

# ANALYSIS OF TENSILE FABRIC STRUCTURE USING THIN CONCRETE DOUBLY CURVED SHELL

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**Abstract-** Tensile fabric structures are used for large-scale iconic structures worldwide, yet analysis and design methodologies are not codified in most countries and there is limited design guidance available. Non-linear material behaviour, large strains and displacements and the use of membrane action to resist loads require a fundamentally different approach to structural analysis and design compared to conventional roof structures. Various forms of shell structure are available for covering large area but as shell is a highly indeterminate structure it involves complex mathematical calculations. Finite element method has become a practical and popular method for all types of structural analysis. Finite element method is very much suited for analysis of shell structure because of its flexibility in accounting for arbitrary geometry, loading and variation in material properties, complex support condition. However, few thin shell structures are built today and many of the most enduring structures, such as those of Felix Candela who is world's leading designers and builders of thin-shell concrete structures have not been analyzed. This project performed a finite-element analysis of Candela's doubly curved shell structures in order to better understand its structural efficiency and gain insight into its design. A 3D model was generated using FEA based software STAAD.Pro and the analysis was carried out by using material properties of reinforced cement concrete and ferrocement and the appropriate loads acting on the structure. Analysis results shows the effect of stress results with respect to their characteristics strength..

**Index Terms-** fabric structure, thin shell, In-plane forces, finite element method, Felix Candela.

## 1. INTRODUCTION

Various forms of shell structures are being increasingly used in order to cover large clear area using the minimum of intermediate supports such as in commercial and industrial buildings, auditoriums, island platforms, storage reservoir and overhead water tanks, pressure vessels. Now a days shell structures are becoming a popular due to advanced construction techniques and invention of new construction materials like steel, light alloys, plastic and high performance concrete. No structural forms perhaps does greater justice to special attribute of these advanced materials than thin shell construction, which have made shell lighter and economical. In general a shell structure may be defined as the solid continuum lying between two closely spaced doubly curved surfaces. If the thickness of the shell is small compared to the radii of curvature of the mid surface, the shell is referred to as geometrically thin shell. If the transverse shear force per unit length is small enough so that transverse shear deflections are insignificant, then it is referred to as structurally thin shell. Thin shells are examples of strength through forms rather than mass. Thin shells and folded plates belong to the class of stressed-skin structure which, because of their geometry and small flexural rigidity

of the skin, tend to carry loads primarily by direct stress acting in their plane with little or no bending.

### 1.1 GENERAL

With the ability to span large distances in a structurally efficient way, tension membrane structures offers a lot of interesting possibilities; from a sustainable, engineering and an architectural perspective. These elegant structures' complex designs require an understanding of shape and form, and the behaviour of the materials and the forces acting on it. The flexibility of the structure means that applied loads have a big impact on the shape. The design process is made more complex by the fact that the shape of tensioned cable net and membrane structures cannot be described by simple mathematical methods. They have to be found through a form-finding process either using physical or computer models. The final shape then has to be translated from a three dimensional undeveloped surface into two-dimensional cutting patterns. This is a complicated procedure since textiles have anisotropic properties (warp and weft). Fabric canopies are one of the earliest forms of roofing, and have been used for traditional forms of construction for thousands of years. However, modern fabric structures using synthetic materials have only been in

use for about 50 years. A fabric membrane acts as both structure and cladding, thereby reducing the weight, cost and environmental impact of the construction. These structures combine striking architectural forms with high levels of structural stability and durability, with expected life spans in excess of thirty years depending on the type of material used. Architectural fabrics have negligible bending and compression stiffnesses, and therefore fabric structures must be designed with sufficient curvature to enable wind and snow loads to be resisted as tensile forces in the plane of the fabric. With advances in computer hardware and software nonlinear analysis of larger structure system becomes simpler.



FIG.1.1 Fabric Canopies

### 1.2 Classification of shells

There are three types of classification for the shell structure which are given below:

1. According to types of surfaces
2. According to gauss curvature
3. According to Indian standard specification

#### 1.2.1 Types of surfaces

There are three types of surfaces

- 1) Shell of revolution
- 2) Shell of translation
- 3) Ruled surfaces

#### 1.2.2 Classification of shells according to gauss curvature

The product of two principal curvatures is defined as the gauss curvature at the point. The surface is called synclastic, developable or anticlastic according as the gauss curvature is positive, zero or negative.

#### 1.2.3 Classification of Shells According To I.S. Code

Chart based detail classification of stressed skin surfaces is described in the Indian standard code 'Criteria for design of reinforced concrete shell structures and folded plates I.S.:2210-1988'.

### 1.3 Application Of Tension Structure

(1) They are lightweight and collapsible and therefore easy to transport and erect.

(2) They can be prefabricated in a factory, have low installation costs, and are potentially relocatable.

(3) For air-supported structures, the primary load-carrying mechanism is the habitable environment itself, i.e., a pressurized mixture of gases.

(4) The environmental loads are efficiently carried by direct stress without bending.

### 2. OBJECTIVE OF STUDY

(1) Review Candela's approach to structural optimization.

(2) Examine one structure in particular, the Chapel Lomas de Cuernavaca, and optimize the shape and thickness using the most sophisticated structural optimization techniques available today.

(3) Understanding the finite element modelling and analysis of doubly curved shell structures.

(4) Application of finite element analysis using shell element to doubly curved shell structures.

(5) Use of two different materials like ferrocement and reinforced cement concrete.

(6) Comparison of finite element analysis results for the doubly curved surface while using ferrocement and reinforced cement concrete structures.

(7) Study the effect of stress results with respect to their characteristics strength.

(8) Interpret the results and find the suitability of the solutions.

Double curvature (also, but rarely known as, anticlastic curvature) is used in nearly all fabric structures to give stability to the membrane. However, whilst it has its uses, it is not actually an essential requirement for smaller tensile structures.

This explains more about the principles behind tensioned membranes and the tensioning methods most frequently used.



Fig.2.1 Square rubber

Imagine four people holding out a large thin square rubber or cotton sheet, one at each corner, pulling fairly hard. The sheet is flat and tight around the edges, and yet the sheet has very little resistance to movement in the central area. For example, even a light wind will cause it to bulge up or down, and a ball thrown onto the surface will deflect it significantly.

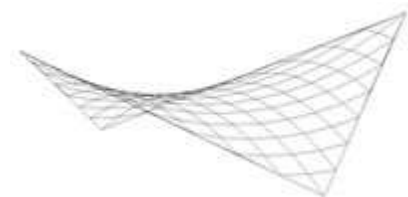


Fig.2.2 Hypar shape

Now imagine that two diagonally opposing people peg their corners to the ground, and the other two maintain their position. The middle of the sheet is now halfway between the low points and high points. From this middle point, fabric is curving both downwards toward the corners on the ground, and upwards toward the people holding out the other two corners. This is a much more stable shape which will inherently resist movement from download or uplift. The fabric is in double curvature, the form in this instance is a "hypar". Survey from various literatures such as research papers and different books has been carried out to support the present work. This includes various applications of finite element analysis in the field of shell structures.

### 2.1 Cosmic Rays Laboratory

Félix Candela's fourth thin concrete shell built, the Cosmic Rays Laboratory, was the first of his stunning hyperbolic paraboloids, the form of his most famous structures. The laboratory is the thinnest major structure ever built. Candela was able to construct a lightweight shell that expresses thinness by its cantilevered edges.



Fig.2.1 Cosmic rays laboratory

The original form chosen by the collaborating architect was a barrel shell which Candela redesigned to be a hyperbolic paraboloid because he believed that its extreme thinness would require the extra stiffening offered by this form. He also changed the supports to their present form and added the concrete screens on the ends of the shell. The upward curvature of the cantilevered ends of the shell enhances its visual lightness. However, Candela doubted if the shell would be strong enough, so he added three stiffening arches not visible from the outside. The structure still stands in fine condition on the UNAM campus. However, the mystery of cosmic rays has been replaced by the mastery of a board game, as the lab is gone and the building is now the home of the chess club. It is remarkable that Candela was able to build a shell so thin at such an early point in his career. However, after his experiences building other

hypars, Candela realized that he made a mistake with the Cosmic Rays Laboratory design. The form was so efficient that he did not need the stiffening arches. The structure one sees from the outside is also not completely honest. While the cantilevered edges attempt to express the thinness of the shell, the actual size of the shell at its thinnest is hidden from observers. In addition, there is no evidence of the existence of the interior stiffening arches.

### 2.2 Los Manantiales Restaurant At Xochimilco

Candela's stimulus for the form of Los Manantiales Restaurant in Xochimilco, Mexico City came from Colin Faber, who was working with Candela at Cubiertas Ala. Faber had made a rough sketch that somewhat resembled the final form of the restaurant; Candela liked the idea, so he took it and redesigned it into a more graceful shape. The form of the shell was a play of the hypar with free curved edges, that is, the edges of the shell are parabolic and free of any edge stiffeners that would conceal the thinness of the shell. The groined vault consists of four intersecting hypars, a structure that he had not yet attempted.



Fig.2.2 Los manantiales restaurant at xochimilco

The Cosmic Rays Laboratory, Candela's first hypar shell, has curved edges just like those of the restaurant in Xochimilco. Where the laboratory has two saddles, one in front of the other, the restaurant belongs to a type of shell structure called groined vaults. The groins are the valleys in the shell formed at the convergence of the intersecting hypars. The restaurant was not Candela's first groined vault. He had designed a few others before Xochimilco, but none so striking. The V-beams are reinforced with steel, while the rest of the shell has only nominal reinforcing, not for added strength, but to address temperature effects and other properties of the concrete material that can cause cracking. At the supports, Candela anchored the V-beams into inverted umbrella footings, which cup the earth to prevent the shell from sinking into the soft Mexican soil. To resist lateral thrusts, he linked adjacent footings with steel tie-bars, thus allowing the umbrella footings to carry only vertical loads. Candela was pleased with the unique visual design of his

support detail, where instead of a sharp V-shape, he formed it into a curve to give it continuity. He commented that this is "what makes [the shell] so graceful, the regularity and the proportion it looks good and I like it."

### **2.3 Bacardi Rum Factory**

The impetus for Felix Candela's Bacardi Rum Factory was Minoru Yamasaki's and Anton Tedesko's 1956 Lambert-St. Louis Airport Terminal. It consisted of three cylindrical groined vaults with stiffening arches along the groins and stiffening ribs at the edges. In an interview, Candela recalled that he first saw the structure in a magazine and told himself, "I'm going to do it." The factory roof consisted of three adjacent hyperbolic paraboloid groined vaults 4 cm. (1.6 in.) thick and 26 m. (85.3 ft.) square in plan with 2.5 m. (27.9 ft.) overhangs on each side. Skylights fill the voids between adjacent shells and enclose the structure but provide no support for the shell roof.



**Fig.2.3 Bacardi rum factory**

Bacardi's shell is not in direct contact with the footings, but instead each of the four corners is supported on a leg that transfers the loads from the shells to the footings which in turn place the vertical weight on the ground. Steel ties connect the footings to carry the horizontal forces. The groin stiffeners are completely hidden from inside view and are essentially invisible from the outside. They are V-beams, which Candela used in all his groined vaults. Additionally the edge stiffeners are set back from the edge, allowing for the thinness of the shell to be fully expressed. The arches are located directly above the glass walls to ensure that in the case of unexpected wind loadings the shell is stiff enough that it does not deflect into the glass. Similarly, stiffening ribs frame the skylights that are fitted between adjacent shells.

### **2.4 Construction Techniques**

The construction of concrete shells requires scaffolding (sometimes referred to as falsework), a temporary structure of wood or metal that supports the form boards and wet concrete. These boards are

placed on top of the scaffolding and allow the concrete when hardened to take its proper form. Designers and contractors have often shied away from curved concrete shapes believing that they would require expensive, custom, curved forms. Candela, however, understood that hypars, while doubly curved, can actually be formed by straight lines. Once the forms are placed, steel reinforcing is added and finally the workers cast the concrete, typically 4 centimeters (1.5 inches) thick. Candela indicated that on steep surfaces the placing of the concrete was done using a dry mix with the reinforcement bars laid out close together so that they could keep the wet concrete from sliding down.

Because Mexico City is on the site of what once was a lake, its soil, composed of lacustrine and volcanic sediments and organic matter, is soft and compressible, one of the worst on which to build. In addition, the city is in a region of high seismic activity as illustrated by the earthquake of 1985, which resulted in enormous settling and tilting of the substructures of numerous buildings, followed by total collapse or substantial damage to superstructures. Candela was aware of the poor soil conditions and the earthquakes that would challenge the integrity of his structures. But according to Candela, no earthquake has ever damaged his structures. Since his structures were light, due to the thinness of the concrete shell, the forces induced by the earthquakes would be relatively small (the earthquake force imposed on a structure is proportional to the building weight times the ground acceleration).

## **3 THIN CONCRETE SHELLS**

A thin shell is defined as a shell with a thickness which is small as compared to its other dimensions and in which deformations are not large compared to thickness. The thin concrete shell structures are a lightweight construction composed of a relatively thin shell made of reinforced concrete, usually without the use of internal supports giving an open unobstructed interior. The shells are most commonly domes and flat plates, but may also take the form of ellipsoids or cylindrical sections, or some combination thereof. Most concrete shell structures are commercial and sports buildings or storage facilities.

### **3.1 History Of Thin Concrete Shell**

There are two important factors, the shape and the thickness, to be account to better understanding the evolution of the thin concrete shell structures. The first factor was developed along the history of these constructions: The pioneer structures, as the dome in Jena, can be classified as synclastic shells. As it was explained before, these shapes are more resistant and can be erected easier than other surfaces with single curvature. The second factor to be considered in the

thin concrete shell structures is the thickness, which is usually less than 10 centimetres. A primary difference between a shell structure and a plate structure is that, in the unstressed state, the shell has curvature as opposed to plate surface, which is flat. In this chapter, only the thin concrete shells structures with curvature were studied. The modern era of thin concrete shells began in 1922 with the construction of the dome in Jena, Germany by Frank Dischinger of the German engineering firm Dyckerhoff and Weidman (Hines 2004, p.1641). This modern structure was 16 meters in diameter, 30 millimeters thick and the span to thickness ratio was near to 550:1. Subsequently, after these three decades, the number of new concrete shell structures constructed declined noticeably due mainly to the high cost of construction and removal of temporary formwork and associated false work for concrete casting in the construction of a thin concrete shell.



**Fig.3.1 Dome in Jena designed by Dischinger**

Over the years, there have been several methods for eliminating the need for temporary formwork in the construction of thin concrete shell roofs. Until now, the most successfully techniques have been on one hand, the use of inflated membranes as forms. On the other hand, the use of precast concrete panels with in-situ cast joints. Both methods are explained in this section. The inflated membrane method was appreciated by many engineers. For example, the President of Monolithic Constructors and Chair of Joint ACI-ASCE Committee 334, David South, argued that “The construction of thin shells nearly came to a standstill until inflated membrane forms were introduced” (Meyer 2005).

The origin of the inflated membrane forms, also known as air-inflated forms, was in 1942 when Wallace Neff received a patent on a system where the form was inflated to the shape of the structure, and after that, the reinforcing bar and shot concrete were placed on the exterior of the structure. Particularly noteworthy was the system invented by Dante Bini. In this method, in approximately 120 minutes, the formwork is constructed. Final forms are spherical sectors with radius less than 40 metres. The Bini’s system is divided into two successive phases. Firstly,

the reinforcing steel and concrete are placed over a layer of fabric while it lies flat on the ground. Finally, the fabric is inflated by air pressure in order to create the shell form. In the late 1970s, David and Barry South developed other system, which consisted of a shotconcrete applied to the inside of an inflated fabric form. This technique had some differences compared with the Bini’s System: First, shell is inflated using polyurethane foam. This material gives the form the stiffness required to support the weight of reinforcing steel placed on the inside. The second difference is that the shotconcrete is applied to the interior of the form when this shape has been inflated. According to David South, spans of up to 300 meters can be obtained using this technique (Meyer 2005, p.45).



**Fig.3.1.1 First phase of the Bini’s System.**





**Fig.3.1.2** *Second phase of the Bini's System.*



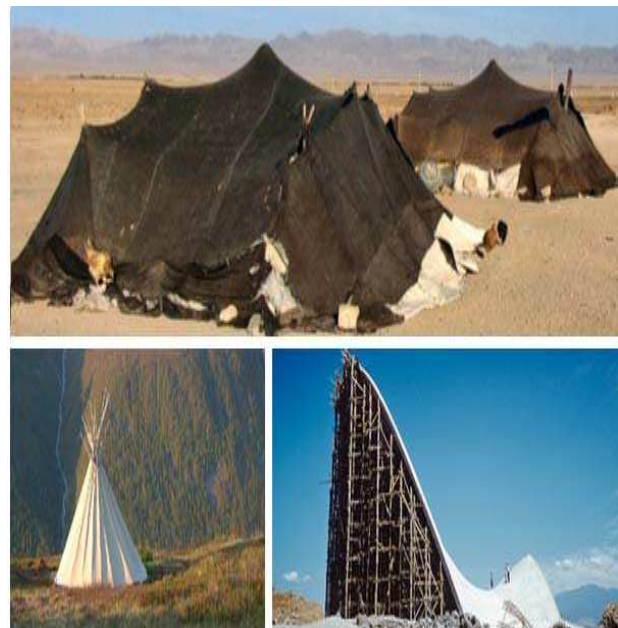
**Fig:3.1.3** **Shotcrete applied to inside of inflated fabric form**

The shells constructed by inflated membrane techniques have some disadvantages. Firstly, the shape and thickness of the shell as well as the position of reinforcement is difficult to control during the construction process. The second problem is that these techniques require the use of special construction equipment increasing the cost of the roof. Lastly, these methods are limited to the construction of circular-based domes with a spherical or nearly spherical meridian and therefore, the architect has less freedom in their designs because the shape of the formwork cannot be practically changed.

### **3.2 Characteristics**

Since the beginning of the architecture, the designers have dreamt about one light surface, like the skin used in the ancient tents or in the African villages (figure 18), to cover large spans in buildings. This dream, considered before as unachievable, was come truth

when appeared the thin concrete shells. The material of these structures was able to be casted forming any imaginable shape. For example, the tent's shape was imitated by Candela in the Lomas de Cuernavaca's shell. The thin concrete shells are designed with the purpose to resist loads through membrane forces. These forces consist of compression stresses, resisted by the concrete, and tension stresses, resisted by the reinforcement bars made of steel, in the direction of the tangent plane. Consequently, shells made of reinforced concrete can resist moderate bending stresses and be constructed thinner and lighter.



**Fig.3.2.1** **African tent in the Sahara desert, Sami tent and Lomas de Cuernavaca designed by Candela.**

Nevertheless, when the bending moments are needed in order to achieve the equilibrium of the shell, the thickness and the reinforcements bars have to be increased and therefore, the advantages of the thin concrete shells are reduced. These structures are constructed by casting onto a mould called formwork, which is kept in place until the concrete has hardened. When the formwork is removed, the shell is obliged to carry its own weight. The shell exists originally under condition of effectively zero gravity in a perfect shape, and with zero stress throughout. Afterwards, at a certain time, gravity is switched on, and the shell thereafter carries its own weight. To improve the structural behavior, the formwork tends to provide single or double curved surfaces. Furthermore, the curved surfaces made of reinforced concrete, above all the synclastic shells, are naturally. In addition to the possibility of covering areas without internal supports, the thin concrete shells have the following benefits. Firstly, the efficient use of the material

because the structural lightness is the common starting point in designing. Secondly, the method of construction has been used since the concrete was discovered and is therefore well known. Thirdly, the concrete is relatively inexpensive and easily cast into desired curves. Finally, the thin concrete shells offer the possibility of more visually interesting geometries to improve the aesthetic value of the building.

Thin concrete shells have historically had the following problems:

- 1) Functional obsolescence because the small thickness makes worse the bars isolation and corrosion can occur easily.
- 2) The structure has to be intensely maintained in order to avoid the functional obsolescence and this factor increase the future cost of the building.
- 3) Rainwater can seep through the roof and leak into the interior of the building because the concrete is a porous material and therefore, this material is usually complemented with waterproof isolation.
- 4) The thin thickness produces that these structures usually need thermal and acoustic insulation.

### 3.3 Application of shell structures.

It is instructive to assemble a list of applications from a historical point of view, and to take as a connecting theme the way in which the introduction of the *thin shell* as a structural form made an important contribution to the development of several branches of engineering. The following is a brief list, which is by no means complete.

**Architecture and building.** The development of masonry domes and vaults in the Middle Ages made possible the construction of more spacious buildings.

**Power and chemical engineering.** The development of steam power during the Industrial Revolution depended to some extent on the construction of suitable boilers. These thin shells were constructed from plates suitable formed and joined by riveting.

**Structural engineering.** An important problem in the early development of steel for structural purposes was to design compression members against buckling.

**Vehicle body structures.** The construction of vehicle bodies in the early days of road transport involved a system of structural ribs and non-structural paneling or sheeting.

**Composite construction.** The introduction of fiberglass and similar lightweight composite materials has impacted the construction of vehicles ranging from boats, racing cars, fighter and stealth aircraft, and so on.

**Miscellaneous Examples.** Other examples of the impact of shell structures include water cooling towers for power stations, grain silos, armour, arch dams, tunnels, submarines, and so forth.

## 4 FINITE ELEMENT MODELLING OF DOUBLY CURVED SHELL STRUCTURES

Felix Candela designed and built a number of thin shell concrete structures in and around Mexico City during the 1950s and 1960s. Nearly all of these structures still stand in good condition after 50 years of continuous use often under harsh seismic loads. Candela employed the form of a hyperbolic paraboloid for many of these structures, the strength of which allowed for a remarkable thinness.

### 4.1 Chapel of Lomas De Cuernavaca

The Chapel of Lomas de Cuernavaca, or Cuernavaca Chapel is located on a plateau overlooking the town of Cuernavaca, Morelos Mexico.

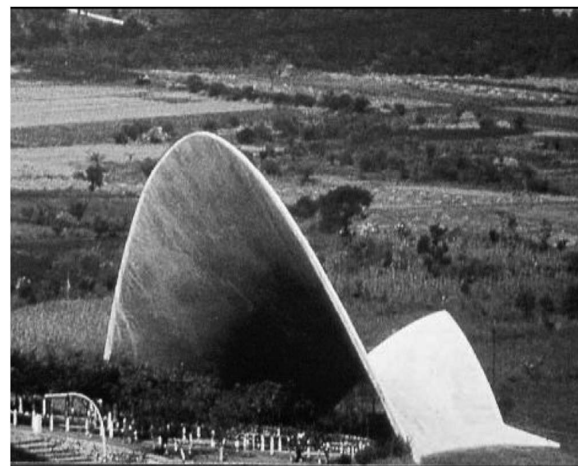
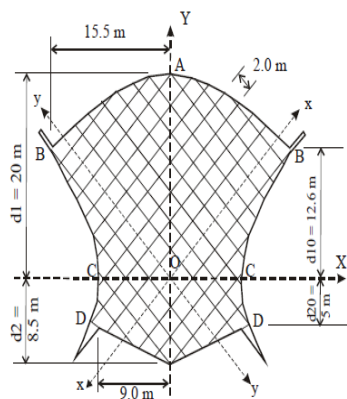


Fig.4.1 Chapel of Lomas de Cuernavaca, by Felix Candela

### 4.2 Hyperbolic paraboloid

The Hyperbolic Paraboloid (Hypar) Candela stated that “of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid.” Candela used both straight edges and curved edges to create his designs. Rather, Candela used his engineering knowledge and expertise as a builder to select those forms that were rational structural solutions. For Candela, the doubly curved hyperbolic paraboloid. It had two primary attributes that made it an ideal shape for a thin shell concrete structure. The first was its ease of construction. Designed properly, thin shell concrete structures have proven durable, lasting, and economical over long periods of time. However, their initial construction costs can appear prohibitive if they require extensive specialized formwork.



(a) plan

(b) elevation

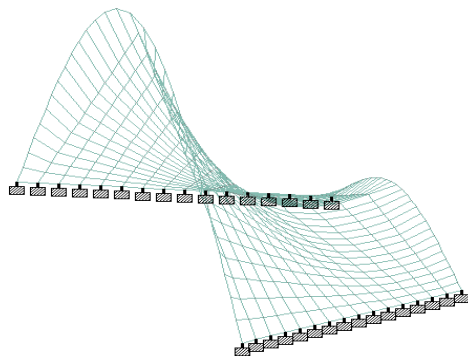
**Fig.4.2 Generation and dimensions of original design for Chapel Lomas de Cuernavaca.**

The other benefit of the hyperbolic paraboloid is that in Candela's parlance it is a *proper* shell form (Candela 1958). By this he meant the form could distribute stresses without excessive bending arising in the shell. Bending is anathema to thin shells.

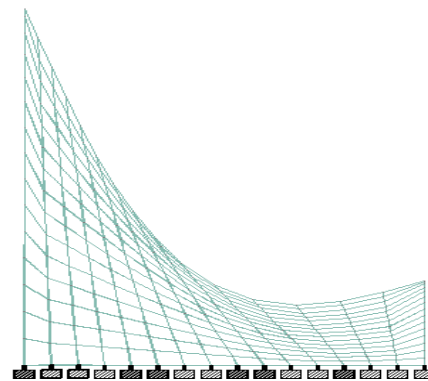
When large moments arise in a shell structure, greater thickness is required to assume and distribute the load without excessive deformation, cracking, or failure. Candela therefore instead designed forms that through their very shape would minimize the bending in the shell. These he referred to as proper shells.

#### 4.3 Structural model

The finite-element model of the Cuernavaca Chapel is shown in Fig. 4.3.1 and Fig.4.3.2.



**Fig 4.3.1 Isometric view**



**Fig.4.3.2 Elevation**

### 5. PROPERTIES OF FERROCEMENT & RCC

The properties of RCC and ferrocement which are taken for analysis are as follows

#### Ferrocement:-

- Thickness(tk) = 30mm
- Modulus of elasticity = 20000N/mm<sup>2</sup>
- Characteristics strength( $f_{ck}$ ) = 35N/mm<sup>2</sup>
- Density of ferrocement = 2000kg/m<sup>3</sup>
- Poissons ratio = 0.2

#### RCC:-

- Thickness(tk) = 80mm
- Modulus of elasticity = 22360N/mm<sup>2</sup>
- Characteristics strength( $f_{ck}$ ) = 20N/mm<sup>2</sup>
- Density of RCC = 2400kg/m<sup>3</sup>
- Poissons ratio = 0.2

As stated in the definition, ferrocement is a type of reinforced concrete construction. While, such a definition implies many similarities between ferrocement and reinforced concrete, there is a number of differentiating factors sufficiently important to explain the differences in their behavior. Compared to reinforced concrete, ferrocement.

- Is a thinner material.
- Has distributed reinforcement.
- Is reinforced in two directions (transverse and longitudinal).
- Has matrix made of fine mortar or paste instead of concrete which contains larger size aggregates (the maximum size of the particles in ferrocement is controlled by the average opening of the stack of mesh system to be encapsulated).

**Table No 1: Materials Specification**

R.C.C	FERROCEMENT
Min Thickness – 75 mm	Thin Walled , 25-50 mm
Matrix : Cement Content	Micro-Concrete ( Rich Cement Mortar)

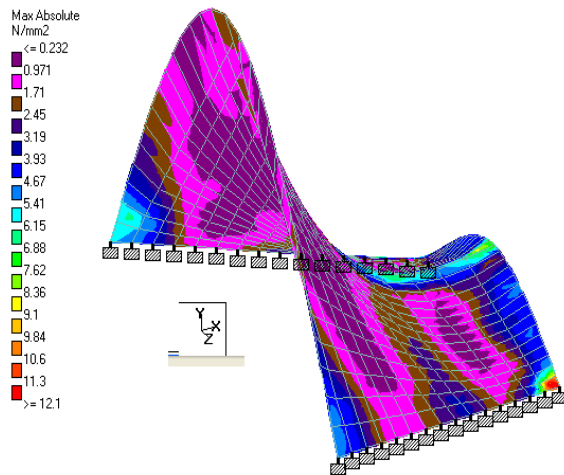


R/F – Steel Bars > 6mm dia , spaced apart	Continuous Fine Wire mesh dispersed throughout the body of structure
Strength – Weak in tension , bond & Shear	High tensile strength, superior bond & shear strength.
Strength to Weight Ratio – In tension & Compression, Very Low.	Very High
For casting- Formwork & shuttering are quite essential.	Tightly tied wire meshes act as forms for mortar casting.

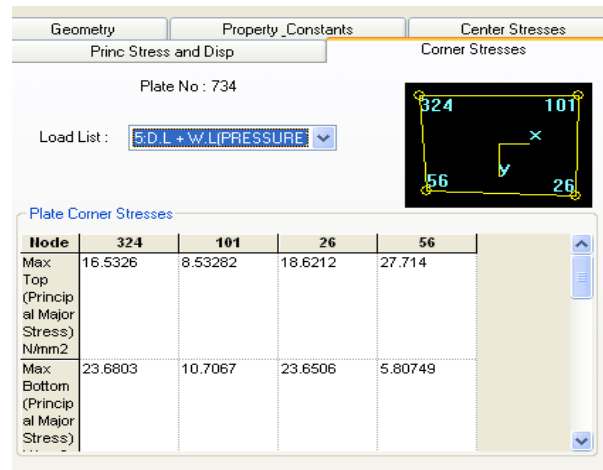
**6. FINITE-ELEMENT ANALYSIS RESULTS**

The force and stress results of the finite-element analysis reinforce Candela’s selection of a structurally efficient form. Using the uniform shell thickness model, Compressive stress values are well under what we can assume to be a minimum compressive strength of concrete used. Tension is kept low enough so that it can suitably be assumed by the reinforcement in the shell.

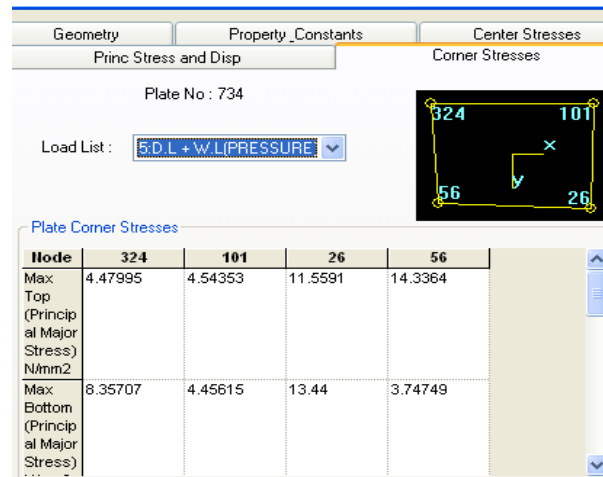
By obtaining a max absolute stresses we have to compare the maximum absolute stresses occur in the structure. Stresses are shown below in Fig.6.1.



**Fig.6.1 Stress value for D.L+W.L(pressure) for ferrocement**



**Fig.6.2 Maximum corner stresses for Ferrocement**



**Fig.6.3 Maximum Corner node stresses for RCC**

**7. CONCLUSION**

A structural analysis of Candela’s Cuernavaca Chapel reveals the genius behind this form. The shape of the hyperbolic paraboloid minimizes bending in the shell and precludes the need for ribs or a masking of the thinness. Despite the large size of this structure, stresses are kept low enough to allow for a remarkable thinness and free edge.

Comparison of three finite-element models of varying complexity and precision shows that the simplest model, which represents the shell with uniform thickness and no edge beams, yields conservative stress results. Yet these results indicate that the stresses are well within the strength limits.

The current dearth of thin shell concrete structures continues to confound those who are aware of how effectively they provide an attractive, efficient structural solution. This study has sought to demonstrate how the medium of thin shell structures was mastered by one structural artist through a

thorough investigation of one of the master works of his oeuvre.

Through careful attention to the design and construction of structurally efficient forms, Felix Candela was able to demonstrate the strength and durability of a remarkably thin structure.

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