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A Review on Thin-shell Structures: Advances and Trends

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A B S T R A C T

This paper provides a review of research advances and trends in the area of thin shell structures. The art of building thin-shell structures has been with us since ancient times. In practical civil engineering, the necessity of covering large column free open areas with shell surfaces is often an issue. Over the course of time, this shell form became very popular to engineers due to a number of advantages it offers, and started drawing the attention of a number of researchers. A thin shell is a term not in itself as readily understandable by the layman as the terms dome or vault would be. It is in a sense a word coined on the basis of its structural connotations, as exhibited in the artifacts it creates. There are many interesting aspects of the use of shells in engineering, but one alone stands out as being of paramount importance: it is the structural aspect. At the beginning of this century, under the influence of the art movement and the dominance of industrialized building materials, any remnants of curvilinear architecture were mercilessly banished. Within that period avant-garde art emphatically proclaimed a total repudiation of the traditions and classical revivals that in architecture were symbolized mostly by arches and vaults. Ready-to-use rectilinear steel beams and columns and easy-to build rectilinear concrete forms struck a lethal blow to the curvilinear approach in architecture. Rectilinearity became synonymous with rationality, while curvilinearity came to symbolize decadence. Remember, for instance, the negative stigma given to the baroque for its assumed pomposity in glorifying curves. In practical terms such an attitude in design is clearly manifested in the present cityscapes that are totally free of arches, domes, shells, and any other form that is not rectilinear. With today's almost unlimited computer technology and the knowledge that can be gained from understanding the domes and vaults built both in the past and present, it is hoped that this research work on the review aspects of curvilinear forms will contribute to further exploration and encourage the application of thin shells by the engineers and architects to whom it is addressed. Masonry domes, concrete shells, and large steel contemporary domes are presented in historical terms as case studies and in conceptual terms from the architectural and structural point of view.

Keywords:building materials, curvilinear, shell structures, technology

1. Introduction

1.1. General Overview on Shell Structures

Thin shells as structural elements occupy a leadership position in engineering and in particular, in civil engineering. Examples of shell structures in civil engineering are large-span roofs, liquid-retaining structures and water tanks, containment shells of nuclear power plants, and concrete arch domes. A thin shell is a special kind of vault whose geometry may include many shapes. It could be a spherical or elliptical dome, a parabolic structure, or a barrel vault in any configuration, or be a paraboloid, a conoid, or a hyperbolic paraboloid.
A thin-shelled structure is a three-dimensional form made thicker than a membrane, so that it cannot only resist tension as membranes do, but also compression. On the other hand, a thin shell is made thinner than a slab, which makes it unable to resist bending as a slab does. In short, thin shells are structures thicker than membranes, but thinner than slabs.
Thin shells are made possible by the use of materials that work well under tension and compression. Masonry has no tensile strength, so the thin shell could not exist when masonry was the only technology available. Only the availability of reinforced concrete and ferrocement made the thin shell

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possible. Wood could of course have served the purpose, as the wooden dome and wooden hull quite probably did, even if the wooden shell often was a combination of timber framing and plank sheathing.

The curvature of a shell can be of the same sign throughout that is, be concave or convex everywhere. In such a case the surface is called synclastic. Domes are synclastic surfaces, because any section attained by intersecting the dome with a normal plane produces a line that has only a downward curvature.

The curvature of a shell can also be of a different sign such that the surface is both concave and convex at the same time, which is known as anticlastic. An example of an anticlastic surface is the hyperbolic paraboloid. When such a surface intersects with normal planes, the sections formed can be a parabola with either upward or downward curvature, and at times even be a straight line.

1.2. Examples of Thin Shells Structures in Civil Engineering

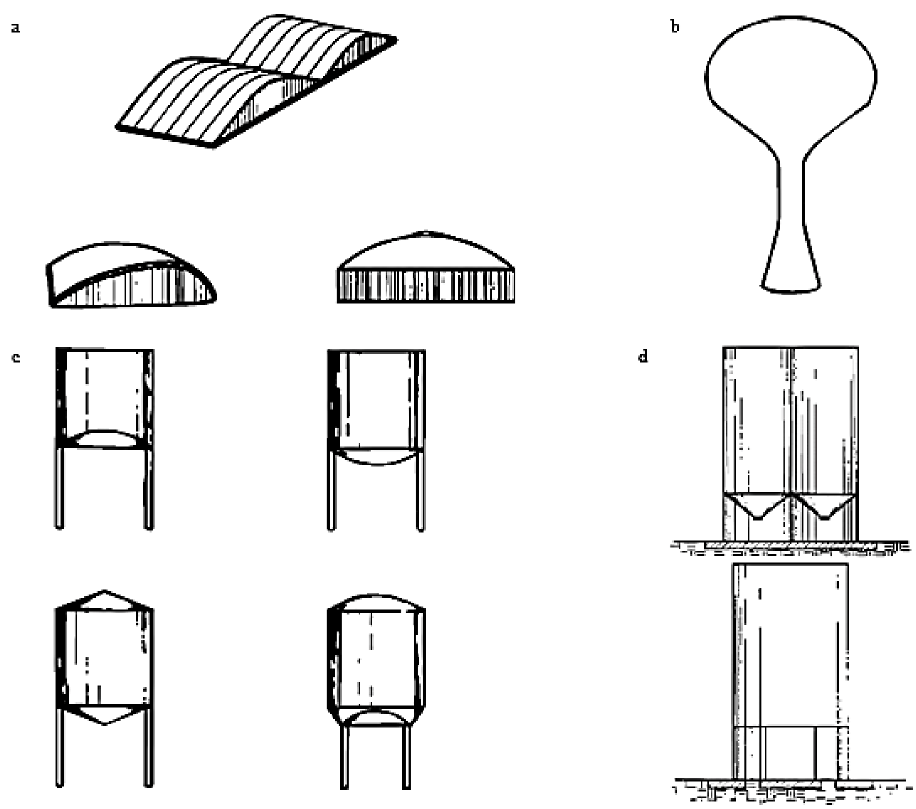

Fig. 1 - (a) Shells in Roof Structure; (b) Elevated Water Tank; (c) Liquid retaining cylindrical Shells; (d) Silos

Source: Eduard Ventsel, Theodor Krauthammer, "Thin Plates and Shells: Theory, Analysis and Applications", ISBN: 0-8247-0575-0, Eastern Hemisphere Distribution, Switzerland

1.3. General Definitions and Fundamentals of Shells

The term shell is applied to bodies bounded by two curved surfaces, where the distance between the surfaces is small in comparison with other body dimensions (Figure 2).

A thin shell is defined as a shell with a thickness which is small compared to its other dimensions and in which deformations are not large compared to thickness. A primary difference between a shell structure and a plate structure is that, in the unstressed state, the shell structure has curvature as opposed to plate structures which are flat. Membrane action in a shell is primarily caused by in-plane forces (plane stress), though there may be secondary forces resulting from flexural deformations. Where a flat plate acts similar to a beam with bending and shear stresses, shells are analogous to a cable which resists loads through tensile stresses. Though the ideal thin shell must be capable of developing both tension and compression.

The locus of points that lie at equal distances from these two curved surfaces defines the middle surface of the shell. The length of the segment, which is perpendicular to the curved surfaces, is called the thickness of the shell and is denoted by h. The geometry of a shell is entirely defined by specifying the form of the middle surface and thickness of the shell at each point.

Shells have all the characteristics of plates, along with an additional one–curvature. The curvature could be chosen as the primary classifier of a shell because a shell's behaviour under an applied loading is primarily governed by curvature. Depending on the curvature of the surface, shells are divided into cylindrical (noncircular and circular), conical, spherical, ellipsoidal, paraboloidal, toroidal, and hyperbolic paraboloidal shells. Owing to the curvature of the surface, shells are more complicated than flat plates because their bending cannot, in general, be separated from their stretching.

There are two different classes of shells: thick shells and thin shells. A shell is called thin if the maximum value of the ratio h=R (where R is the radius of curvature of the middle surface) can be neglected in comparison with unity. For an engineering accuracy, a shell may be regarded as thin if the following condition is satisfied:

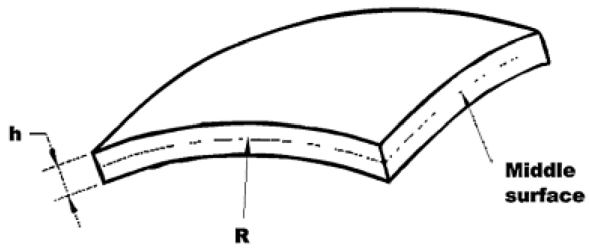

Fig. 2 - Shell Curvature Surface

Source: Eduard Ventsel, Theodor Krauthammer, "Thin Plates and Shells: Theory, Analysis and Applications", ISBN: 0-8247-0575-0, Eastern Hemisphere Distribution, Switzerland.

$$\max\left(\frac{h}{R}\right) \leq \left(\frac{1}{20}\right) \qquad (1)$$

For a large number of practical applications, the thickness of shells lies in the range.

$$\frac{1}{1000} \leq \left(\frac{h}{R}\right) \leq \left(\frac{1}{20}\right) \qquad (2)$$

i.e., in the range of thin shells

1.4. Curvature and Strength

Curvature is an element in structural strength. It can be easily seen through simple visual examples. For instance, a sheet of typing paper held by its short end bends down, incapable of supporting itself, but if it is arched slightly into a half cylinder it gains enough rigidity to hold a horizontal configuration. The difference between these two conditions can be attributed only to the configuration of the cross-sectional shape of the sheet of paper, since nothing else was different. Similarly, a thin sheet of metal has no significant structural strength in its planar shape. However, when that same sheet is forcefully molded by a large press into an automobile fender, astonishing structural strength is acquired from this change in geometry. The well-known shape of automobile fenders displays two major directions of curvature-longitudinal and transverse that give to this form the characteristics of a synclastic, undevelopable surface.

2. Classification of Shell Surfaces

2.1. Classification based on geometric form

(A) Surfaces of revolution: Surfaces of revolution are generated by rotating a plane curve, called the meridian, about an axis that is not necessarily intersecting the meridian. Circular cylinders, cones, spherical or elliptical domes, hyperboloids of revolution, and toroids are some examples of surfaces of revolution.

(B) Surfaces of translation: A surface of translation is defined as the surface generated by keeping a plane curve parallel to its initial plane as we move it along another plane curve. The two planes containing the two curves are at right angles to each other. It is obtained by translation of a parabola on another parabola; both parabolas have their curvatures in the same direction. Therefore, this shell has a positive Gaussian curvature. For this surface sections, x = constant and y = constant which are parabolas, whereas section z = constant which represents an ellipse: hence its name "elliptic paraboloid" (Figure 3).

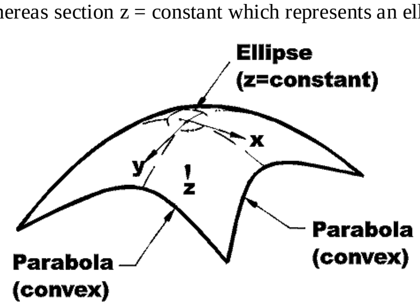

Fig. 3 - Elliptic Paraboloid

Source: Eduard Ventsel, Theodor Krauthammer, "Thin Plates and Shells: Theory, Analysis and Applications", ISBN: 0-8247-0575-0, Eastern Hemisphere Distribution, Switzerland.

2.2. Classification based on shell curvature

(A) Singly curved shells: These shells have a zero Gaussian curvature. Some shells of revolution (circular, cylinders, and cones), shells of translation, or ruled surfaces (circular or noncircular cylinders and cones) are examples of singly curved shells (Figure 4).

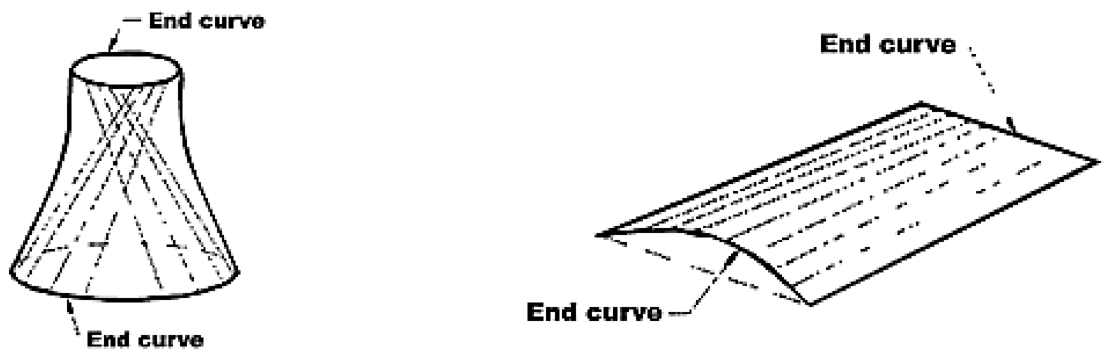

Fig. 4 - Singly Curved Shells

Source: Eduard Ventsel, Theodor Krauthammer, "Thin Plates and Shells: Theory, Analysis and Applications", ISBN: 0-8247-0575-0, Eastern Hemisphere Distribution, Switzerland.

(B) Doubly curved shells of positive Gaussian curvature: Some shells of revolution (circular Domes, Ellipsoids and Paraboloids of revolution) and shells of translation and ruled surfaces (Elliptic Paraboloids, Paraboloids of revolution) can be assigned to this category of surfaces.
(C) Doubly curved shells of negative Gaussian curvature: This category of surfaces consists of some shells of revolution (hyperboloids of revolution of one sheet) and shells of translation or ruled surfaces (Paraboloids, Conoids, hyperboloids of revolution of one sheet).

2.3. Classification based on Geometrical Developability

(A) Developable surfaces: Developable surfaces are defined as surfaces that can be ''developed'' into a plane form without cutting and stretching their middle surface. All singly curved surfaces are examples of developable surfaces.
(B) Non-developable surfaces: A non-developable surface is a surface that has to be cut and stretched in order to be developed into a planar form. Surfaces with double curvature are usually nondevelopable.

3. Types of Thin Shell Structures

(A) Concrete Shell Structures: often cast as a monolithic dome or stressed ribbon bridge or saddle roof.
(B) Lattice Shell Structures: also called grid shell structures, often in the form of a geodesic dome or a hyperboloid structure.
(C) Membrane Structures: which include fabric structures and other tensile structures, cable domes, and pneumatic structures.

4. Geometric Classification of Thin Shell Structures

4.1. Barrel Shells

Barrel shells can easily be visualized from their similarity to a portion of a typical barrel; they are simply part of a cylindrical surface. From the point of view of their morphology, barrel shells are simple-almost intuitive-structures. At present, the thin-shell barrel acts quite differently from the old barrel vault. Whether they are short or long, barrel shells in general are supported at each end by arches that are an integral part of the shell itself and can be considered as stiffening ribs. Barrel thin shells span from arch to arch. More precisely, they can be seen as ruled surfaces originating from straight lines spanning across from one arch to the next. Thus, the spacing between arches coincides with the longitudinal length of the barrel.

(A) Long Barrels: Long barrel shells are characterized by the fact that their longitudinal span is substantially larger than their transverse span (Figure 5).
(B) Short Barrels: Short-barrel shells are those with a width substantially larger than their longitudinal length or span (Figure 6).

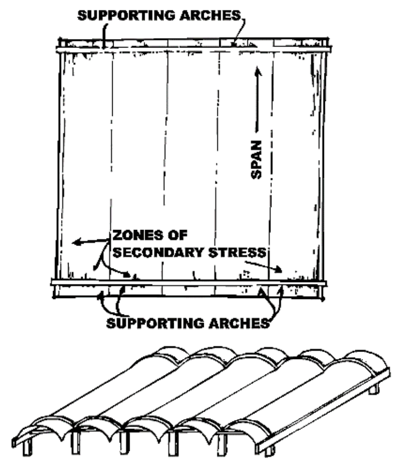

Fig. 5 - Plan (Top) and Perspective (Bottom) of a Design in Long-Barreled Shells

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

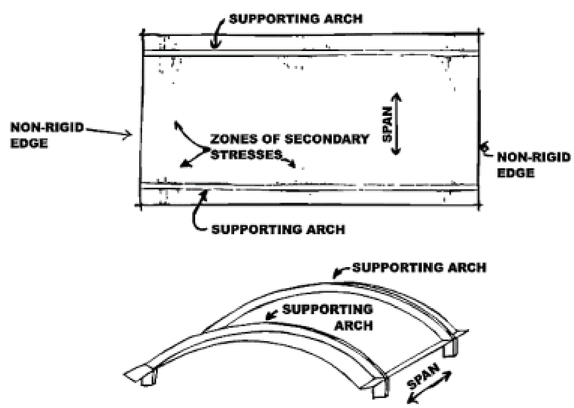

Fig. 6 - Plan (Top) and Perspective (Bottom) of a Short-Barreled Shell with a Nonrigid Edge

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

4.2. Conoidal Shells

Composite conoidal shells are used widely as roofing units to cover large column-free areas because they provide ease of fabrication being single ruled surfaces, look aesthetically elegant and also allow entry of sufficient daylight through inclined sunrays. Doubly curved singly ruled conoidal shells are stiff and easy to fabricate as surfaces and fit excellently to the industrial requirements (Figure 7).

Fig. 7 - Oakland International Airport, California

Source: https://nisee.berkeley.edu/elibrary/getpkg?id=GoddenE66-69

4.3. Spherical Shells

In geometry, a spherical shell is a generalization of an annulus to three dimensions. A spherical shell is the region between two concentric spheres of differing radii.The sphere's structural design is based on a central pillar with a trestle formation that supports the whole building (Figure 8).

Fig. 8 - iGuzziniIlluminazione Headquarters

Source: https://www.domusweb.it/en/architecture/2012/02/23/iguzzini-illuminazione-headquarters.html

In this context, the building was designed with two main bodies. The first is a traditional space for storage, parking, a showroom and an auditorium, all house inside a dark underground floor surrounded by concrete structures. The second body, on the other hand, is a spherical shell designed with a specific technical focus on energy-saving systems. Solar protection is provided by fabric cloak stretched across a three-dimensional metallic structure that envelops the glass facade.

4.4. Cantilevered Shells [Open Cylindrical Shells]

Open circular cylindrical shells are commonly used in civil engineering for roof structures (Figure 9, 10). The curvilinear edges of these shells rest upon some supporting elements in the form of solid diaphragms, tied arches, elevated grid work, and arched truss. These supports are rigid for deformations in their own planes but are flexible for deformations outside their planes. Such cylindrical shells are sometimes referred to as barrel shells.

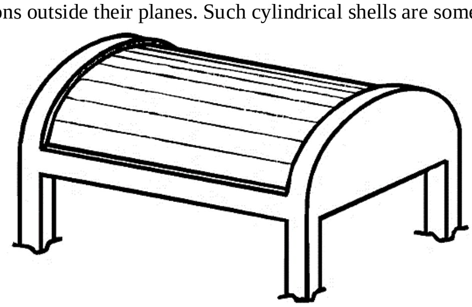

Fig. 10 - Open Cylindrical Shells

Source: Eduard Ventsel, Theodor Krauthammer, "Thin Plates and Shells: Theory, Analysis and Applications", ISBN: 0-8247-0575-0, Eastern Hemisphere Distribution, Switzerland.

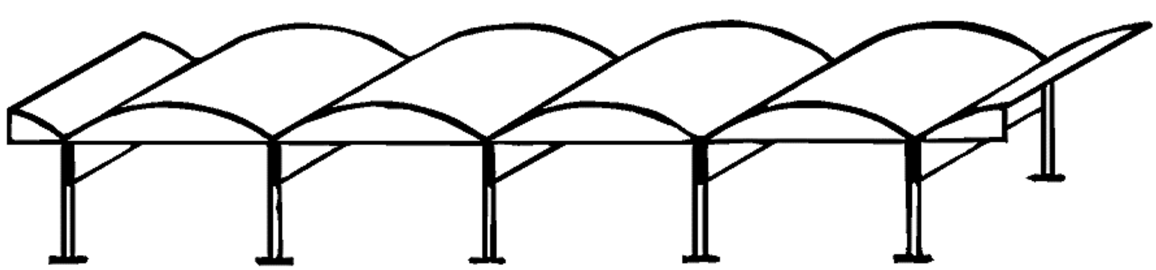

Fig. 10 - Cylindrical Roof Shells

Source: Timoshenko S. and Woinowsky-Krieger S., "Theory of Plates and Shells", 2nd edition, ISBN: 0-07-064779-8, McGraw-Hill Book Company, New York, 1949.

4.5. Hyperboloids

(A) Saddle-Type Hyperbolic Paraboloids [Square Plan on Two Supports (Horizontal)]: The saddle-type Hyperbolic Paraboloids structure has no joint lines marking the connections of different parts and has a unified flow without lines of discontinuity. This structure is a portion of a larger surface form. Its perimeter is constituted of straight lines that in space are skewed but if projected on a horizontal plan would generate a square. This shape consists of a hyperbolic paraboloid enclosed by four edge beams that slope down from two high tips to lower point (Figure 11 and 12).

Table 1 - Optimal Values for the Average Dimensions oftype of Saddle-Type Hyperbolic Paraboloids [Square Plan on Two Supports (Horizontal)]

Sr. No.	Diagonal Span	Tip Height	Reference
1.	100 ft. (30.5 m)	12.5 ft. (3.8 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	200 ft. (61 m)	40 ft. (12.2 m)	
3.	300 ft. (91.4 m)	75 ft. (22.9 m)	

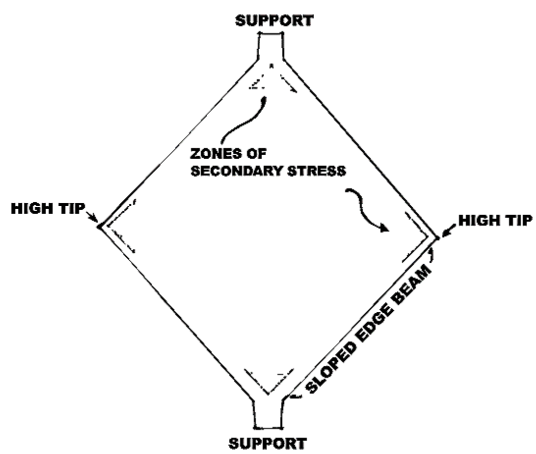

Fig. 11 - A Horizontal Plan of a Saddle-Type Hyperbolic Paraboloid with a Square Plan on Two Supports
Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

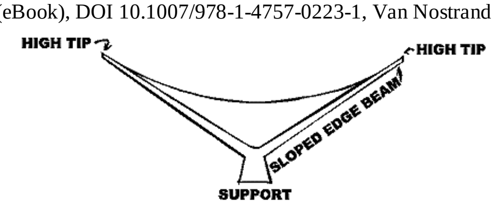

Fig. 12 - An Elevation of a Sloped Saddle-Type Hyperbolic Paraboloid with a Square Plan on Two Supports
Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN: 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(B) Saddle-Type Hyperbolic Paraboloids [Square Plan on Two Supports (Sloped)]: This type of structure is geometrically similar to the saddle-type hyperbolic Paraboloid.The only difference being that in this case the whole structure is rotated around a horizontal axis that passes through the two lower supports. An inclined or sloped structure thus has its two cantilevered tips at different heights from the ground (Figure 13 and 14).

Table 2 - Optimal Values for the Average Dimensions of type of Saddle-Type Hyperbolic Paraboloids [Square Plan on Two Supports (Sloped)]

Sr. No.	Diagonal Span	Tip Height	Reference
1.	100 ft. (30.5 m)	12.5 ft. (3.8 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	200 ft. (61 m)	50 ft. (7.6 m)	
3.	300 ft. (91.4 m)	100 ft. (30.5 m)	

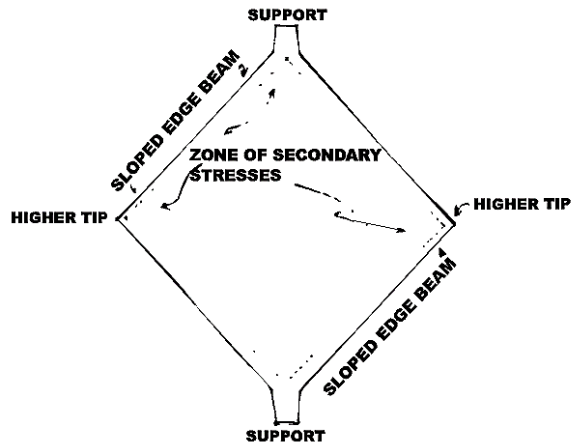

Fig. 13 - The Plan of a Sloped, Saddle-Type, Square-Plan Hyperbolic Paraboloid on Two Supports

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007

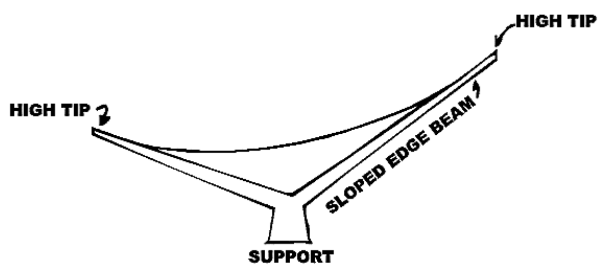

Fig. 14 - The Elevation of a Sloped, Saddle-Type Hyperbolic Paraboloid on a Square Plan on Two Supports

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(C) Four-Gable-Type Hyperbolic Paraboloids (Square Plan): This structure strongly resembles a conventional gable roof. This structure consists of four identical hyperbolic paraboloidal surfaces that form the four quadrants of a square. Each surface has two inclined edge members at its perimeter and two horizontal edge beams, which join adjacent surfaces and form the roofs ridges. The sloped edge beams have variable cross-sections whose depths and thicknesses increase toward the lower corners of the supports. The horizontal edge beams on the ridge where the four quadrants merge also have variable cross-sections, with their depths and widths increasing as the sections progress from the edges of the structure toward its Center. Each edge member produces horizontal thrust that must be counteracted at each corner, which can be done conveniently by using four ties to connect the four corners along the perimeter (Figure 15 and 16).

Table 3 - Optimal Values for the Average Dimensions oftype of Four-Gable-Type Hyperbolic Paraboloids (Square Plan)

Sr. No.	Span	Tip Height	Reference
1.	100 ft. X 100 ft. (30.5 m X 30.5 m)	24 ft. (7.3 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	200 ft. X 200 ft. (61 m X 61 m)	66 ft. (20.1 m)	
3.	250 ft. X 250 ft. (76.2 m X 76.2 m)	93 ft. (28.3 m)	

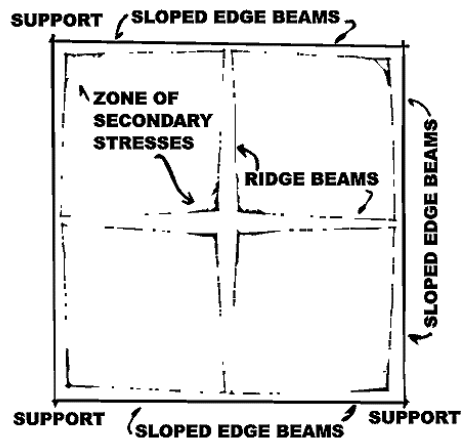

Fig. 15 - The Plan of a Four-Gable-Type, Square Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

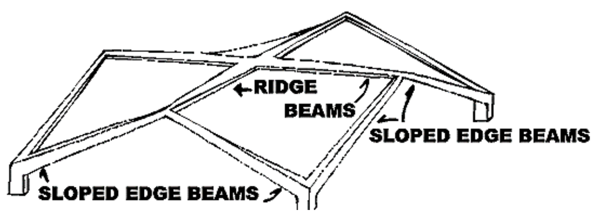

Fig. 16 - The Perspective of a Four-Gable-Type, Square Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(D) Four-Gable-Type Hyperbolic Paraboloids (Rectangular Plan): This type of four-gabled structure is similar to the previous one, except that its plan is rectangular rather than square. Althoughits strong resemblance to a typical gable roof eliminates the dramatic effects that hyperbolic paraboloid surface can produce. This type of assembly of hyperbolic paraboloid surfaces can produce practical roof structures in shell construction, to enjoy its desirable economic values. The economy of this form capitalizes on the simplicity of form work of using straight-line generatrices and the economy that any thin-shell structure offers, due to the minimal amount of concrete it uses (Figure 17 and 18).

Table 4 - Optimal Values for the Average Dimensions of type of Four-Gable-Type Hyperbolic Paraboloids (Rectangular Plan)

Sr. No.	Long Side Span	Short Side Span	Tip Height	Reference
1.	100 ft. (30.5 m)	60 ft. (18.3 m)	20 ft. (6.1 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	140 ft. (42.7 m)	60 ft. (18.3 m)	20 ft. (6.1 m)	
3.	160 ft. (48.8 m)	80 ft. (24.4 m)	32 ft. (9.8 m)	
4.	180 ft. (54.9 m)	80 ft. (24.4 m)	45 ft. (13.7 m)	

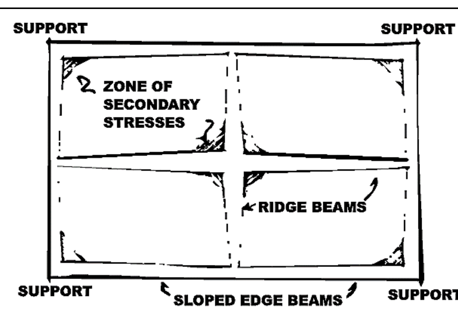

Fig. 17 - The Plan of a Four-Gable-Type, Rectangular Plan, Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

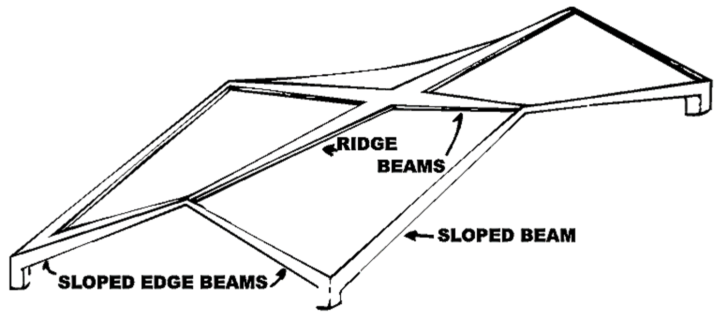

Fig. 18 - The Perspective of a Four-Gable-Type, Rectangular Plan, Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(E) Umbrella-Type Hyperbolic Paraboloids (Square Plan): This type of hyperbolic paraboloid resembles a square pyramid with the support under its apex being like the stem of an umbrella. Though it is less glamorous than the hyperbolic Paraboloids on two supports, this type is quite economical and practical for one-story modular concrete buildings. By using these as the basic model, a large structure can be built in modular formwork to cast individual units that can then be joined together (Figure 19 and 20).

Table 5 - Optimal Values for the Average Dimensions of type of Umbrella-Type Hyperbolic Paraboloids (Square Plan)

Sr. No.	Side Spans	Tip Height	Reference
1.	50 ft. X 50 ft. (15.2 m X 15.2 m)	7.5 ft (2.3 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	100 ft. X 100 ft. (30.5 m X 30.5 m)	29 ft (8.8 m)	
3.	150 ft. X 150 ft. (45.7 m X 45.7 m)	55 ft (16.8 m)	
4.	200 ft. X 200 ft. (61 m X 61 m)	86 ft (26.2 m)	

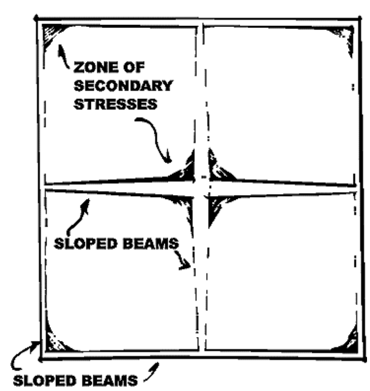

Fig. 19 - The Perspective of a Four-Gable-Type, Rectangular Plan, Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

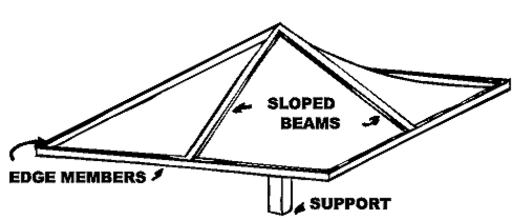

Fig. 20 - The Perspective of an Umbrella-type, Square Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(F) Umbrella-Type Hyperbolic Paraboloids (Rectangular Plan): This structure, which is similar to the previous one, differs only in that the shape of its plan is rectangular rather than square (Figure 21 and 22).

Table 6 - Optimal Values for the Average Dimensions of type of Umbrella-Type Hyperbolic Paraboloids (Rectangular Plan)

Sr. No.	Long Side Spans	Short Side Spans	Tip Height	Reference
1.	120 ft. (30.6 m)	40 ft. (12.2 m)	25 ft. (7.6 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	120 ft. (30.6 m)	60 ft. (18.3 m)	29 ft. (8.8 m)	
3.	130 ft. (39.6 m)	80 ft. (24.4 m)	36 ft. (11 m)	
4.	140 ft. (42.7 m)	100 ft. (30.5 m)	43 ft. (13.1 m)	

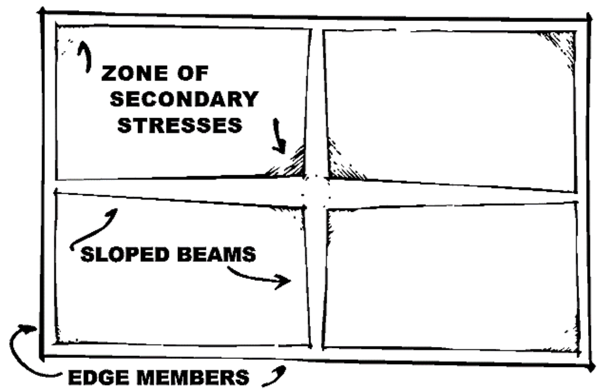

Fig. 21 - The Plan of an Umbrella-Type Rectangular Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

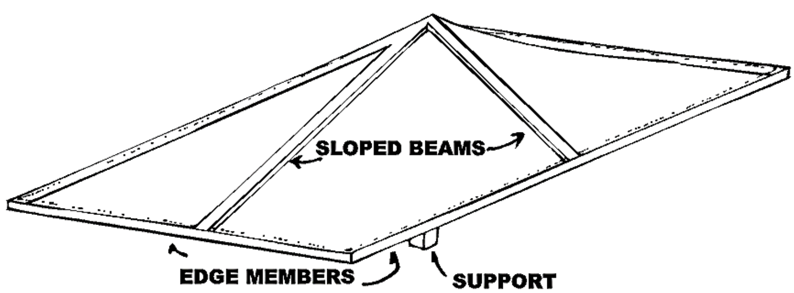

Fig. 22 - A Perspective of an Umbrella-Type Rectanaular Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(G) Inverted Umbrella-type Hyperbolic Paraboloids (Square Plan): This type of structure resembles an umbrella but with the structure inverted (Figure 23 and 24). This inversion creates a drastic difference not only in reversing the types of stresses but also in the way that rain and snow drain off. i.e., rather than flowing outward, the runoff is collected at the center. Drainage pipes are therefore required in the middle of the supporting column. It is particularly critical to be able to guarantee that the drainage system will always work when necessary because failure within the system would create excessive loading. In certain climates, large accumulations of snow can be expected and only melting would make it possible to remove the load. This particular system should thus be considered impractical for high latitudes. As with the umbrella-type hyperbolic paraboloid, the inverted umbrella can also be combined with others to create a system for covering large buildings. The configuration of this structure emphasizes the cantilevered action of the shell, much more so than the umbrella-type previously seen.

Table 7 - Optimal Values for the Average Dimensions of Inverted Umbrella type of Hyperbolic Paraboloid(Square Plan)

Sr. No.	Side Spans	Tip Height	Reference
1.	50 ft. X 50 ft. (15.2 m X 15.2 m)	8 ft. (2.4 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	100 ft. x 100ft. (30.5 m X 30.5 m)	25 ft. (7.6 m)	
3.	200 ft. X 200 ft. (61 X 61 m)	76 ft. (23.1 m)	

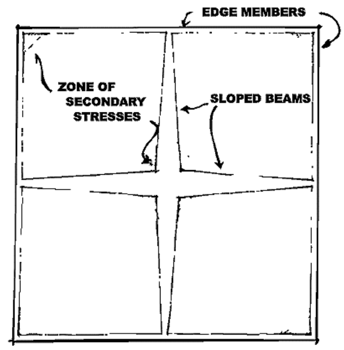

Fig. 23 - The Plan for an Inverted Umbrella-Type, Square Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

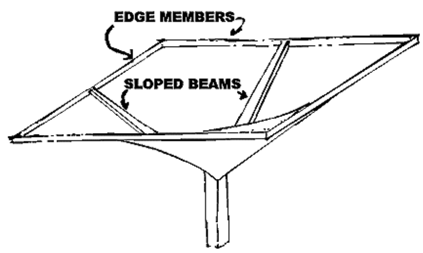

Fig. 24 - The Perspective for an Inverted Umbrella-Type, Square Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

(H) Inverted Umbrella-type Hyperbolic Paraboloids (Rectangular Plan): This structure is similar to the previous one except that its floor plan is rectangular rather than square (Figure 25 and 26).

Table 8 - Optimal Values for the Average Dimensions of Inverted Umbrella Type of Hyperbolic Paraboloid(Rectangular Plan)

Sr. No.	Long Side Spans	Short Side Spans	Tip Height	Reference
1.	100 ft(30.5 m)	40 ft(12.2 m)	19 ft(5.8 m)	Michele Melaragno, *"An Introduction to Shell Structures: The Art and Science of Vaulting"*
2.	150 ft(45.7 m)	40 ft(12.2 m)	30 ft(9.1 m)	
3.	150 ft(45.7 m)	60 ft(18.3 m)	35 ft(10.7 m)	
4.	150 ft(45.7 m)	80 ft(24.4 m)	38 ft(11.6 m)	
5.	200 ft(61 m)	100 ft(30.5 m)	56 ft(17 m)	

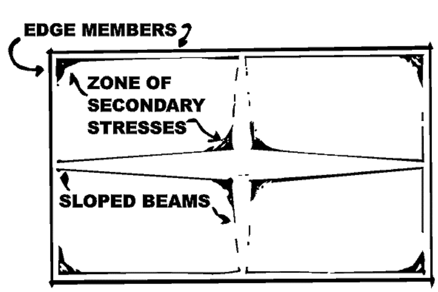

Fig. 25 - The Plan for an Inverted Umbrella-Type, Rectangular Plan Hyperbolic Paraboloid

Source: Michele Melaragno, "An Introduction to Shell Structures: The Art and Science of Vaulting", 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

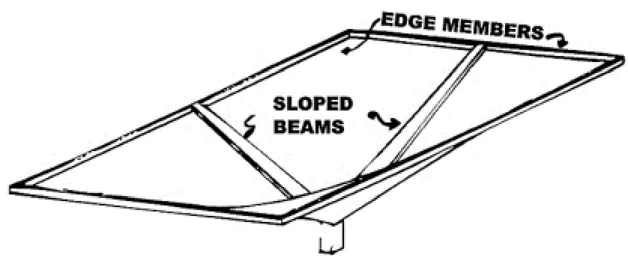

Fig. 26 - The Perspective for an Inverted Umbrella-Type, Rectangular Plan Hyperbolic Paraboloid

Source: Michele Melaragno, “An Introduction to Shell Structures: The Art and Science of Vaulting”, 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

5. The Forming of Shells

5.1. Wood for Formwork

The first material ever used to construct curvilinear forms was wood. It was applied first to the construction of form work for masonry and later for concrete. Although the longitudinal morphology of wood causes it to perform well, especially in rectilinear forms and planar surfaces, it has also done well in the construction of double-curved surfaces. The capabilities of wood in this regard have already been clearly demonstrated not only by the precision of the wood form work used for vaults and domes but even more so with double curvature surfaces used in shipbuilding.

The amazing technological virtuosity of wood in the construction of curved surfaces has been proven in many applications varying according to their geometry and scale. On a small scale, musical instruments, for instance, verify the ability of wood to attain precise, complex geometric shapes in doubly-curved surfaces. On a larger scale, craftsmen have used wood to produce complex shells for entire buildings. Although there is a substantial difference between wood form works and final wood shells, the degree of accuracy and smoothness of wooden forms must be particularly high.It is well known that exposed concrete surfaces reflect glaringly any imperfections in the wood form.

5.2. Special Pneumatic Forming

The adoption of pneumatic forming was an important step toward making feasible the construction of curvilinear concrete forms. In pneumatic forming a membrane is inflated to generate a tensile surface capable of supporting a concrete layer that is then applied on top of it. Concrete spraying has been the most practical method of constructing shells by using pneumatic forms.

A completely new approach toward the inflatable forming method that was devised in the 1950s had several applications that proved the technical feasibility of the method. In this technique, the concrete is poured before inflating the pneumatic form. Then the concrete is lifted by inflating the membrane and spreads uniformly until the membrane is fully raised. This method offers extraordinarily simple construction that looks more and more attractive cost-wise when we recognize that the system can be applied repeatedly.

5.3. Plastic Foam Forming

In the late 1960s, Dow Chemical patented and produced a system using a plastic foam to form concrete thin shells. The name they gave to this process was Spiral Generation, the plastic foam used for the process was manufactured by Dow under the name Styrofoam. Although Styrofoam still has a foot in the market, the Spiral Generation process is no longer in use, although more than two hundred shells were built by it (Figure 27).

Fig. 27 - A 30 ft. (9.15 m) Diameter Styrofoam Dome, 2 in (50 mm) Thick, Nearing Completion

Source: Michele Melaragno, “An Introduction to Shell Structures: The Art and Science of Vaulting”, 1st edition 1991, ISBN 978-1-4757-0225-5, ISBN 978-1-4757-0223-1 (eBook), DOI 10.1007/978-1-4757-0223-1, Van Nostrand Reinhold (VNR), New York.

6. Problems in Building Shell Structures

- A tiny weakness or imperfection on the covering can cause the whole structure to fail.
- When the shell is formed from hot or moist materials, uneven cooling can cause some parts to weaken other parts by pushing on nearby sections.
- Flat materials are difficult to form into the rounded shell shape.
- Assembly of flexible materials is very precise, so that seams are strong where the pieces are joined.

7. Application of Thin-Shell Structure

7.1. Various Application

(A) Architecture and Building: The development of masonry domes and vaults in the Middle Ages made possible the construction of more spacious buildings; and in recent times the development of reinforced concrete has stimulated interest in the use of thin shells for roofing purposes.
(B) 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 suitably formed and joined by riveting. In recent times, the use of welding in pressure-vessel construction has led to much more efficient designs. Pressure-vessels and associated pipework are key components in thermal and nuclear power plant and in all branches of the chemical and petroleum industries.
(C) Structural engineering: An important problem in the early development of steel for structural purposes was to design compression members against buckling. A striking advance was the use of tubular members in the construction of the Forth railway bridge in 1889.Steel plates were riveted together to form reinforced tubes as large as 12 feet in diameter and having a radius/thickness ratio of between 60 and 180, according to function.
(D) Vehicle body structures: The construction of vehicle bodies in the early days of road transport involved a system of structural ribs and non-structural sheeting. The modern form of vehicle construction, in which the skin plays an important structural part, followed the introduction of sheet-metal components, preformed into thin doubly-curved shells by large power presses and firmly connected to each other by welds along the boundaries.
The use of the curved skin of vehicles as a load-bearing member has similarly revolutionised the construction of railway carriages and aircraft. In the construction of all kinds of spacecraft, the idea of a thin but strong skin has been used from the beginning.
(E) Boat Construction: The introduction of fibreglass and similar plastic materials has revolutionised the construction of small and medium-sized boats, since the skin of the hull can be used as a strong, stiff, structural shell.
(F) Miscellaneous: Other examples of the impact of shell construction on technology include the development of large economical natural-draught water-cooling towers for thermal power stations, using thin reinforced-concrete shells and the development of various kinds of economical silos for the storage of grain, etc., by the use of thin steel shells.

8. Advantages And Disadvantages

8.1. Advantages

- The concrete shapes often used for concrete shells are naturally strong structures.
- Shell allowing wide areas to be spanned without the use of internal supports, giving an open, unobstructed interior.
- The use of concrete as a building material reduces both materials cost and the construction cost.
- As concrete is relatively inexpensive and easily cast into compound curves.

8.2. Disadvantages

- Since concrete is a porous material, concrete domes often have issues with Sealing. If not treated, rainwater can seep through the roof and leak into the interior of the building.
- The seamless construction of concrete domes prevents air from escaping, and can lead to buildup of condensation on the inside of the shell.

9. The Future of Thin Shells

The future of thin shells cannot easily be predicted, because there are many factors that can potentially affect the development of such a structural system. A few basic observations may nevertheless serve as indicators.
The present technology makes it feasible to build long-span roof structures in wood, steel or reinforced concrete, as demonstrated by the mega structures recently built for stadiums. Although wood has sporadically been used for these purposes, its cost is usually the highest of the three and its span limitations have already been reached. Steel and reinforced concrete are still competitive in a few countries, but on a worldwide basis steel is definitely higher in cost. Because concrete can easily be produced anywhere in the world, at a lower cost than steel, it thus seems logical that reinforced-concrete thin shells should be the structural system used to erect permanent roof structures enclosing long span buildings. It is important to recognize that concrete thin shells have had only a lifespan of less than a century, quite a short time in comparison to other systems. Building technology has a tradition of moving slowly in accepting or rejecting systems, so it seems probable that thin shells still have a long life ahead of them.

The spherical dome built in reinforced concrete no longer has the limitations of its masonry counterpart. Tension stresses in it can be carried by its steel reinforcement, contrary to the limitations of masonry domes which could carry only compression loads. The thrust at the base of a thin shell can easily be absorbed by a steel-reinforced tension ring. Thin-shell technology has reduced thicknesses in dramatic terms, thereby reducing dead loads, with obvious advantages.

All in all, the concrete dome is a fresh new structure much freer and lighter than its old masonry parent. With this freedom, flat low rise spherical domes can achieve slender ratios never possible before, allowing the free-span diameters of modern domes to exceed several hundred feet in length.

10. Conclusion

- Shell Structures conclude that shell domes can easier to build than large span roof.
- Shell structures, both from the point of view of structural efficiency and esthetic value, can be frequently used to cover large, column-free spaces.
- Shell structures can be very light and yet have a great deal of strength and rigidity.
- Construction cost can be less compare to ordinary floors and roofs construction.
- Maintenance cost is low.
- Due to construction economy and the inherent beauty of these shapes, they can be widely used in recent years.
- For shells of arbitrary shape, the selection of approximate functions is usually difficult and the integration of these functions is very involved.
- A variety of shapes can be formed by different combinations of hyperbolic paraboloid units.
- Thin Shell Structures having thin outside layer means they use very little material.
- The Engineer shall specify the tolerances for the shape of the shell. If construction results in deviations from the shape greater than the specified tolerances, an analysis of the effect of the deviations shall be made and any required remedial actions shall be taken to ensure safe behavior.
- In some types of shells, small local deviations from the theoretical geometry of the shell can cause relatively large changes in local stresses and in overall safety against instability. These changes can result in local cracking and yielding which may make the structure unsafe or can greatly affect the critical load producing instability. The effect of such deviations should be evaluated and any necessary actions should be taken promptly.

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