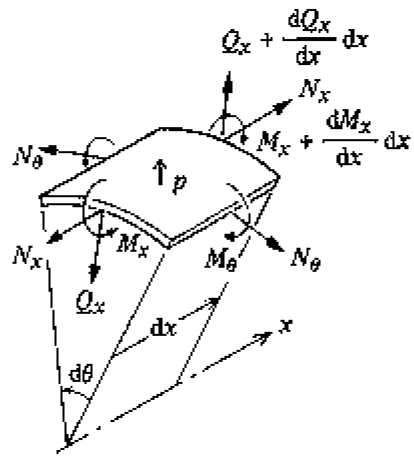

FIGURE 2.2Shear ,Bending Moment And Twisting Moment[3]

The equations of the equilibrium then reduced to:

$$\frac{\partial}{\partial \alpha\chi}\left(N'xay\right) - N'y\frac{\partial \alpha y}{\partial \alpha x} + N'xy\frac{\partial \alpha x}{\partial \alpha y} + \frac{\partial}{\partial \alpha y}\left(N'yxax\right) + pxaxay = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. 2.8.5.4.1}$$

$$\frac{\partial}{\partial \alpha y}\left(N'yax\right) - N'x\frac{\partial ax}{\partial \alpha x} + N'xy\frac{\partial \alpha y}{\partial \alpha x} + \frac{\partial}{\partial \alpha x}\left(N'yxay\right) + pyaxay = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. 2.8.5.4.2}$$

$$\frac{N'x}{rx} + \frac{N'xy}{rxy} + \frac{N'yx}{rxy} + \frac{N'y}{ry} + pz = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq. 2.8.5.4.3}$$

The validity of the results obtained by the Membrane Theory depends upon a number of conditions. First, the boundary conditions must be compatible with the conditions of equilibrium. Second, the application of the loading must be compatible with the conditions of equilibrium.

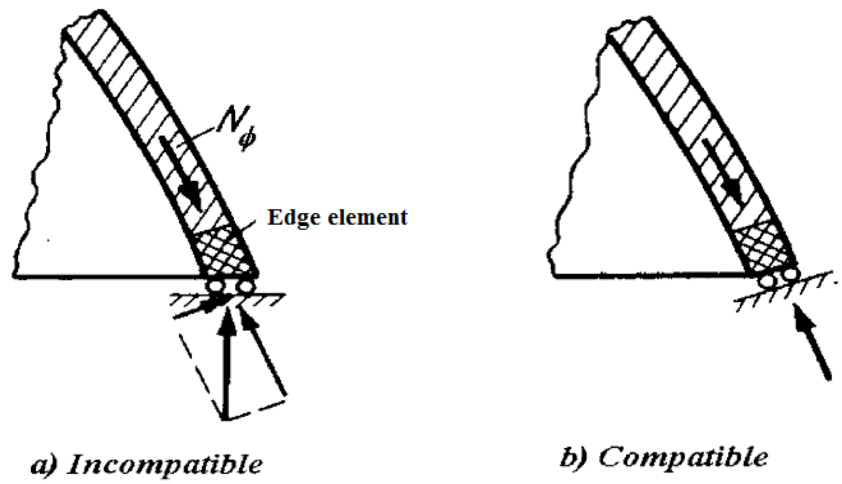

FIGURE 2.3Compatibility of Boundary Conditions with the Membrane Theory [8]

Figure 2.7 shows the shell edge with different boundary conditions. The system depicted in(a) is free to translate horizontally. There is therefore a component of the reaction that acts normal to the shell surface at the edge. Yet the Membrane Theory neglects all forces that act out of plane, so the element is out of equilibrium. The boundary condition displayed in (b) supplies a reaction that acts only in the plane of the shell. Therefore, the support is compatible with both the Membrane Theory and the conditions of equilibrium.

Now consider the case of a shallow shell subjected to a smoothly distributed load. As the radius of curvature of the shell approaches infinity, the shell becomes a plate. Under Membrane Theory, this shell possesses no internal force system capable of contributing to the vertical equilibrium. Clearly, either normal shear of bending must occur in order for the plate to carry the loading. Thus the Membrane theory is not applicable to plates.

As the previously discussed examples have shown, the Membrane Theory is not suitable for all shell analysis. While the assumptions of the Membrane Theory clearly simplify the mathematics involved in the solution of shell problems, they do not fully explain the behavior of shells. Under certain circumstances the Membrane Theory may provide the complete solution to a shell problem. Under different circumstances, however, serious incompatibilities may occur and a more rigorous analysis method must be employed.

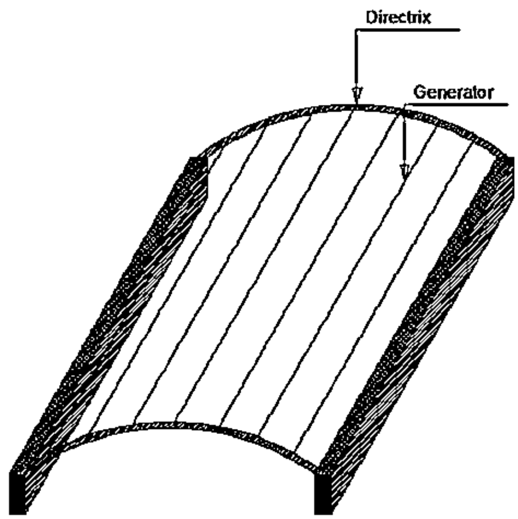

FIGURE 2.4Cylindrical Shell with Edge Beam[12]

A cylindrical shell is formed by the motion of straight line, called the generator, parallel to itself such that its end describes a plane curve which may be circle, ellipse, parabola, etc. Or may be of arbitrary shape. A section normal to the generator is called profile.

A point p on the middle surface of the shell is defined by the distance x along the generator, measured from a profile of reference, and the angle θ which the normal n to the surface makes with a certain reference axis .Thus, a system of right handed orthogonal axes at point p consists of the tangent to the surface, where the positive directions of such axes are taken as shown in the figure.

Consider now an infinitesimal element (fig) of the cylindrical shell bounded by the two profiles at x and x+dx and the two generators at θ and θ+dθ, where all the external loads and internal actions are represented as components along the chosen axes. The surface loadings have the components p_x, p_θ and p_n per unit area of surface .In the membrane analysis, the only internal actions considered are the normal forces N_x and the shearing force $N_{x\theta}$, acting per unit length of the side x=constant, whereas a unit length of the side θ = constant is acted upon by the normal force N_θ and the shearing force $N_{\theta x}$ as indicated in the figure

Now if r denotes the radius of curvature of the shell profile at any point, then, the length of the side x= constant, of the infinitesimal element of fig., is rdθ. Taking moment about the normal to the surface of the infinitesimal element, it follows that:

$$N_{x\theta} = N_{\theta x} \qquad \text{Eq. 2.8.5.4.4}$$

Resolving forces acting in the element in the direction of the axes x, θ and n, one obtains, respectively:

$$\frac{\partial N_x}{\partial x} dxrd\theta + \frac{1}{r}\frac{\partial N_{x\theta}}{\partial \theta} + P_x rd\theta dx = 0 \qquad \text{Eq. 2.8.5.4.5}$$

$$\frac{\partial N_\theta}{\partial \theta} d\theta dx + \frac{\partial N_{x\theta}}{\partial x} dxrd\theta + p_\theta rd\theta dx = 0 \qquad \text{Eq. 2.8.5.4.6}$$

$$-N_\theta dxd\theta + P_n rd\theta dx = 0 \qquad \text{Eq. 2.8.5.4.7}$$

Dividing the above equation by r dθdx and reducing, one obtains:

$$\frac{\partial N_x}{\partial x} = -\left[\frac{1}{r}\frac{\partial N_{x\theta}}{\partial \theta} + P_x\right] \qquad \text{Eq. 2.8.5.4.8}$$

$$\frac{\partial N_{x\theta}}{\partial x} = -\left[\frac{1}{r}\frac{\partial N_\theta}{\partial \theta} + P_\theta\right] \qquad \text{Eq. 2.8.5.4.9}$$

$$N_\theta = P_n r \qquad \text{Eq. 2.8.5.4.10}$$

It, thus, appears that N_θ depends only on the local intensity of the normal load component p_n (Eq. 2.7.5.4.5) and is independent of the boundary conditions. This is not so important in the case of shells having closed profiles; however, this condition puts practical limitations on the validity of the membrane analysis for shells with open profiles due to the difficulty of prescribing the required values of N_θ along the straight edge.[7]

In the special case when p_x=0 and p_θ, p_n are independent of x (same loading over all profiles), it will be expected that N_θ is also independent of x and Eq. 2.7.5.4.6, 7&8 reduce to:

$$\frac{\partial N_x}{\partial x} = -\left[\frac{1}{r}\frac{\partial N_{x\theta}}{\partial \theta}\right] \text{.....Eq. 2.8.5.4.11}$$

$$\frac{\partial N_{x\theta}}{\partial \theta} = -\left[\frac{1}{r}\frac{\partial N_\theta}{\partial \theta} + P_\theta\right] = -F(\theta) \text{.....Eq. 2.8.5.4.12}$$

$$N_\theta = P_n r \text{.....Eq. 2.8.5.4.13}$$

Substituting fromEq. 2.7.5.4.7 into Eq. 2.7.5.4.6 and integrating, one has:

$$N_{\theta x} = -xF(\theta) + f_1(\theta) = 0 \text{.....Eq. 2.8.5.4.14}$$

$$F(\theta) = \left[\frac{1}{r}\frac{d}{d\theta}(rP_n) + P_\theta\right] \text{.....Eq. 2.8.5.4.15}$$

Where the prime denotes differentiation with respect to θ and f_1, f_2 are arbitrary functions to be determined from the support conditions over an edge x= constant. Such edge supports are often provided by stiffening members, known as diaphragms or traverses, which may be arches, trusses, beam plate, etc. The diaphragm is usually assumed to be very stiff in its own plane, but flexible out of this plane. In other words, a diaphragm carries loads (Nxθ) in its own plane, but cannot receive any loads applied normal to its plane. Hence, a usual boundary condition is N_x= 0 along the edge x=constant.[2]

The corresponding displacement is

Transverse displacement:

$$V = \frac{8g}{\pi Et}\sin\theta\cos\frac{\pi x}{l}\left(\frac{2}{K^2}+\frac{1}{R^2K^4}\right) \text{..........Eq. 2.8.5.4.16}$$

$$K = \frac{\pi}{l} \text{..........Eq. 2.8.5.4.17}$$

Normal displacement

$$W = \frac{\partial v}{\partial\theta} = -\frac{8g}{\pi Et}\cos\theta\cos\frac{\pi x}{l}\left(\frac{2}{K^2}+\frac{1}{R^2K^4}\right) \text{..........Eq. 2.8.5.4.18}$$

Longitudinal displacement

$$U = -\frac{1}{Et}\frac{8g}{\pi RK^3}\cos\theta\sin\frac{\pi x}{l} \text{..........Eq. 2.8.5.4.19}$$

2.8.5.5 BENDING THEORY

The more general and rigorous approach for solving shell problems is the so-called bending theory, also referred to as the shallow-shell theory as it is often called, and it considers the effects of the longitudinal moment and transverse shear (in the direction of the axis of the cylinder)

The bending theory is based on two assumptions; these are:

i. The shell is so flat that the out-of-plane translational displacements w are much greater than the in-plane ones, u and v.
ii. The shell is steep enough so that in-plane stress resultants N_x, N_y and N_{xy} contribute to resisting the loads that do the out-of-plane stress resultants Q_x and Q_y.

Both the membrane theory and the bending theory are very important and widely applicable to solving various kinds of thin shell structures. The edge-load solutions (bending solutions), together with the membrane solution, will yield the complete solution of a shell problem.[7]

For solving shell problems, therefore, the general procedure will be to obtain membrane forces under a given loading, and then superimpose on these the bending theory solutions for edge loads. The edge loads are determined so that the membrane and edge load solutions together satisfy the boundary conditions; i.e., the edge loads are obtained by solving equations of compatibility at the boundaries.[7]

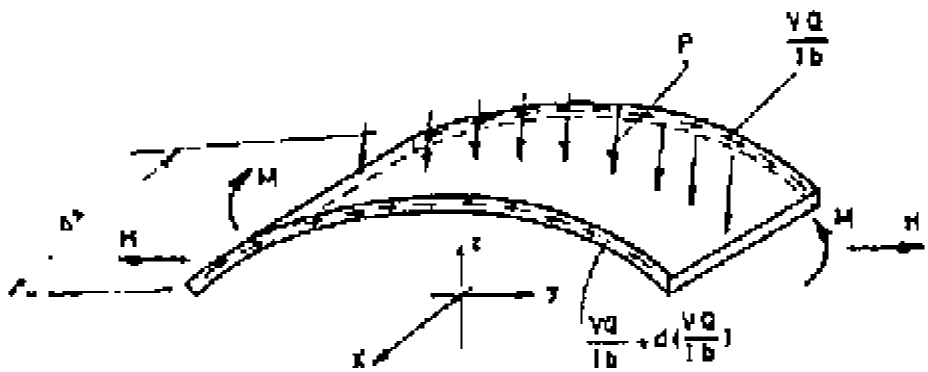

FIGURE 2.5Edge Reactions and Load Applied

2.8.6 ANALYSIS PROCEDURE

After defining design assumptions, the general theory of shell can be formulated in the following five steps [8]

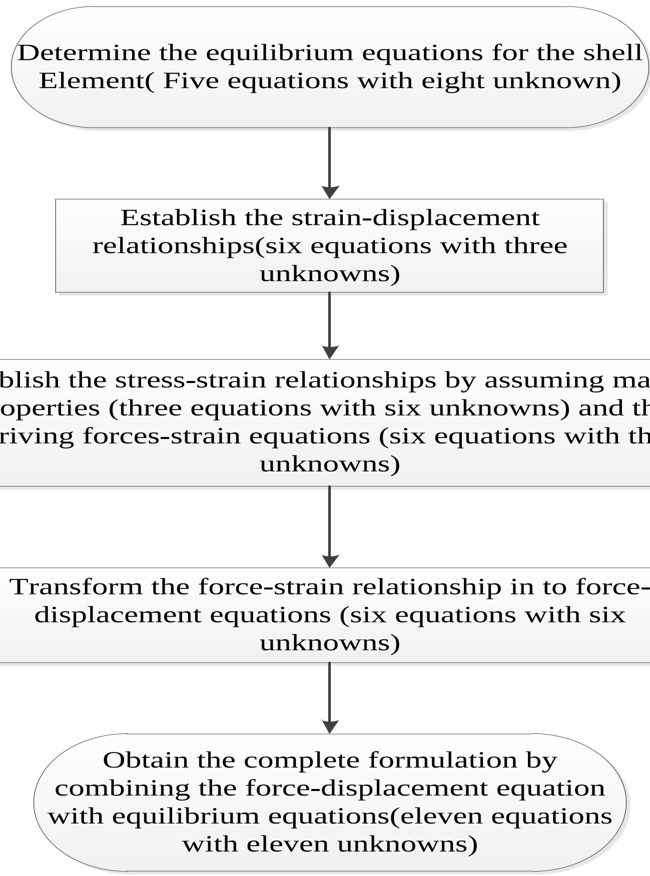

FIGURE 2.6 Analysis Procedure

a) Forces affecting the equilibrium of the shell element are set up

$$\frac{\partial N_x}{\partial x} + \frac{1}{R}\frac{\partial N_{x\theta}}{\partial \theta} = 0 \quad \text{Eq. 2.8.6.1}$$

$$\frac{\partial N_\theta}{\partial \theta} + R\frac{\partial N_{\theta x}}{\partial x} = 0 \quad \text{Eq. 2.8.6.2}$$

$$R\frac{\partial Q_x}{\partial x} + \frac{\partial Q_\theta}{\partial \theta} + N_\theta = 0 \quad \text{Eq. 2.8.6.3}$$

$$R\frac{\partial M_{x\theta}}{\partial x}+\frac{\partial M_{\theta}}{\partial \theta}-R_{Q\theta}=0 \qquad \text{……………………………………………………Eq. 2.8.6.4}$$

$$\frac{\partial M_{x\theta}}{\partial x}+R\frac{\partial M_{x}}{\partial x}-R_{Q\theta}=0 \qquad \text{……………………………………………………Eq. 2.8.6.5}$$

$$N_{x\theta}-N_{\theta x}=0 \qquad \text{……………………………………………………...Eq. 2.8.6.6}$$

Let us consider an open barrel cylindrical shell loaded by uniform distributed load, as seen in Figure.

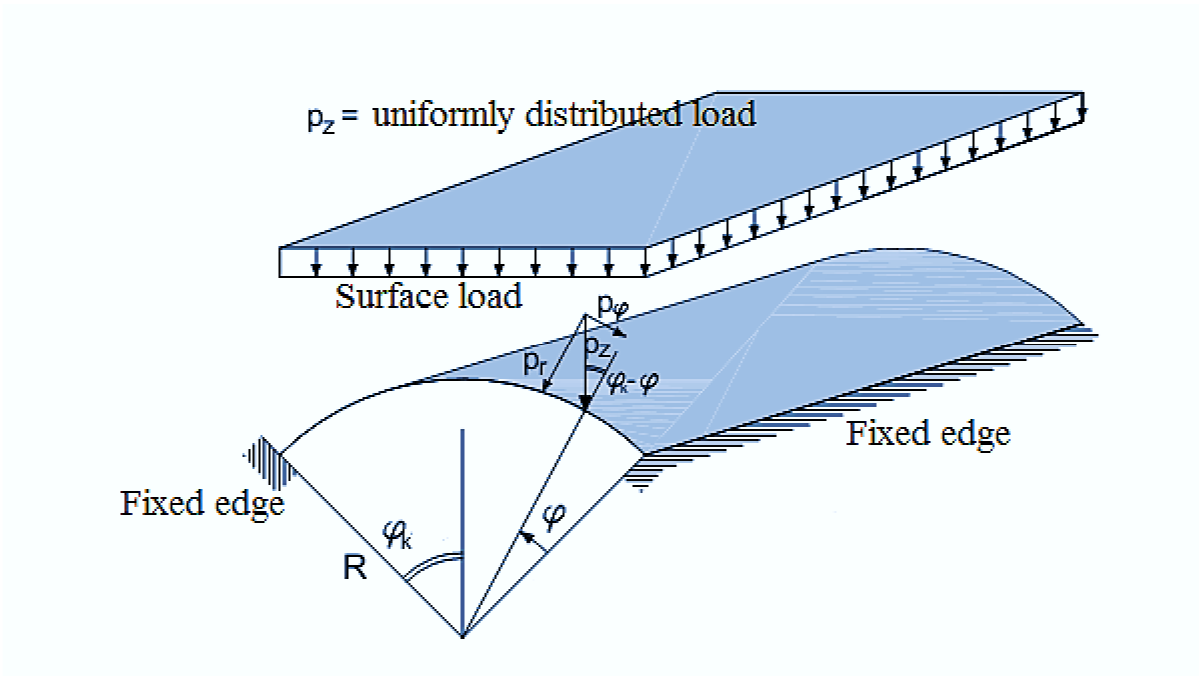

FIGURE 2.7Barrel cylindrical shell under uniformly distributed load [4]

The boundaries of the shell along its length are considered as fixed support in the analysis. Stress functions will depend only on one variable, namelyϕ leading to the following differential equations system:

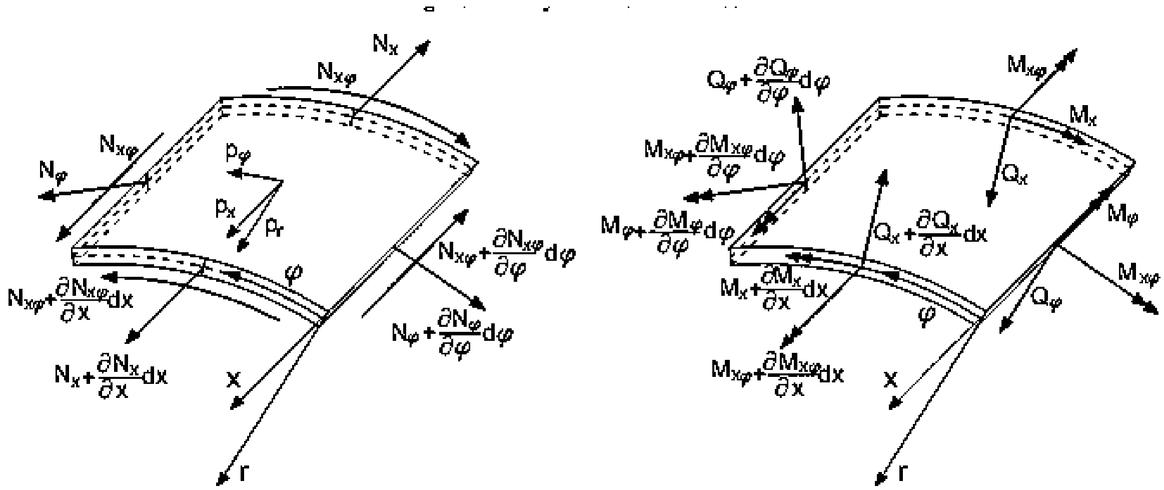

FIGURE 2.8Membrane Stresses, Moment and Shear Forces Acting on Infinitesimal Element of Shell. [4]

2.8.6.1 THIN CYLINDERICAL SHELL DESIGN

Let us consider a cylindrical coordinate system (x,ϕ,r) and a cylindrical shell with thickness.Thincylindrical shell structure subjected to uniform loading responds by equilibrium equation. A stress element with its faces parallel to the axis of the cylinderis shown on the wall of the shell. The normal stresses σ_1 and σ_2 acting on the side faces of the element. No shear stresses act on these faces because of symmetry of the vessel and its loading. Therefore, the stresses σ_1 and σ_2 are principal stresses. Because of their directions, the stress σ_1 is called the circumfrancial stress or the hoop stress, and the stress σ_2 is called the longitudinal stress or axial stress. Each of these the stresses can be calculated from static equilibrium equations.[15]

Several assumptions have been made to derive the following equations for circumfrancial and longitudinal stresses:

1. Plane sections remain plane
2. $\frac{r}{t} \leq 10$ with t being uniform and constant
3. Material is linear-elastic, isotropic and homogenous
4. Stress distributions throughout the wall thickness will not vary
5. Weight of the fluid is considered negligible[15]

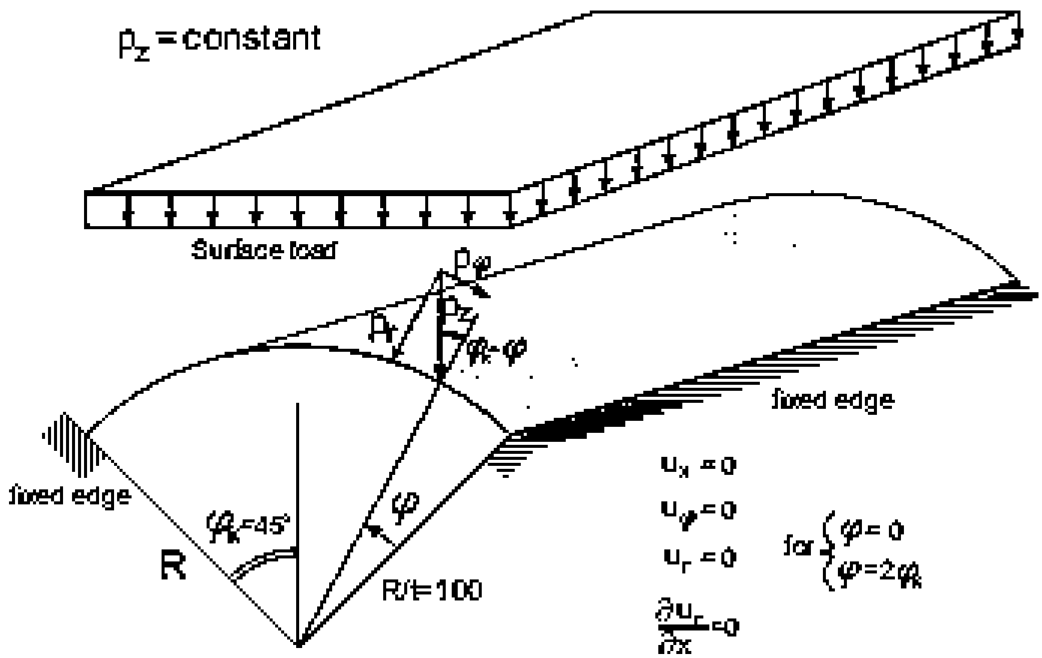

FIGURE 2.9Shell under Uniformly Distributed Load [1]

$$\sigma_{hoop} = \frac{(-P * R)}{2 * t} \quad \text{...Eq.2.8.6.7}$$

$$\sigma_{radial} = \frac{-p}{2} \quad \text{...Eq.2.8.6.8}$$

But while deriving the longitudinal stress the shell is considered to be closed at both sides.

$$\sigma_{axial} = \frac{-p * d}{4 * t} \quad \text{...Eq.2.8.6.9}$$

Strain of the shell can be calculated as:

Hoop strain:

$$\varepsilon_h = \frac{1}{E}\left[\sigma_h - \nu\sigma_r - \nu\sigma_t\right]$$ ……………………………………………………………......Eq. 2.8.6.10

Longitudinal strain:

$$\varepsilon_t = \frac{1}{E}\left[\sigma_t - \nu\sigma_r - \nu\sigma_h\right]$$ ……………………………………………………….......Eq. 2.8.6.11

Radial strain:

$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \nu\sigma_h - \nu\sigma_t\right]$$ ……………………………………………………………Eq.2.8.6.12

Change in diameter can be calculated from the strain on diametral, i.e. the diameter diametral strain.

$$Diametral\ strain = \frac{change\ in\ diameter}{original\ diameter}$$ ……………………………………………..Eq.2.8.6.13

Now the change in diameter may be found from a consideration of the circumferential change. The stress acting around a circumference is hoop or circumferential stress σ_H giving rise to the circumferential strain $\varepsilon_{H.}$ [15]

$$New\ circumference = \Pi * d + \Pi * d * \varepsilon_H$$ …………………………………………....Eq.2.8.6.14

$$= \Pi d * (1 + \varepsilon_H)$$

But this is circumference of a circle of diameter d(1+ε_H)

$$New\ diameter = d * (1 + \varepsilon_H)$$

$$change\ in\ diameter \quad = d * \varepsilon_H$$

$$Diameteral\ strain\ \varepsilon_D = \frac{d\varepsilon_H}{d} = \varepsilon_H \text{……………………………………Eq.2.8.6.15}$$

i.e the diametrical strain equals the hoop or circumferential strain

$$change\ in\ diameter = d\varepsilon_H = \frac{d}{E}[\sigma_H - \nu\sigma_{L:}] \\ = \frac{pd^2}{4tE}\left[2-\nu\right] \text{…………………………………………Eq.2.8.6.16}$$

Deflection in the radial direction:

$$\delta = \frac{F \times L^3}{384 \times E \times I} \text{……………………………………………………………………E.q.2.8.6.17}$$

Assuming the cylindrical shell to be fixed at both ends of the longitudinal direction. The above equation can be used to find the maximum deflection.

2.8.6.2 THICK CYLINDERICAL SHELL DESIGN

The theoretical treatment of thin cylindrical shells assumes that hoop stress is constant across the thickness of the shell wall and also that there is no pressure gradient across the thickness of shell wall and also that there is no pressure gradient across the wall. The Lame theory for determination of the stress in the walls of thick cylindrical shells considers a mutually perpendicular, triaxial, principal-stress system consisting of the radial hoop or tangential, and longitudinal stresses acting at any element in the wall. For the case of the shell depicted in figure 2.14, subjected to internal pressure only, radial stress $\sigma_{r,}$ and hoop stress σ_h are given by[17]

$$\sigma_r = \frac{pr_i^2}{\left(r_o^2 - r_i^2\right)}\left(\frac{\left(r^2 - r_o^2\right)}{r^2}\right) \text{…………………………………………………………......Eq. 2.8.6.19}$$

$$\sigma_r = \frac{pr_i^2}{\left(r_o^2 - r_i^2\right)}\left(\frac{\left(r^2 + r_o^2\right)}{r^2}\right) \qquad \text{Eq. 2.8.6.20}$$

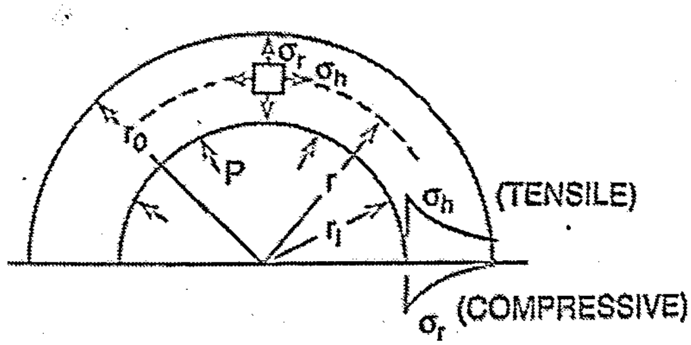

FIGURE 2.10 Thick Cylindrical Shell Subjected to Internal Pressure [17]

Where r_i and r_o is inside and outside radii of the shell, respectively, and r is any radius such that $r_i<r<r_o$. [17]

In order to get an expression for the longitudinal stress σ_t, the shell is considered closed at both ends, as shown in figure 2.15.Simple consideration of the force equilibrium in longitudinal direction yields [17]

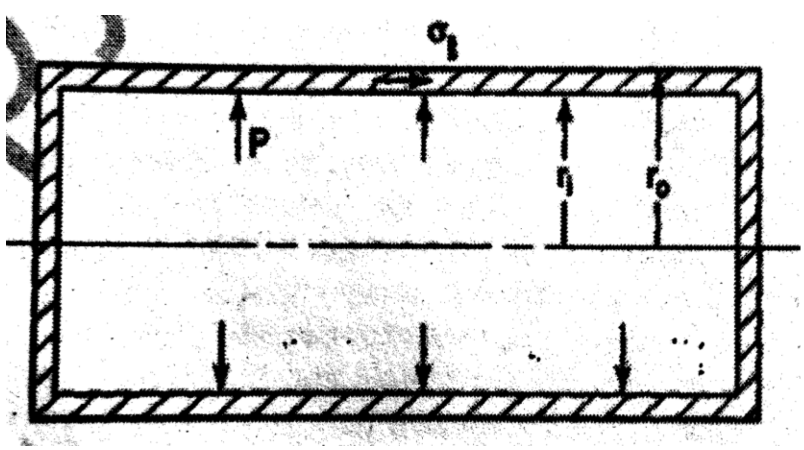

FIGURE 2.11Thick Cylindrical Shell Closed at Both Ends and Subjected to Internal Pressure [17]

$$\sigma_t = \frac{pr_i^2}{r_o^2 - r_i^2} \quad \text{Eq. 2.8.6.21}$$

The changes in the dimensions of the cylindrical shell can be determined by the following strain formulas:

Hoop strain:

$$\varepsilon_h = \frac{1}{E}\left[\sigma_h - \nu\sigma_r - \nu\sigma_t\right] \quad \text{Eq. 2.8.6.22}$$

Longitudinal strain:

$$\varepsilon_t = \frac{1}{E}\left[\sigma_t - \nu\sigma_r - \nu\sigma_h\right] \quad \text{Eq. 2.8.6.23}$$

Radial strain:

$$\varepsilon_r = \frac{1}{E}\left[\sigma_r - \nu\sigma_h - \nu\sigma_t\right] \quad \text{Eq. 2.8.6.24}$$

It can be shown easily that diametral stress and the circumferential or hoop stress are equal. It is seen that the inside diameter-to-thickness ratio d_i/t is an important parameter in the stress formulas. For d_i/t valuesgreater than 15, the error involved in using the thin-shell theory is within 5 percent. If, however, the mean diameter d_m is used for calculation of thin-shell values instead of inside diameter, the error reduces from 5 percent to approximately 0.25 percent at d_m/t=15.0.[17]

When the cylindrical shell is subjected to both the external pressure p_o and the internal pressure p_i, p is the pressure on the the radial and hoop stresses can be expressed by

$$\sigma_r = \frac{r_i^2 p_i - r_o^2 p_o + r_i^2 r_o^2 (p_o - p_i)/r^2}{r_0^2 - r_i^2} \quad \text{Eq. 2.8.6.25}$$

$$\sigma_h = \frac{r_i^2 p_i - r_o^2 p_o - r_i^2 r_o^2 (p_o - p_i)/r^2}{r_0^2 - r_i^2} \quad \text{Eq. 2.8.6.26}$$

It is observed from the preceding equations that the maximum value of σ_h occurs at the inner surface. The maximum radial stress σ_r is equal to the larger of the two pressure P_i and P_o. These equations are known as the Lamé solution. The sum of the two stress remains constant, which indicates that the deformation of all element in the axial direction is the same, and the cross sections of the cylinder remain plane after deformation. [17]

The maximum shearing stress at any point in the wall of cylinder is equal to one-half the algebraic difference between the maximum and minimum principal stress at that point. The axial or longitudinal stress is usually small compared with the radial and tangential stresses. The shear stress τ at any radial location in the wall is given by[17]

$$\tau = \frac{\sigma_h - \sigma_r}{2} \quad \text{Eq. 2.8.6.27}$$

$$\tau = \frac{(p_i - p_o) r_i^2 r_o^2}{(r_o^2 - r_i^2) r^2} \quad \text{Eq. 2.8.6.28}$$

Deflection in the radial direction can be calculated as:

$$U_r = \frac{-P_0 r_0^2 r}{E(r_o^2 - r_i^2)} \left[(1-\nu) + (1+\nu)\frac{r_i^2}{r^2} \right] \quad \text{Eq. 2.8.6.29}$$

CHAPTER 3DESIGN OF THE STRUCTURE USING ANALYTICAL METHOD

3.1 INTRODUCTION

In this section, structural design of underwater cylindrical shell structure is done. There are five methods of design for thin cylindrical shell design. They are thoroughly explained in chapter two. But combination of bending analysis and membrane analysis is chosen for the design. Because combination of this two analysis gives a result that describes the reaction of the cylindrical shell.

There are multiple of software’s that can be used to calculate the analysis. Microsoft excel is one of those software’s. When using this software by substituting the equations and trying to find a stable structure it is tedious as well as takes time. This software is not effective for this purpose. Writing a program using C++ language was tried. While doing this it was important to choose what kind of program was needed. Structural design by is designing the structure to its stable dimension and material type depending on the purpose of the structure.so this softer should do just that for the design.

The design considers minimum volume per usable area of the structure. This is considered because the structure is needed for qua zoo. And much as possible the usable area should be maximum. The volume should be minimum because the cost will increase as the volume increases. The design considers this function and compares some combination of dimensions. The stability is checked based on ultimate limit state design and serviceability limit state design.The initial design concept is based on a cylindrical shell with edge beams described by Billington. The design model is presented for two different modeling.

3.2 MODELING

The underwater cylindrical shell has edge beam. Furthermore, an ideal load bearing wall is added at the end of the cylindrical shell so that the water won't flood the space inside the shell.

Fiber glass is used as a construction material and the material is fabricated as per the design results. The thickness is limited between 4cm and 8cm which is recommended by Typification of the German Democratic Republic at Berlin. This new material offers possibilities for the design of efficient shell structures that can be installed easily, which will be confirmed by production companies. There are different kinds of fiber glass so the design is done for different type of fiber glass and different dimension. The length of the fiber glass is limited from 20meters to 40 meters. The radius is limited from 4meters to 9meters. The last two dimensions are limited as per the judgment of the designer. So for each type of fiber glass there will be a search for stable structure.

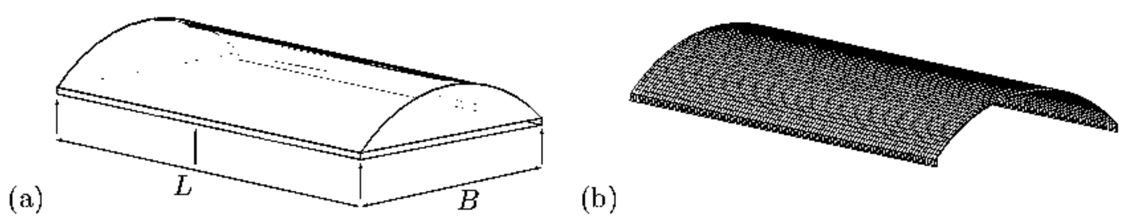

FIGURE 3.1Underwater Cylindrical Shell: (A) Design Model and (B) Analysis Model [2]

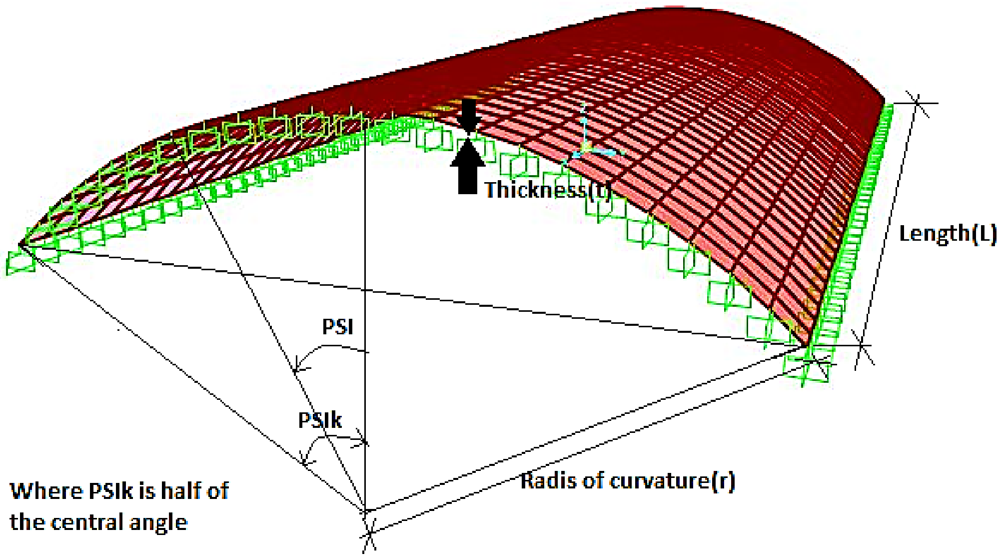

Figure 3.2 Design Variables.

Five parameterizations of the underwater cylindrical shell are presented. The comparison of the design results for each alternative will clearly demonstrate the importance of the parameterization. In figure 3.2, the design variables are indicated on the structure. In the first parameterization, is the first type of fiber glass is presented. The next parameterization the value of the next stronger fiber glass is presented.The type of fiber glass is chosen based on the stability of the structure. The shell thicknesst is assumed to be constant over the shell surface.

CONSTRAINTS

In summary the constraints are

1. DESIGN CONSTRAINTS

$$Design\ constra\mathrm{int}\begin{cases} -\sigma_{compressive} \le \sigma^{\min}(x) \le \sigma^{\max}(x) \le \sigma_{tensile}. \\ u_h^{\max} \le H_t / 200 \\ u_v^{\max} \le B/300 \end{cases}$$

The horizontal deflection is limited to $u_h^{\max} \le H_t / 200$ and the vertical deflection is limited to $u_v^{\max} \le B / 300$. [14]

The behavior constraints are related to stresses and displacements. For the ultimate limit state (ULS) load combinations, the maximal and minimal principal stress σ max (x) and σ Min (x) are taken from the table that is provided by East coast manufacturers. Which are the ultimate compression and tension strength $\sigma_{compressive}$ and $\sigma_{tensile}$. For the serviceability limit state (SLS) load combinations, the maximal horizontal displacement Uhmax is limited to a fraction of the total height $H_t/200=(R-R\cos\Psi_k)/200$ m, the maximal vertical displacement Uvmax is limited to a fraction of the total height $B/300=2*R\sin\Psi_k$ m/200.

2. SIDE CONSTRAINTS

A. For thin cylindrical shell
   1. The length(L) ranges from 20m to 40m
   2. The radius(R) ranges from 12m to 17m
   3. The thickness(t) is in the interval of 0.04m to 0.266m
   4. Angle of curvature(Ψ_k) is between45^0 to 90^0
   5. Height of the shell above the ground(H_t) is 3.52m to 17m

B. For thick cylindrical shell
   1. The length(L) is ranges from 20m to 40m
   2. The radius(R) is free from 19m to 24m
   3. The thickness (t) is in the interval of0.38m to 0.424m.
   4. Angle of curvature(Ψ_k) is between30^0 to 45^0
   5. Height of the shell above the ground(H) is 2.545m to 7.029m

MATERIAL PROPERTY

1. Polyester and Woven Rovings Laminate 45% E-glass

   Tensile stress allowable is 250Mpa

   Compressive stress allowable is 150Mpa

Modulus of elasticity is 2.48Gpa

2. Polyester and Satin Weave Cloth Laminate 55% E-glass

   Tensile stress allowable is 300Mpa

   Compressive stress allowable is 250Mpa

   Modulus of elasticity is 2.968Gpa

3. Polyester and Continuous Rovings Laminate 70% E-glass

   Tensile stress allowable is 800Mpa

   Compressive stress allowable is 350Mpa

   Modulus of elasticity is 7.846Gpa

4. E-glass

   Tensile stress allowable is 3455 Mpa

   Compressive stress allowable is 1080Mpa

   Modulus of elasticity 2.58Gpa

5. S-2 glass

   Tensile stress allowable is 4890 Mpa

   Compressive stress allowable is 1600 Mpa

   Modulus of elasticity 2.46Gpa

LOADING

Depends on the material property and the geometry of the structure it changes according to this data’s.

Load combination for ultimate limit state design

PL=1.35DL+1.5LL(Eurocode basis of structural design sec 6.4.3.2 Equation 6.9a)

Load combination for serviceable limit state design

PL=DL+LL (Eurocode basis of structural design sec 6.4 Equation 6.14)

Dead load=self-weight +water load

$$=\gamma \times t + \gamma_w \times h_0 + \gamma_w * \left(r - r * \cos(\varphi)\right);$$

- γ is the specific gravity of the fiber glass
- t is the thickness of shell
- γ_w is the specific gravity of water
- h_o the height of the water above the cylindrical shell which is 2meters.
- r is radius of curvature
- φ is design variable that changes from zero to φ_k

Live load =220KN as recommended on American committee institution code(ASCE 7-05 Table4-1) to use the load asking experts on the field the value load of largest shark is 220KN when distributed on the whole area.

ADJUSTMENT REGARDING VOLUME PER USABLE AREA

The purpose of the structure is for aqua zoo. The structure needs to be serviceable. But the cost must be as minimum as possible. If the function is only volume then when the volume is zero or minimum is when it is efficient but this can’t be used. If only usable area is used then this will result in infinite answer. So there is a need for deriving a formula which will take in to consideration both the functions.

If minimizing volume per usable area is used. This function will be minimum when the volume is as minimum and the usable area is maximum. Which means that the structure will be modified to achieve maximum efficiency by adjusting the ratio of volume per usable area to be minimum.

Volume of the cylindrical shell can be calculated as:

$$Volume = \varphi \times R \times t \times L$$

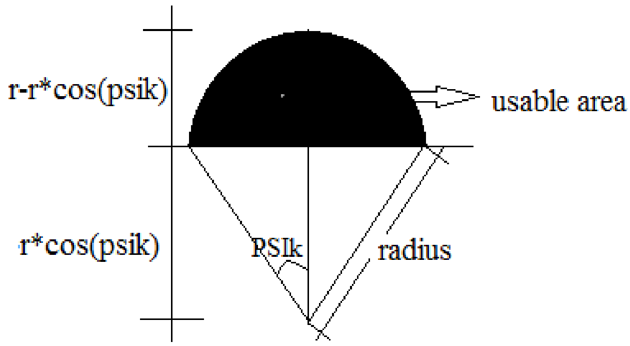

Figure 3.3 Dimension and usable area

$$usable\ Area = Area\ of\ \sec tor - Area\ of\ triangle \quad \text{.................................Eq.3.2.1}$$

$$= \frac{r^2 \times 2 \times \varphi_k}{2} - \frac{r\cos\varphi_k \times 2 \times r\sin\varphi_k}{2}$$

$$= r^2 \times \varphi_k - r^2 \times \cos\varphi_k \times \sin\varphi_k$$

Therefore volume per usable area can be calculated as:

$$\frac{V(\varphi_k, R, L, t)}{usable\ A(\varphi_k, R)} = \left[\frac{\varphi_k \times r \times t \times L}{((r^2 \times \varphi_k) - (r^2 \times \cos(\varphi_k) \times \sin(\varphi_k)))}\right] \text{.....................................Eq.3.2.2}$$

3.3 PROGRAM DEVELOPMENT FOR ANALYTICAL DESIGN OF UNDERWATER CYLINDRICAL SHELL STRUCTURE

3.3.1 FLOW CHART OF THE PROGRAM

The flow chart is a simple way to analyze and describe the program used for the optimization process.

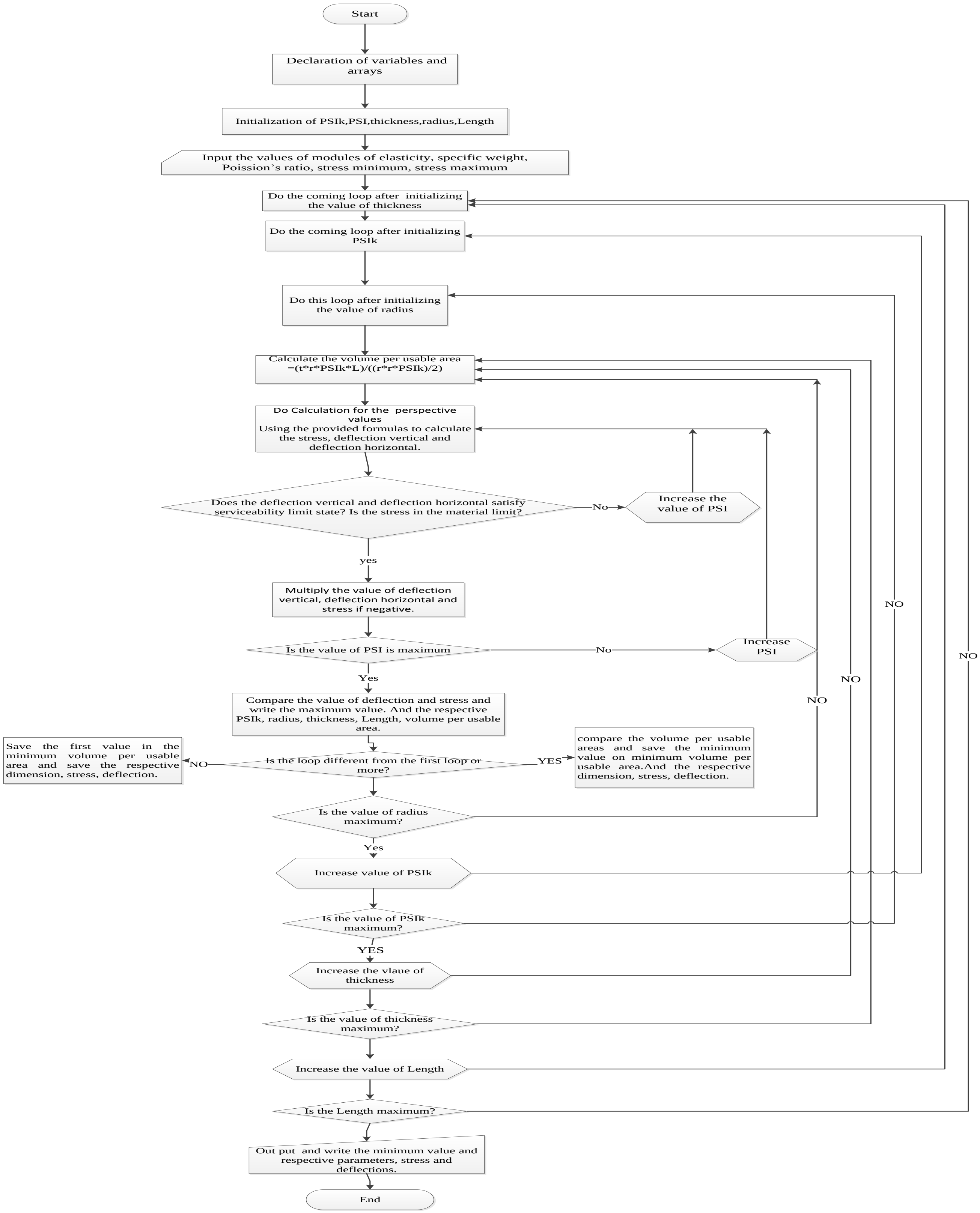

FIGURE 3.4 flow chart of the analytical method of design

3.3.2 DESIGNUSING C++ PROGRAM

There are different method of analysis which is used to find the stress and deflection of cylindrical shell structure. This methods are load balancing method, Beam theory, arch analysis, membrane theory and bending theory. From this methods both membrane analysis and bending analysis are combined together to find accurate result of the actual behavior of the thin cylindrical shell structure. The detail program is attached APPENDIX I.

3.3.2.1 EXAMPLE HOW THE PROGRAM WORKS.

TRIAL ONE

STEP 1: *Taking the assumption of dimension from the lower bound of thin cylindrical shell*

Length=20meters

Radius=12meters

Thickness=0.04meters

Half of the central angle (φ_k) $=45^0=0.7854$rad

Height of the cylinder from the ground level to the selling 3.52 meters

STEP 2: *Material property*

Polyester and Woven Rovings Laminate 45% E-glass

Tensile stress allowable is 250Mpa

Compressive stress allowable is 150Mpa

Modulus of elasticity is 2.48Gpa

Factored tensile stress $= \frac{250Mpa}{2.5} = 100Mpa$

Factored compressive stress $= \frac{150Mpa}{2.5} = 60Mpa$

STEP 3: *Load*

PL=1.35DL+1.5LL for ultimate limit state design

PL=DL+LL for serviceable limit state design

Dead load=self -weight +water load

$$= \gamma \times t + \gamma_w \times h_0 + \gamma_w * (r - r * \cos(\varphi))$$

$$= 15.696KN/m^3 * 0.04m + 9.81KN/m^3 * 2m + 9.81KN/m^3 * (9m - 9m * \cos(45^0))$$

=46.107KN/m^2

Live load $= \frac{2.224}{9m * 20m * 0.7854rad} = 0.01573KN/m^2$

PL=1.35*46.107KN/m^2+1.5*0.01573KN/m^2

=62.268KN/m^2

PL=46.107KN/m^2+0.01573KN/m^2

=46.123KN/m^2

STEP 4: *Analysis*

Then the change in diameter and stress of the lower bound of design variables are calculated using the following equations Eq.2.8.6.7, Eq.2.8.6.8, Eq.2.8.6.14, and Eq.2.8.6.15.

Deflection horizontal Direction(m)	**Deflection radius direction(m)**	**Radial Stress(KN/m^2)**	**Hoop Stress(KN/m^2)**	**Volume per usable area(m)**
0.0002	0.00002	32.715	9814.38	0.183

TABLE 3.1 Result of Analysis

STEP 5: *Check for stability*

As the program starts to calculate the result taking in to consideration the design constraints the structure is stable. Because the deflection is much less than serviceability limit state design consideration. The radial stress and hoop stress are below the compressive and tensile strength of the fiber glass.

$$u_{\varphi}^{\max} \le H_t / 200 = \frac{2.636m}{200} = 0.013m > 0.0002m$$

$$u_r^{\max} \le B/300 = \frac{2*r*\sin(\varphi_k)}{300} = \frac{2*9*\sin(45^0)}{300} = 0.042m > 0.00002m$$

Allowable Compressive stress=-60000KN/m^2

Allowable Tensile stress=100000KN/m^2 from Eq.2.8.6.7and Eq.2.8.6.8 shows both the hoop and radial stress are compressive stress. Therefore greatest of the radial stress and hoop stress is hoop stress.

$$\sigma_{compressivehoop} = 9814.38KN/m^2 < 60{,}000KN/m^2 = \sigma_{compressivestress}$$

This just the first trial but the global efficient result using the function derived above can be calculated as follows:

3.3.2.2 INPUT OF THE PROGRAM

The input of the program can be written on a note pad created in a folder named file. The note pad should consist first modulus of elasticity after a space Poisson's ratio space factored compressive strength space factored tensile strength of the material.Where the factor of safety suggested by the Manuel for fiber glass is for flexural member is 2.5.

	Polyester and Woven Rovings Laminate 45% E-glass (fiberglass 1)	Polyester and Satin Weave Cloth Laminate 55% E-glass (fiberglass2)	Polyester and Continuous Rovings Laminate 70% E-glass (fiberglass3)	E-glass (fiberglass 4)	S-2 glass (fiberglass 5)
Modules of elasticity (E) (KN/m^2)	$2.48*10^6$	$2.968*10^6$	$7.846*10^6$	$76*10^6$	$97*10^6$
Gamma(Y)(KN/m^3)	15.696	16.677	18.639	25.506	24.426
Poisson's ratio	0.3	0.3	0.3	0.3	0.3
factored compressive strength(KN/m^2)	$-6*10^4$	$-1*10^5$	$-1.4*10^5$	$-4.32*10^5$	$-6.4*10^5$
Factored tensile strength(KN/m^2)	$1*10^5$	$1.2*10^5$	$3.2*10^5$	$1.378*10^6$	$1.956*10^6$

TABLE 3.2Input Values forthe Program

3.3.2.3 PROCESS OF THEPROGRAM

The program takes the input values as described in the flow chart the program has different loops which will find the best result. The program uses Brute force method to do this. Brute force method is trying every combinations of values and choosing the best suited answer for that function. The loops take in to consideration the design variables, the design constraints and volume per usable area. The following table shows the arrangement of the input file. The program starts by reading this.

Material type	*Modulus of*	*Specific*	*Poisson's*	*Factored*	*Factored tensile*

	elasticity	*weight*	*ratio*	*compressive strength*	*strength*
fiberglass 1	$2.48*10^6$	15.696	0.3	-60000	100000
fiberglass 2	$2.968*10^6$	16.677	0.3	-100000	120000
fiberglass 3	$7.846*10^6$	18.639	0.3	-140000	320000
fiberglass 4	$7.6*10^7$	25.506	0.3	-432000	1378000
fiberglass 5	$9.7*10^7$	24.426	0.3	-640000	1956000

Table 3.3 Input Data for different types of fiber glass

The program all in all works by changing different design variable and choosing one value between intervals with lower volume per usable area. Volume per usable area is a function embedded in the program. The program will take the input value and after running different iteration the final result will be written on a black page and after stroking any key on the keyboard the result will be saved on a different note pad in the same folder the C++ program is saved. If the program uses the first type of fiber glass then the output file name will be fiberglass1.

The first program used for the analysis is the program written for thin shell structure. As mentioned above the particular constraints for thin shell design is included in the program.

3.3.2.4 OUTPUT OF THE PROGRAM

To find the final result for the design of the shell different dimensions and their respective structural responses should be checked. The dimension with minimal volume perusable area will be chosen form the first iteration.

The output of the program for different combination using the boundaries as:

1. The length(L) ranges from 20m to 21m interval of iteration 0.1m
2. The radius(R) ranges from 12m to 13m interval of iteration 0.1m
3. The thickness(t) is in the interval of 0.04m to 0.05m interval of iteration 0.001
4. Angle of curvature(Ψ_k) is between0.7854radian to 0.955radian interval of iteration 0.017radians

Based on the function volume perusable area the best result in these interval is:

Length(m)	Thickness(m)	PSIk(rad)	Radius (m)
20	0.04	0.935	17

Table 3.4 Dimension of the Output of the Program

Material type	Deflection psi-direction(m)	Deflection radius direction(m)	Radial Stress(KN/m^2)	Hoop stress(KN/m^2)	Volume per usable area(m)
fiberglass 1	0.0002	0.00002	51.489	21882.9	0.095
fiberglass 2	0.0002	0.000016	51.516	21894.2	0.095
fiberglass 3	0.00007	0.000006	51.5686	21916.7	0.095
fiberglass 4	0.000008	0.0000006	51.754	21995.5	0.095
fiberglass 5	0.000006	0.00000006	51.725	21983.1	0.095

Table 3.5 Output Result for Different Type of Fiber Glass

Best result of the analysis is fiberglass 5 but the cost of this fiber glass is 20dollar per kilogram. The next best result is fiberglass 4 which costs 2 dollar per kilogram. Therefore fiberglass 4 is the best design result.

If the designer didn’t find a stable structure it can be revised. And changing the design of the thin shell in to thick shell by changing the design variables. The first thing that was takenin to consideration is the ratio of thickness to radius of the cylindrical shell. Look Eq.1.2 and Eq.1.3.As described in the equations the ratio of thickness to radiusshould be increased. To do this the thickness of the shell should be increased.The program for thick cylindrical shell structure is attached APENDEX II.

CHAPTER 4ANALYSIS OF THE STRUCTURE USING FINITE ELEMENT ANALYSIS

4.1 INTRODUCTION

Structural analysis program is one of finite element analysis software. This software is used for different structural design and analysis. Structural analysis program is like any other software. The output values depend on the input values. The input values are the final result of the analytical design.

4.2 ANALYSIS PROCEDURE

1) Type of structure designed is thick shell
2) The design variables are:resulting dimension on table 3.3
3) Support condition

   The support condition on the length direction is gone be fixed at both sides.
4) Defining material type

   All the properties of E-glass is used except the weight per volume is zero. Because factored combination of both live load and dead load are gone be used.so self-weight will not be considered twice. The factored compressive stress and factored tensile stress are defined using non-linear analysis. The structure is elastic so both the compressive strain and tensile strain can be calculated using modulus of elasticity and respective stresses.
5) Defining section property

   The section is defined as thick shell and both the membrane and bending thickness are the same thickness which is the whole thickness of the shell.
6) Define load type

   Dead load factored by 1
7) Define load combination

The factor for the dead load is 1 because the load is already factored. The load applied as uniform shell load in the gravity direction.

8) Loading

Since the load varies for different values of PSI the average load of the edges of the row of shell elements are taken. Loading table is found APPENDIX III.

4.3 ANALYSIS RESULT

The analysis result for

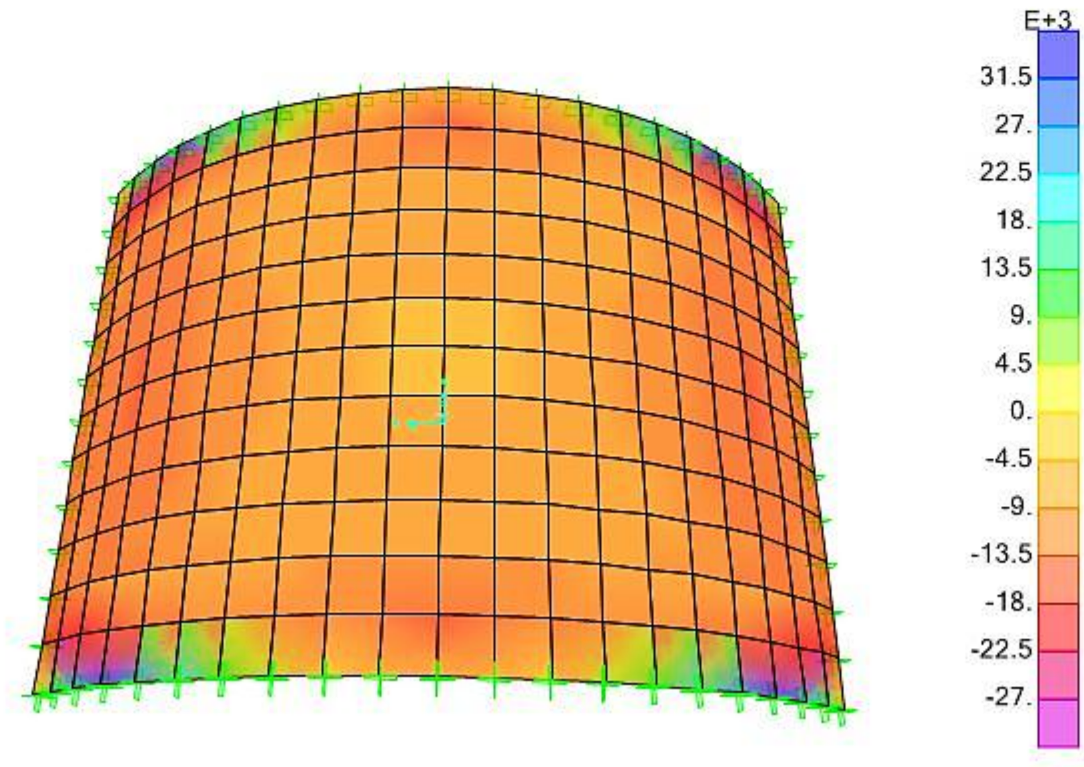

FIGURE 4.1 Maximum Stress (KN/m^2)

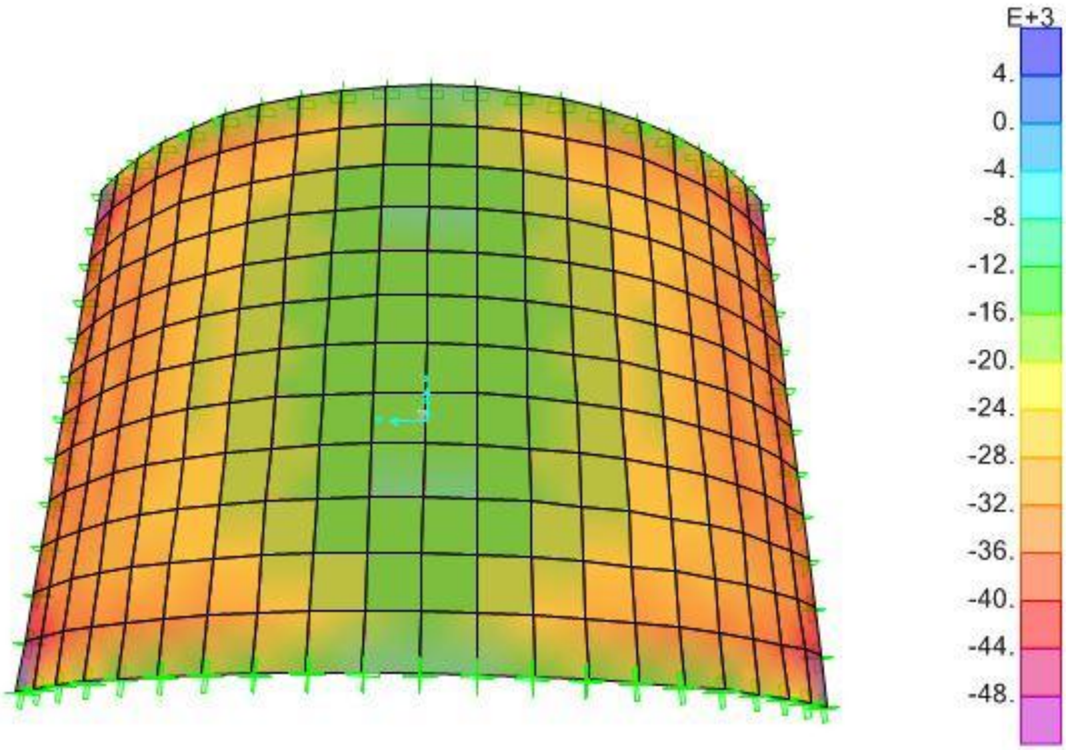

FIGURE 4.2 Minimum Stress (KN/m^2)

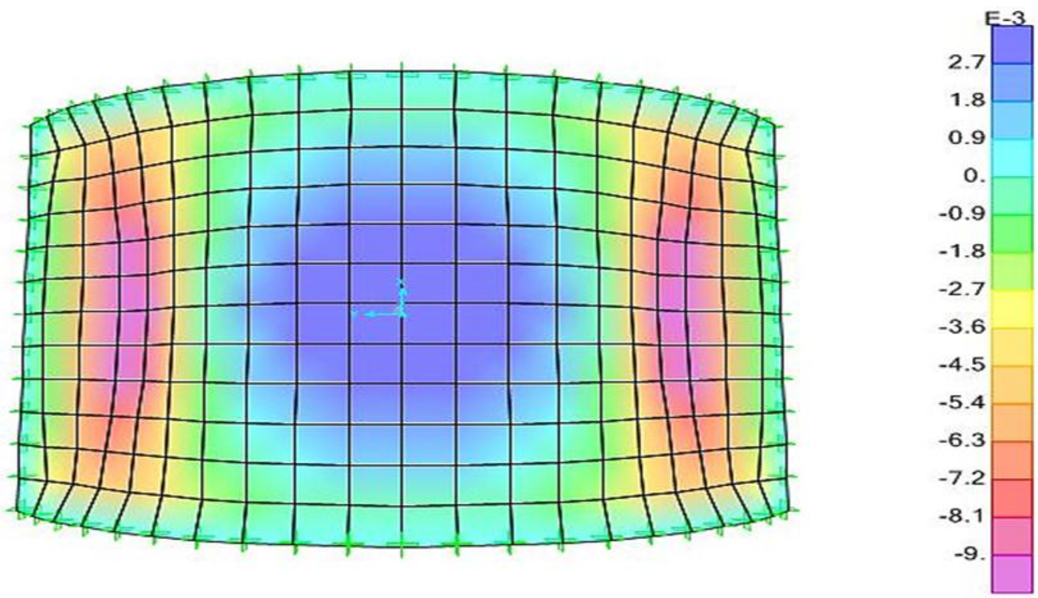

FIGURE 4.3 Deflection in the Z-Direction (m)

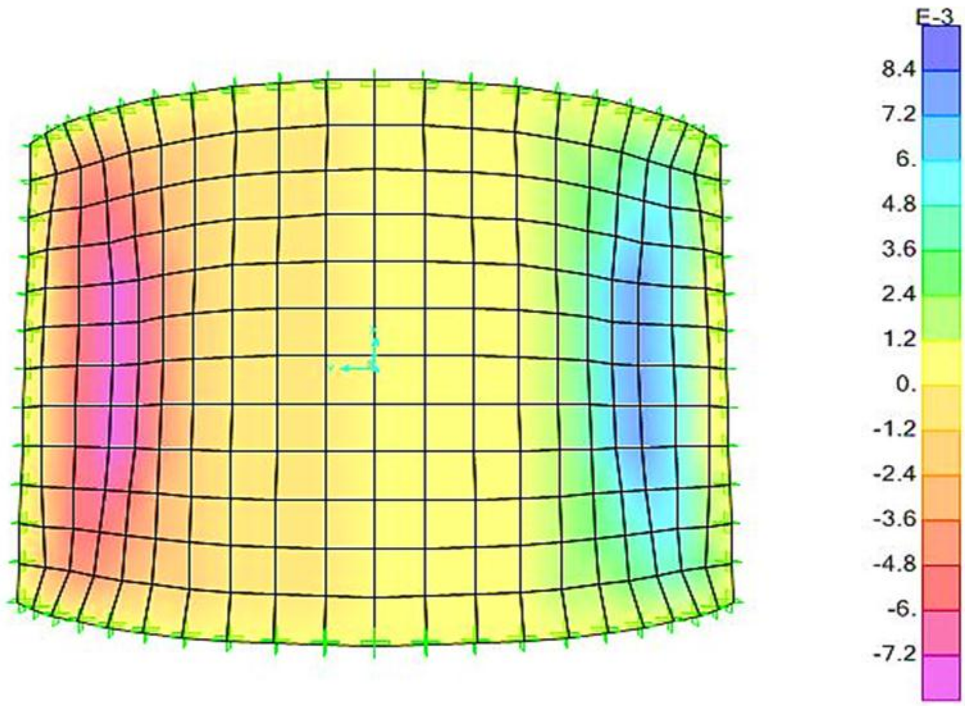

FIGURE 4.4 Deflection in the Y-Direction

Maximum values	Finite element analysis result	Maximum allowable deflection and stress
Maximum deflection y-direction(mm)	**8.4**	**13**
Maximum deflection z-direction(mm)	**-9**	**42**
Maximum compressive stress(KN/m^2)	**-47,966.364**	**-60,000**
Maximum tensile stress(KN/m^2)	**28,911.23**	**100,000**

Table 4.1 Maximum Values of the Finite Element Analysis

CHAPTER 5 COMPARISON OF ANALYTICAL DESIGN AND FINITE ELEMENT ANALYSIS

5.1 INTRODUCTION

Both analytical method of design using different theories of design and finite element analysis using structural analysis program can be used in design and analysis. The particular dimension and the material type is taken form the analytical design result. Second the loading is approximated by using average method. For each strip in the X axis average of the highest and the lowest of the segment is taken. The support condition is the same for both the analytical design and the finite element analysis

5.2 COMPARISON

Maximum values	Analytical results	Finite element analysis results
Maximum deflection y-direction(mm)	0.008	8.4
Maximum deflection z-direction(mm)	0.0002	-9
Maximum compressive stress(KN/m^2)	-21,995.5	-47,966.364
Maximum tensile stress(KN/m^2)	-	28,911.23

TABLE 5.1 Comparison of the Result of Finite Element Analysis and Analytical Design

5.3 RESULT AND DISCUSSION

The values of the structural analysis program and the numerical formula were not the same because there were different assumptions when deriving the formulas. When deriving longitudinal stress the cylindrical shell is considered as closed at both ends. Which brings the difference in the horizontal displacement. In case of vertical deflection the equation used assumed the shell as a beam with both ends fixed in the longitudinal direction. The more accurate result of deflection response is the result of the finite element analysis method.

Both hoop stress and radial stress are negative values which means compressive stress. Since the structure is under uniform load in the gravity direction the equation used shows only the compressive stress of the shell. Compressive stress comparison the analytical result is almost half of the finite element analysis result. But while designing the finite element analysis the loading was taken average as shown in APPENDIX III. Due to this different assumptions the results differ.

It is recommended to take the finite element analysis result because it takes in to consideration the behavior of the structure both in the hoop direction and in the longitudinal direction.

Even though the result of the finite element analysis method is greater than the analytical result, both the ultimate limit state and serviceability limit state stability criteria are satisfied. The structure is stable.

CHAPTER 6CONCLUSION AND RECOMMENDATION

6.1CONCLUSION

The analysis and the steps taken to get the stable design of underwater cylindrical shell structure can be summarized as follows. The first step is to choose the type of cylindrical shell structure needed for the specific purpose. The first choice for design was thin cylindrical shell structure. The reason for this is because its cost is less than thick shell.

Using this information formulating the analytical formula for the design of this shell structure is searched and simplified for use. Since there are many combinationsMicrosoft Excel for manual calculation takes longer time.so a program was developed to design by taking different intervals between the constraints. Even though developing a program which is able to calculate the values of the functions was great. It was also complex and took a lot of time to consider different combination in between the constraints. The program failed repeatedly one because of the complexity of the formula, second because of the arrangement of the loops. After extensive formulation and thinking how the program can be developed the program started working. Although, the program started working there was no result for many trials. Which was tedious and repetitive.

In order to get an expression for longitudinal stress the shell is considered closed at both ends. Since this is assumed in the formula for the longitudinal stress the value of the deflection in the horizontal direction is not exact. While deflection in the radial direction is not the same because the shell was assumed as a hollow beam fixed in both direction. Even though determination of the response of the structure is different, the results shows that the structure is stable.

While trying to find the dimension of the structure efficient for aquarium the results showed the behavior of cylindrical shell structure. Which is whenvolume per usable area decreases, the internal stress increases, the cost decreases and deflection increases.

6.2 RECOMMENDATION

Every research needs further study and recommendation on how to do that for this paper is:

- To develop a more easier C^{++} program
- To do chart for design of different volume per usable area and their stresses, deflection graph. For different range of dimensions.
- To prepare charts even for both thin and thick shell
- To study further more advanced materials in designing this kind of underwater structure
- To design the structure using structural analysis program with a more exact model

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Appendix I: program code for thin shell

```
#include <iostream>

#include <cstdlib>

#include <math.h>

#include <conio.h>

#include <fstream>

using namespace std;

void loadFromFile(double& E,double& gamma,double& poisson,double& compressivestrength,
double& tensilestrength);




int main() {

//Initialization of i which helps in keeping the out put in array,radius PSIk,thickness,Length

//declaring variables

      int i = 0,k=0,m=0;

    double r = 12, PSIk = 0.7854 , t =0.04 , L=20 ;

    double
p,E,gamma,poisson,compressivestrength,tensilestrength,ro,ri,PSI,volumeperusablearea,Uvmax,U
hmax,Nhmaxfinalr,Nhmaxfinalt,Lminm,tminm,PSIKminm,rminm,UVminm,Uhminm,Nhminmr,
Nhminmt,Volumeperusableareaminm;




     double Uv[12];

     double Uh[12];

     double Nhr[12];
```

```
double Nht[12];

double Nhl[12];

double er[12];




//Taking the value of modules of elasticity(E),poisson's ratio,stress maximum and stress minimum of the material

loadFromFile(E,gamma,poisson,compressivestrength,tensilestrength);

ofstream write("optimization result of fiberglass 1out.txt",ios::out);



// the outer loop is the Loop where the length increases since when the loop inters the outer loop and increase the Length

//the thickness has reached maximum so it should be initialized

cout <<"\t" <<"No"<< "\t" <<"Length"<< "     "<<"Thickness"<< "     "<<"PSIk"<< "     "<<"Radius" <<"          "<<"Uvmax"<<"          "<<"Uhmax"<<"     "<<"Nhmaxr"<<"     "<<"Nhmaxt"<<"     "<<"Volumeper usable area" <<endl;

write <<"\t" <<"No"<< "\t" <<"Length"<< "\t\t\t"<<"Thickness"<< "\t"<<"PSIk"<< "\t\t"<<"Radius"
<<"\t\t"<<"Uvmax"<<"\t\t"<<"Uhmax"<<"\t\t"<<"Nhmaxr"<<"\t\t"<<"Nhmaxt"<<"\t\t"<<"Volu
me per usable area"<<"\t\t"<<endl;



do {



t=0.04;

//the this loop is where the thickness increases since when the loop inters this loop and increase the thickness

//the PSIk has reached maximum so it should be initialized
```

```
do {

PSIk=0.7854;
```

//the this loop is where the PSIk increases since when the loop inters this loop and increase the PSIk

//the radius has reached maximum so it should be initialized

```
do {

r=12;
```

//if the loop didn't have a result the output no length,thickness,PSIk,radius Uhmax,Uvmax,Nhmax

```
do {

//assignment operation for volume per usable area

volumeperusablearea= (t*r*PSIk*L)/(((r*r*PSIk))-(r*r*sin(PSIk)*cos(PSIk)));
```

//This loop initializes PSI and increases it from zero to twice PSIk to know the value stress and deflection in each interval and take the maximum.

```
PSI=0,k=0,Uhmax=0,Uvmax=0,Nhmaxfinalr=0,Nhmaxfinalt=0;

do{
```

```
//assignment of operation for the variables necessary to calculate the stress and deflection where p is the combination of dead load and live load.

//Uv is vertical deflection,Nhr is radial stress,Nht is tangential stress

//use the following load combination to check if the structure is stable for ultimate limit state design criteria

//p=(1.35*(2*9.810+9.810*(r-r*cos(PSI))+gamma*t)+1.5*(2.224/(r*L*PSIk)));

//activate the following load combination while check if the structure is stable for serviceability limit state design criteria

p=(1*(2*9.810+9.810*(r-r*cos(PSI))+gamma*t)+1*(2.224/(r*L*PSIk)));

Nhr[k]=(-p/2);

Nht[k]=((-p*r)/(2*t));

Nhl[k]=((-p*r)/(4*t));

er[k]=(1/E)*(Nhr[k]-poisson*Nht[k]-poisson*Nhl[k]);

Uv[k]=((p*PSIk*(L*L*L*L))/(384*E*r*r*r*3.14*t));

Uh[k]=((4*(2*r*sin(PSIk))/(4*t*E))*((2-poisson)/2));

//checking whether the deflection and the stresses are in their maximum and minimum interval

if ( (((r*(-1+cos(PSIk))/(200))<=Uh[k]) && (Uh[k]<= (r*(1-cos(PSIk))/(200)))) && ((((-2*r*sin(PSIk))/300)<= Uv[k]) && (Uv[k]<=((2*r*sin(PSIk))/300)) ) && ((compressivestrength<=Nhr[k]) && (Nhr[k]<=tensilestrength)) && ((compressivestrength<=Nht[k]) && (Nht[k]<=tensilestrength)))

{

// if the values are negative absolute value is needed to assist the comparison.
```

```
if(Uh[k]<0)
{
  Uh[k]=Uh[k]*-1;

}

if(Uv[k]<0)
{
  Uv[k]=Uv[k]*-1;

}

if(Nhr[k]<0)
{
  Nhr[k]=Nhr[k]*-1;

}

if(Nht[k]<0)
{

  Nht[k]=Nht[k]*-1;
```

```
      }
     k++;

   }

    PSI=PSI+(PSIk)/10;
  }while(PSI<=PSIk);
```

//since Uvmax ,Nhmaxfinalr and Nhmaxfinalt has a random number before comparing anything the initial values are assigned to it and comparison starts.

```
  if(k>0)
      {
       Uhmax=Uh[0];
       Uvmax=Uv[0];
       Nhmaxfinalr=Nhr[0];
       Nhmaxfinalt=Nht[0];

      for(int l=1;l<k;l++)
          {
      if(Uhmax<Uh[l])

           {
```

```
   Uhmax=Uh[l];

  }

 if(Uvmax<Uv[l])

  {

    Uvmax=Uv[l];

  }

  if(Nhmaxfinalr<Nhr[l])

  {

    Nhmaxfinalr=Nhr[l];

  }

if(Nhmaxfinalt<Nht[l])

  {

    Nhmaxfinalt=Nht[l];
```

```
  }
}

 if (i=0)
 {
    Volumeperusableareaminm=volumeperusablearea;
           Lminm=L;
           tminm=t;
           PSIKminm=PSIk;
           rminm=r;

           Uhminm=Uhmax;
           UVminm=Uvmax;
           Nhminmr=Nhmaxfinalr;
           Nhminmt=Nhmaxfinalt;

 }

 else
   {
     if(Volumeperusableareaminm > volumeperusablearea)
        {
           Volumeperusableareaminm=volumeperusablearea;
```

```
            Lminm=L;

            tminm=t;

            PSIKminm=PSIk;

            rminm=r;


            Uhminm=Uhmax;

            UVminm=Uvmax;

            Nhminmr=Nhmaxfinalr;

            Nhminmt=Nhmaxfinalt;


          }


        }
```

// the output is saved and written in the note pad.

```
        i++;
```

// if the designer wants to see all the combination of different dimension and their respective response the following output command can be activated

```
//cout  <<"\t" << i << "\t" <<L << "       "<<t<< "       "<<PSIk<< "      "<<r <<"       "<<Uvmax<<"       "<<Uhmax<<"       "<<Nhmaxfinalr<<"       "<<Nhmaxfinalt<<"       "<<volumeperusablearea << endl;

//write  <<"\t" << i << "\t" <<L << "\t\t\t"<<t<< "\t\t\t"<<PSIk<< "\t\t\t"<<r <<"\t\t\t"<<Uvmax<<"\t\t\t"<<Uhmax<<"\t\t\t"<<Nhmaxfinalr<<"\t\t\t"<<Nhmaxfinalt<<"\t\t\t" <<volumeperusablearea << endl;
```

```
            }

              r+=0.5;

        }while(r<=17);

            PSIk+=0.017;

       }while(PSIk<=0.955);

          t+=0.004;

      }while(t<=0.08);

         L+=0.5;

   }while(L<=25);
// if the designer wants the final best result the following out put command can be used

  cout  <<"\t" << i << "\t" <<Lminm << "       "<<tminm<< "      "<<PSIKminm<< "    "<<rminm <<"       "<<UVminm<<"          "<<Uhminm<<"       "<<Nhminmr<<"       "<<Nhminmt<<"  "<<Volumeperusableareaminm<<endl;

  write  <<"\t" << i << "\t" <<Lminm << "\t\t"<<tminm<< "\t\t"<<PSIKminm<< "\t\t"<<rminm <<"\t\t"<<UVminm<<"\t\t\t"<<Uhminm<<"\t\t"<<Nhminmr<<"\t\t"<<Nhminmt<<"\t\t"<<Volumeperusableareaminm<<endl;

}
```

```
void loadFromFile(double& E, double& gamma,double& poisson,double& compressivestrength,double& tensilestrength) {

    ifstream fin("file/fiberglass 1in.txt");


    if(fin.fail()) {

        system("cls");

        cout << endl << "ERROR OPENING FILE !!!";

        getch();

        exit(1);

    } else {

        while(!fin.eof()) {

            //coping from the file to the variables

            fin >> E;

            fin >> gamma;

            fin >> poisson;

            fin >> compressivestrength;

            fin >> tensilestrength;

        }

    }

}
```

Appendix II: program code for thick shell

```
#include <iostream>

#include <cstdlib>

#include <math.h>

#include <conio.h>

#include <fstream>

using namespace std;

void loadFromFile(double& E,double& gamma,double& poisson,double& compressivestrength,
double& tensilestrength);




int main() {

//Initialization of i which helps in keeping the out put in array,radius PSIk,thickness,Length

//declaring variables

    int i = 0,k=0,m=0;

  double r = 19, PSIk = 0.524 , t =0.38 , L=20 ;

  double
ro,ri,p,E,gamma,poisson,compressivestrength,tensilestrength,PSI,Uhmax,volumeperusablearea,U
vmax,Nhmaxfinalr,Nhmaxfinalt,Lminm,tminm,PSIKminm,rminm,rominm,riminm,Uhminm,UV
minm,Nhminmr,Nhminmt,Volumeperusableareaminm;



   double Uh[12];

   double Uv[12];

   double Qh[12];

   double Nhr[12];
```

```
    double Nht[12];

    double eh[12];




//Taking the value of modules of elasticity(E),poisson's ratio,stress maximum and stress minimum of the material

   loadFromFile(E,gamma,poisson,compressivestrength,tensilestrength);

   ofstream write("optimization result of fiberglass 1out.txt",ios::out);



// the outer loop is the Loop where the length increases since when the loop inters the outer loop and increase the Length

//the thickness has reached maximum so it should be initialized

  cout <<"\t" <<"No"<< "\t" <<"Length"<< "      "<<"Thickness"<< "      "<<"PSIk"<< "      "<<"Radius" << "         "<<"Uhmax" <<"         "<<"Uvmax"<<"         "<<"Nhmaxr"<<"     "<<"Nhmaxt"<<"     "<<"Volumeper usable area" <<endl;

  write <<"\t" <<"No"<< "\t" <<"Length"<< "\t\t\t"<<"Thickness"<< "\t"<<"PSIk"<< "\t\t"<<"Radius" << "\t\t"<<"Uhmax" <<"\t\t"<<"Uvmax"<<"\t\t"<<"Nhmaxr"<<"\t\t"<<"Nhmaxt"<<"\t\t"<<"Volume per usable area"<<endl;



  do {



  t=0.38;

 //the this loop is where the thickness increases since when the loop inters this loop and increase the thickness

//the PSIk has reached maximum so it should be initialized

   do {
```

PSIk=0.524;

//the this loop is where the PSIk increases since when the loop inters this loop and increase the PSIk

//the radius has reached maximum so it should be initialized

do {

r=19;

//if the loop didn't have a result the out put no length,thickness,PSIk,radius Uhmax,Uvmax,Nhmax

do {

//assignment operation for volume per usable area

volumeperusablearea= (t*r*PSIk*L)/(((r*r*PSIk))-(r*r*sin(PSIk)*cos(PSIk)));

//This loop initializes PSI and increases it from zero to twice PSIk to know the value stress and deflection in each interval and take the maximum.

PSI=0,k=0, Uhmax=0,Uvmax=0,Nhmaxfinalr=0,Nhmaxfinalt=0;

do{

//assignment of operation for the variables necessary to calculate the stress and deflection where p is the combination of dead load and live load.

```
//Uh is stress horizontal,Uv is stress vertical,Nhr is radial stress,Nht is tangential stress.

ro=r + ( t / 2 );

ri=r - ( t / 2 );

//use the following load combination to check if the structure is stable for ultimate limit state design criteria

p=(1.35*(2*9.810+9.810*(r-r*cos(PSI))+gamma*t)+1.5*(2.224/(r*L*PSIk)));

//activate the following load combination while check if the structure is stable for serviceability limit state design criteria

//p=(1*(2*9.810+9.810*(r-r*cos(PSI))+gamma*t)+1*(2.224/(r*L*PSIk)));

Nhr[k]=-p;

Nht[k]=((-2*p*ro*ro)/(ro*ro-ri*ri));

Qh[k]=(((-p)*ri*ri*ro*ro)/((ro*ro-ri*ri)*r*r))/(PSIk*r);

eh[k]=((1/E)*(Nht[k]-(poisson*Nhr[k])-(poisson*Qh[k])));

Uh[k]=eh[k]*PSI*r;

Uv[k]=(-((p*ro*ro*r)/(E*(ro*ro-ri*ri))))*((1-poisson)+((1+poisson)*((ri*ri)/(r*r))));

//checking whether the deflection and the stresses are in their maximum and minimum interval

if ( ( ((r*(-1+cos(PSIk))/(200))<=Uh[k]) && (Uh[k]<= (r*(1-cos(PSIk))/(200)))) && ((((-2*r*sin(PSIk))/300)<= Uv[k]) && (Uv[k]<=((2*r*sin(PSIk))/300)) ) && ((compressivestrength<=Nhr[k]) && (Nhr[k]<=tensilestrength)) && ((compressivestrength<=Nht[k]) && (Nht[k]<=tensilestrength)))

{

// if the values are negative absolute value is needed to assist the comparison.
```

```
if(Uh[k]<0)
{
  Uh[k]=Uh[k]*-1;

}

if(Uv[k]<0)
{
  Uv[k]=Uv[k]*-1;

}

if(Nhr[k]<0)
{
  Nhr[k]=Nhr[k]*-1;

}

if(Nht[k]<0)
{

  Nht[k]=Nht[k]*-1;
```

```
      }

     k++;


   }


     PSI=PSI+(PSIk)/10;



  }while(PSI<=PSIk);
```

//since Uhmax ,Uvmax Nhmaxfinalr and Nhmaxfinalt has a random value before comparing any thing the initial values are assigned to it and comparison starts.

```
  if(k>0)

       {

        Uhmax=Uh[0];

        Uvmax=Uv[0];

        Nhmaxfinalr=Nhr[0];

        Nhmaxfinalt=Nht[0];



       for(int l=1;l<k;l++)

           {

           if(Uhmax<Uh[l])
```

```
 {
   Uhmax=Uh[l];
 }
if(Uvmax<Uv[l])
 {
   Uvmax=Uv[l];
 }
 if(Nhmaxfinalr<Nhr[l])
 {
   Nhmaxfinalr=Nhr[l];
 }
if(Nhmaxfinalt<Nht[l])
```

```
  {
    Nhmaxfinalt=Nht[l];


  }



}

if (i=0)
{
   Volumeperusableareaminm=volumeperusablearea;
         Lminm=L;
         tminm=t;
         PSIKminm=PSIk;
         rminm=r;
         rominm=rminm+(tminm/2);
         riminm=rminm-(tminm/2);

         Uhminm=Uhmax;
         UVminm=Uvmax;
         Nhminmr=Nhmaxfinalr;
         Nhminmt=Nhmaxfinalt;
```

```
}


else
 {
    if(Volumeperusableareaminm > volumeperusablearea)
      {
         Volumeperusableareaminm=volumeperusablearea;


         Lminm=L;
         tminm=t;
         PSIKminm=PSIk;
         rminm=r;
         rominm=rminm+(tminm/2);
         riminm=rminm-(tminm/2);


         Uhminm=Uhmax;
         UVminm=Uvmax;
         Nhminmr=Nhmaxfinalr;
         Nhminmt=Nhmaxfinalt;


      }


 }
```

```
// the output is saved and written in the note pad.

                i++;

        // if the designer wants to see all the combination of different dimension and their
respective response the following out put command can be activated

        //cout   <<"\t" << i << "\t" <<L << "          "<<t<< "        "<<PSIk<< "      "<<r << "
"<<Uhmax    <<"          "<<Uvmax<<"          "<<Nhmaxfinalr<<"          "<<Nhmaxfinalt<<"
"<<volumeperusablearea << endl;

         //write <<"\t" << i << "\t" <<L << "\t\t\t"<<t<< "\t\t\t"<<PSIk<< "\t\t\t"<<r <<
"\t\t\t"<<Uhmax
<<"\t\t\t"<<Uvmax<<"\t\t\t"<<Nhmaxfinalr<<"\t\t\t"<<Nhmaxfinalt<<"\t\t\t"<<volumeperusable
area << endl;



            }



             r+=0.5;



        }while(r<=24);



           PSIk+=0.02618;



      }while(PSIk<=0.786);



         t+=0.0044;
```

```
    }while(t<=0.424);


        L+=1;


   }while(L<=30);

// if the designer wants the final best result the following out put command can be used

  cout  <<"\t" << i << "\t" <<Lminm << "       "<<tminm<< "      "<<PSIKminm<< "    "<<rminm << "             "<<Uhminm  <<"      "<<UVminm<<"       "<<Nhminmr<<"       "<<Nhminmt<<" "<<Volumeperusableareaminm<<"   "<<endl;

  write   <<"\t" << i << "\t" <<Lminm << "\t\t"<<tminm<< "\t\t"<<PSIKminm<< "\t\t"<<rminm << "\t\t"<<Uhminm <<"\t\t"<<UVminm<<"\t\t"<<Nhminmr<<"\t\t"<<Nhminmt<<"\t\t"<<Volumeperusableareaminm <<"\t\t"<<endl;

}

void loadFromFile(double& E, double& gamma,double& poisson,double& compressivestrength,double& tensilestrength) {

   ifstream fin("file/fiberglass 1in.txt");


   if(fin.fail()) {

      system("cls");

      cout << endl << "ERROR OPENING FILE !!!";

      getch();

      exit(1);

   } else {

      while(!fin.eof()) {

         //coping from the file to the variables
```

```
            fin >> E;
            fin >> gamma;
            fin >> poisson;
            fin >> compressivestrength;
            fin >> tensilestrength;
        }
    }
}
```

Appendix III: Loading for the analysis of thin shell using Structural analysis program

Ultimate limit state load combination

E(KN/m^2)	Gamma(KN/m^3)	poisson
76000000	25.506	0.3

No. of division	PSI (rad)	r (m)	t(m)	2*Y water (KN/m^2)	Y water*(r-r*cos(PSI)) (KN/m^2)	gamma*t (KN/m^2)	1.35*DL (KN/m^2)	1.5*LL (KN/m^2)	Pd (KN/m^2)	load avg (KN/m^2)
1	0	17	0.04	19.620	0	1.020	27.864	0.006	27.871	28.362
2	0.094	17	0.04	19.620	0.728	1.020	28.848	0.006	28.854	30.325
3	0.187	17	0.04	19.620	2.907	1.020	31.789	0.006	31.796	34.233
4	0.281	17	0.04	19.620	6.518	1.020	36.663	0.006	36.670	40.052
5	0.374	17	0.04	19.620	11.528	1.020	43.427	0.006	43.434	47.731
6	0.468	17	0.04	19.620	17.895	1.020	52.022	0.006	52.029	57.204
7	0.561	17	0.04	19.620	25.562	1.020	62.373	0.006	62.379	68.387
8	0.655	17	0.04	19.620	34.463	1.020	74.389	0.006	74.395	81.183
9	0.748	17	0.04	19.620	44.519	1.020	87.965	0.006	87.971	95.480
10	0.842	17	0.04	19.620	55.644	1.020	102.983	0.006	102.989	111.154
11	0.935	17	0.04	19.620	67.739	1.020	119.312	0.006	119.318	

Serviceability limit state load combination

$E (KN/m^2)$	Gamma (KN/m^3)	poisson
76000000	25.506	0.3

No. of division	PSI (rad)	r (m)	t(m)	2*Y water (KN/m^2)	Y water *(r-r*cos(PSI)) (KN/m^2)	gamma*t (KN/m^2)	DL (KN/m^2)	LL (KN/m^2)	Pd (KN/m^2)	load avg (KN/m^2)
1	0	17	0.04	19.620	0	1.020	20.640	0.004	20.644	21.009
2	0.094	17	0.04	19.620	0.728	1.020	21.369	0.004	21.373	22.462
3	0.187	17	0.04	19.620	2.907	1.020	23.548	0.004	23.552	25.357
4	0.281	17	0.04	19.620	6.518	1.020	27.158	0.004	27.162	29.667
5	0.374	17	0.04	19.620	11.528	1.020	32.168	0.004	32.173	35.356
6	0.468	17	0.04	19.620	17.895	1.020	38.535	0.004	38.539	42.373
7	0.561	17	0.04	19.620	25.562	1.020	46.202	0.004	46.206	50.657
8	0.655	17	0.04	19.620	34.463	1.020	55.103	0.004	55.107	60.135
9	0.748	17	0.04	19.620	44.519	1.020	65.159	0.004	65.164	70.726
10	0.842	17	0.04	19.620	55.644	1.020	76.284	0.004	76.288	82.336
11	0.935	17	0.04	19.620	67.739	1.020	88.379	0.004	88.383	