

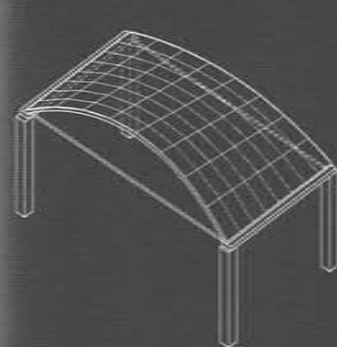
**Shells** are composed of surfaces that distribute loads in plane and have the greatest efficiency when resisting evenly distributed loads. Shells distribute loads along surfaces that can be made of steel-reinforced concrete in combination with masonry or glass to decrease their weight or increase their porosity with respect to light.

The system of shells is subdivided into three primary subsystems: conical shell, hyper-curved umbrella column shell, and three-pointed hyper-curved shell. This subdivision is based primarily on the curvature of the shell – the bending of the surface in two or three directions.

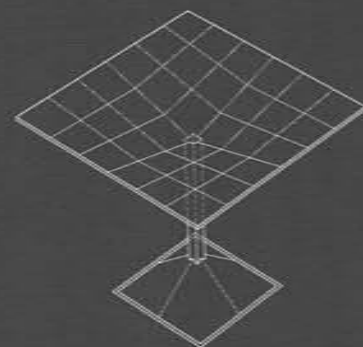
**Conical shells** are formed as a double-curved surface that passes through a single apex at its centre, subdividing the surface into two congruent halves. In geometrical terms, a conical surface is the infinite surface formed by the union of all the straight lines that pass through a fixed point, or its apex, and any point of a fixed curve that does not include the apex. Characteristically, conical surfaces are ruled and developable, and consist of two congruent halves joined by the apex.

**Hyper-curved umbrella column shells** are formed by four rectangular hyperbolic paraboloidal surfaces that extend from the four faces of a column, each bending in two different directions.

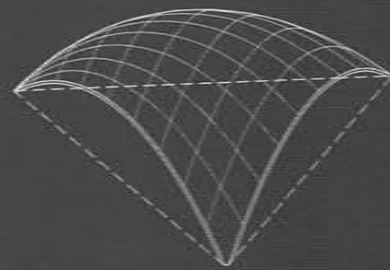
**Three-pointed hyper-curved shells** are formed by hyperbolic surfaces that are double-curved and rest on three points.



Conical Shell



Hyper-Curved Umbrella  
Column Shells

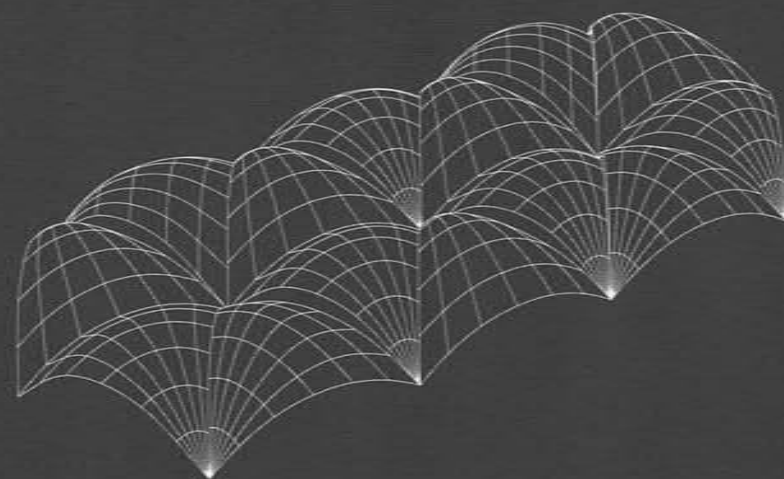


Three-Pointed  
Hyper-Curved Shells

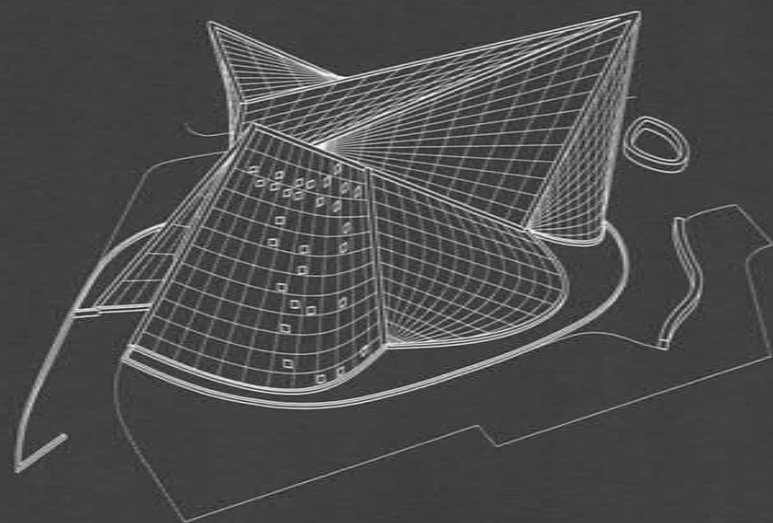
Shells are able to tessellate along horizontal and curved lines of growth to produce horizontal and curved structural forms. The lines of force are distributed along the surface of the shell, a form which is inherently structural, with the resulting differentiated section offering flexibility, in plan, with respect to the distribution of the load-bearing points.

**Horizontal tessellation** can occur in conical shells and hyper-curved umbrella column shells because the protogeometry of these systems is capable of distributing loads along the horizontal axis. Horizontal tessellation introduces flexibility at ground level and in the surface of the roof.

**Curved tessellation** can occur in hyper-curved shells because their protogeometry allows for a differentiated pattern which is not axial, to produce an eccentric overall form that differs from the inherently curved form of the base unit. Curved tessellation is different from that of horizontal, in that it does not follow a linear or radial pattern of repetition, but one that is based on an irregular and differentiated pattern of repetition that stems from a varying relationship between each of the base units, resulting in an eccentric overall form.



Horizontal Tessellation



Curved Tessellation

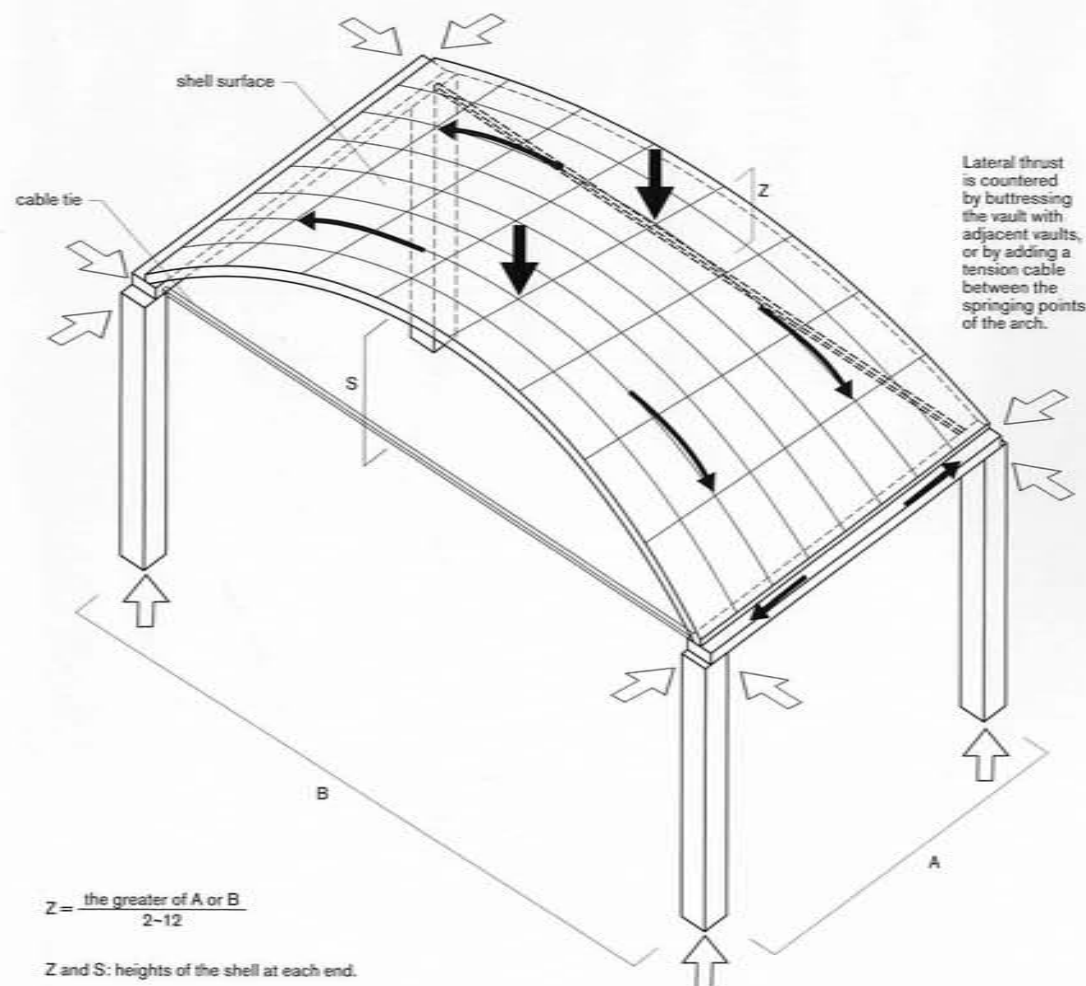
**The base unit of a conical shell** is composed of a surface that is extruded perpendicularly to join two hyperbolic curves, spanning primarily longitudinally to meet edge beams resting on columns or load-bearing walls, with a cable tie located at the abutment of these edge beams and the columns or load-bearing walls. Conical shells direct the primary loads along the surface of the shell. Conical shells can be made of steel-reinforced concrete, which can also be mixed with lightweight terracotta or glass bricks to reduce the overall weight. Conical shells derive their structural strength when their curvature approximates to that of an arch or catenary. The distribution of loads along the surfaces of a conical shell embeds it with an optical affective property of arching and directionality that remains consistent within any space it defines. The acoustical affect of a shell is determined by the curvature of its surface. Consequently, a concave shell has an affect of focusing near the centre of curvature, and a convex one has an affect of diffusion. At a distance from the center of a concave shell, or in the case of a concave shell with a shallow curvature, the shell has an affect of specularity.

Conical shells are flexible in several ways:

**Span:** Conical shells can be flexible in the degree of curvature in the shell surface, which allows for a range in the spans that bridge the edges, with the curvature increasing as the span increases. Accordingly, they can tessellate horizontally along straight or curved lines of growth to produce primarily horizontal structures, or sheds.

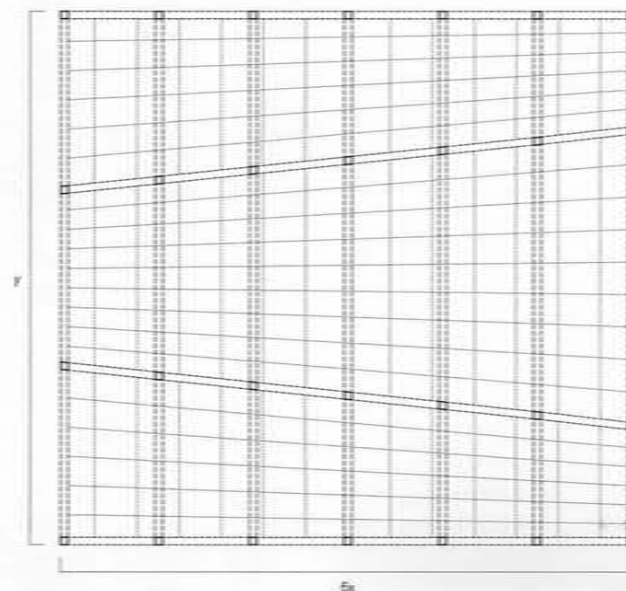
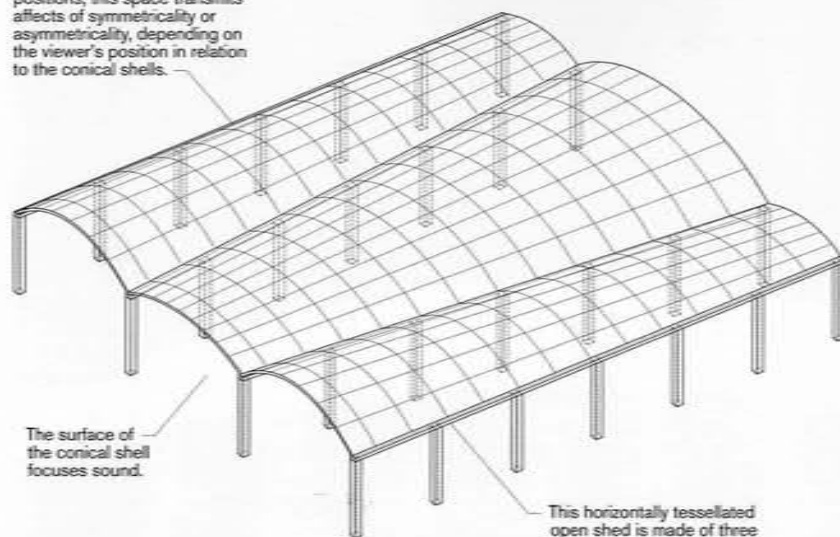
**Profile:** The degree of curvature of the shell's surface can vary, resulting in a wide range of profiles. The more the curvature of the shell approximates to that of an arch or a catenary, the more it gains in structural strength as well as the ability to be self-supporting.

**Affect:** The optical affective properties of a conical shell can be multiplied when the base unit imbricates or intertwines with external factors, such as asymmetries that respond to the physical constraints of the site, environmental considerations, programmatic concerns, etc. As a result, in addition to arching and directionality, a conical shell can transmit other affects, including quilting, piercing, linearity, orientedness, braiding, hyper-curving. The acoustical affect of conical shells can be focusing or specularity.

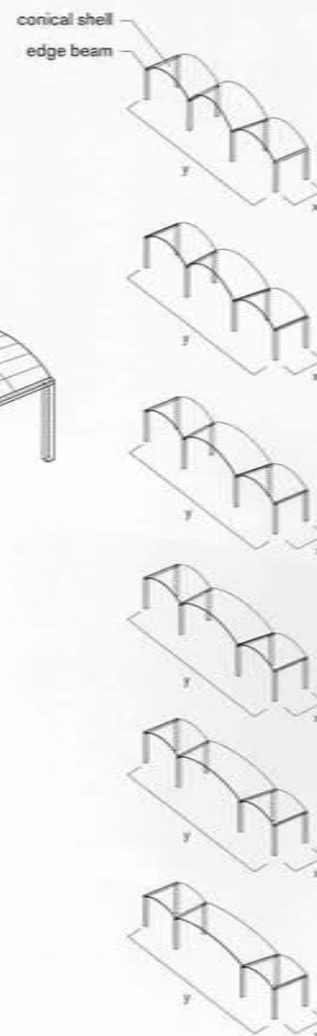




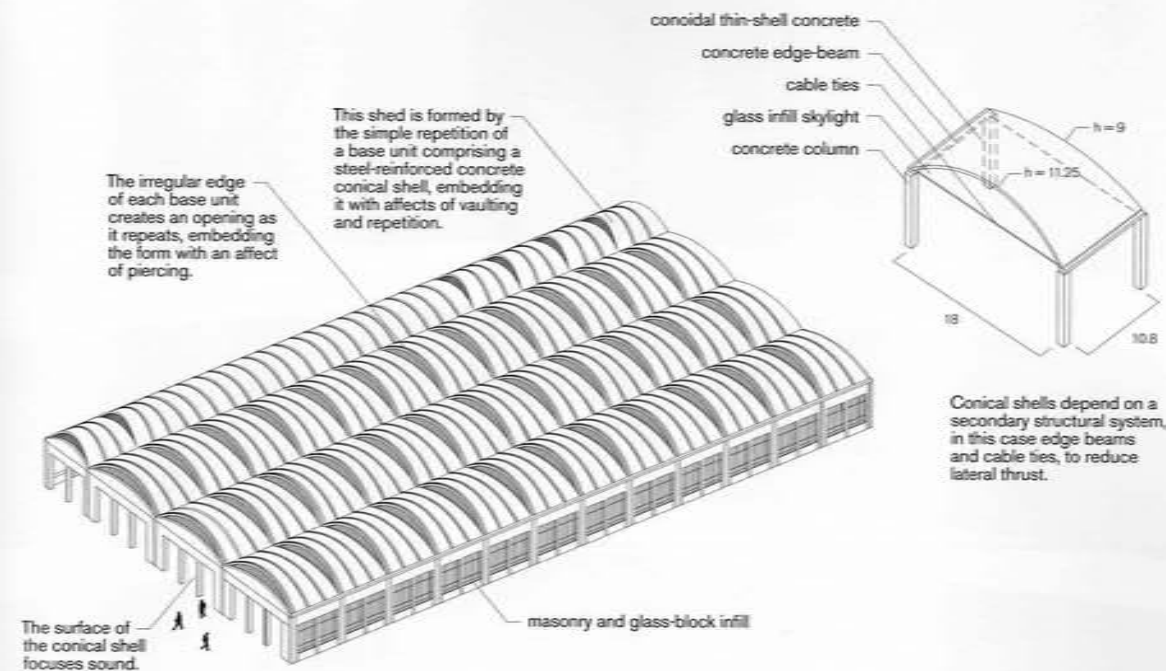
Owing to changes in the ceiling profile and column positions, this space transmits affects of symmetricality or asymmetricality, depending on the viewer's position in relation to the conical shells.



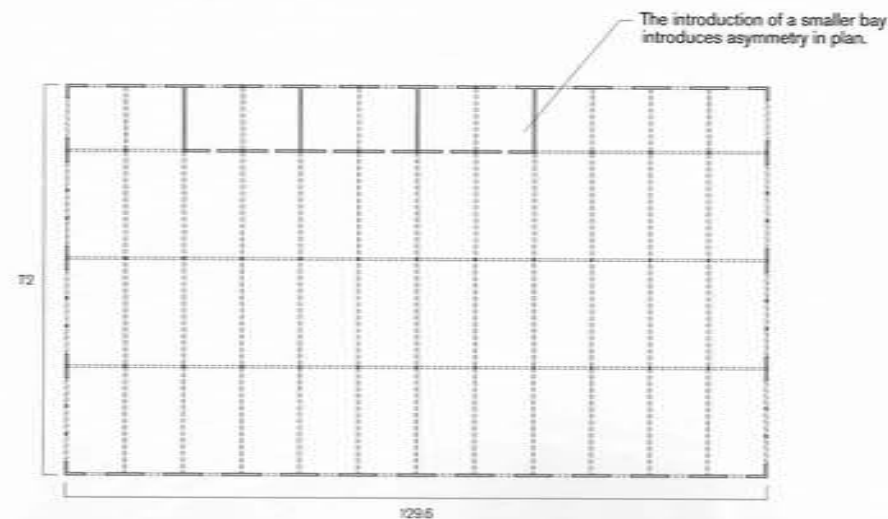
This horizontal form is produced by the tessellation of a conical shell base unit to create three long bays spanning four axes of columns positioned so as to reduce or increase gradually the width of the bays. Gradually increasing or decreasing the space between the columns causes the curvature of the conical shell to change in section, increasing or decreasing its depth correspondingly and enabling the base unit to respond to asymmetrical conditions along the perimeter. This assemblage transmits an optical affect of vaulting, symmetricality and asymmetricality, and an acoustical affect of focusing.







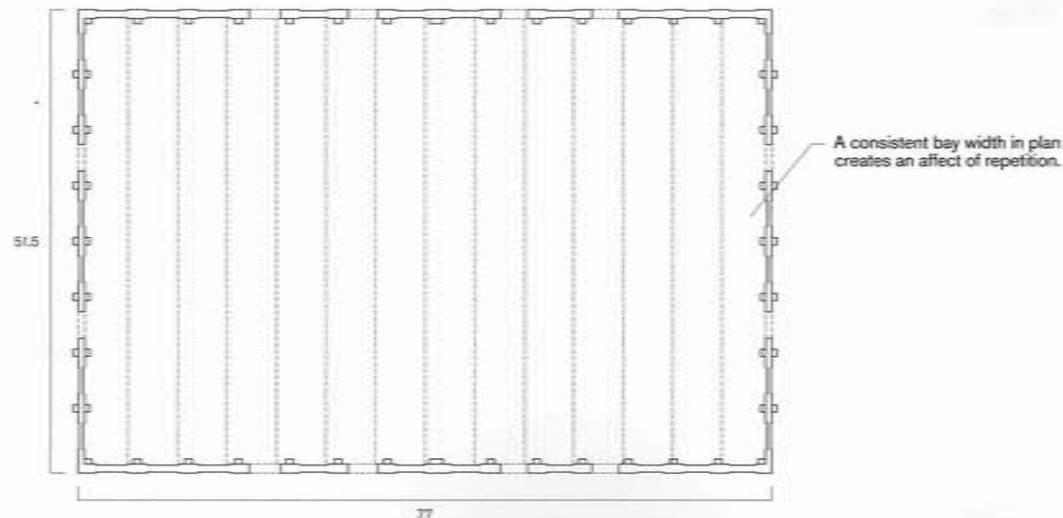
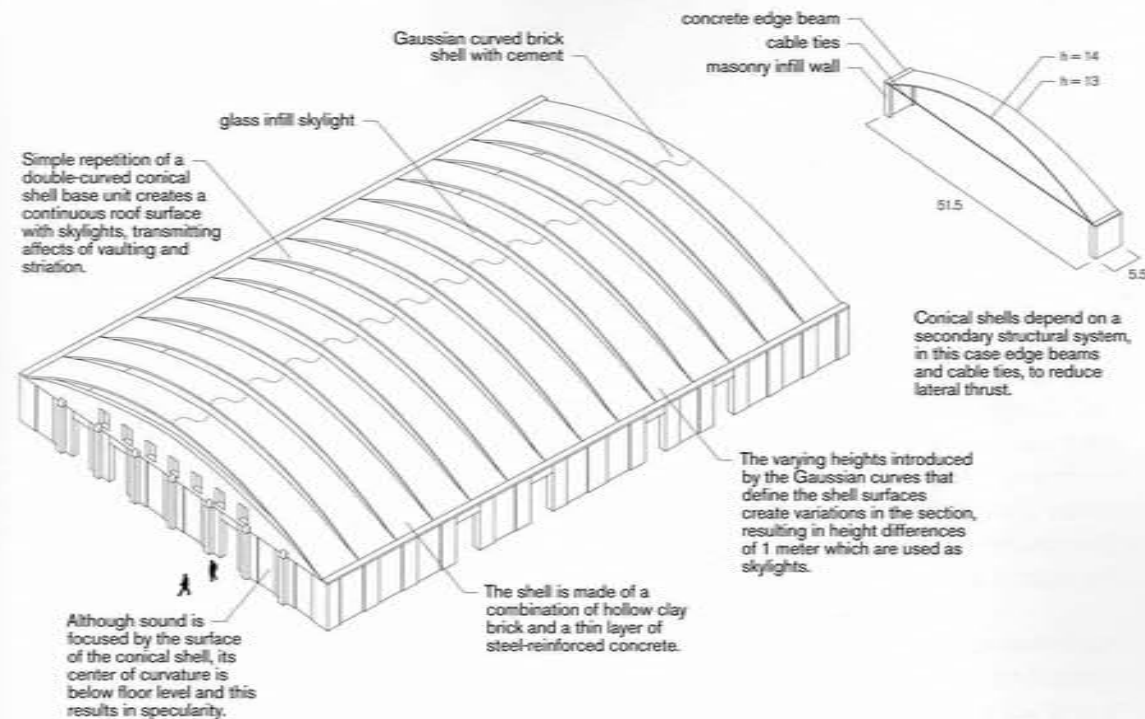
Conical shells depend on a secondary structural system, in this case edge beams and cable ties, to reduce lateral thrust.



This railway workshop is produced by the tessellation of a curved conoidal shell base unit, to create four barrel-vaulted bays that span four axes of columns and the walls along the perimeter to rest on edge beams. The flexibility offered by this assemblage of base units lies in its section. The apertures in the surface of the roof can be altered by adjusting the double curvature of each of the shells to enable the structure to respond to programmatic or environmental requirements. This railway workshop transmits an optical affect of piercing, vaulting and repetition, and an acoustical affect of focusing.



PORT WAREHOUSE E. DIESTE MONTEVIDEO, URUGUAY 1979



The Port Warehouse is produced by the tessellation of a curved conical shell base unit spanning the full bay to create a series of shells resting on the perimeter walls. The flexibility of this type of assemblage lies in its section. The number and size of the apertures in the roof can be controlled by gradually adjusting the Gaussian curve located at the central apex, which defines the double curvature of each surface, and, similarly, the overall section can be adjusted to increase or decrease the volume to enable the structure to respond to programmatic or environmental requirements. The Port Warehouse transmits an optical affect of vaulting, striation and repetition, and an acoustical affect of specularity.

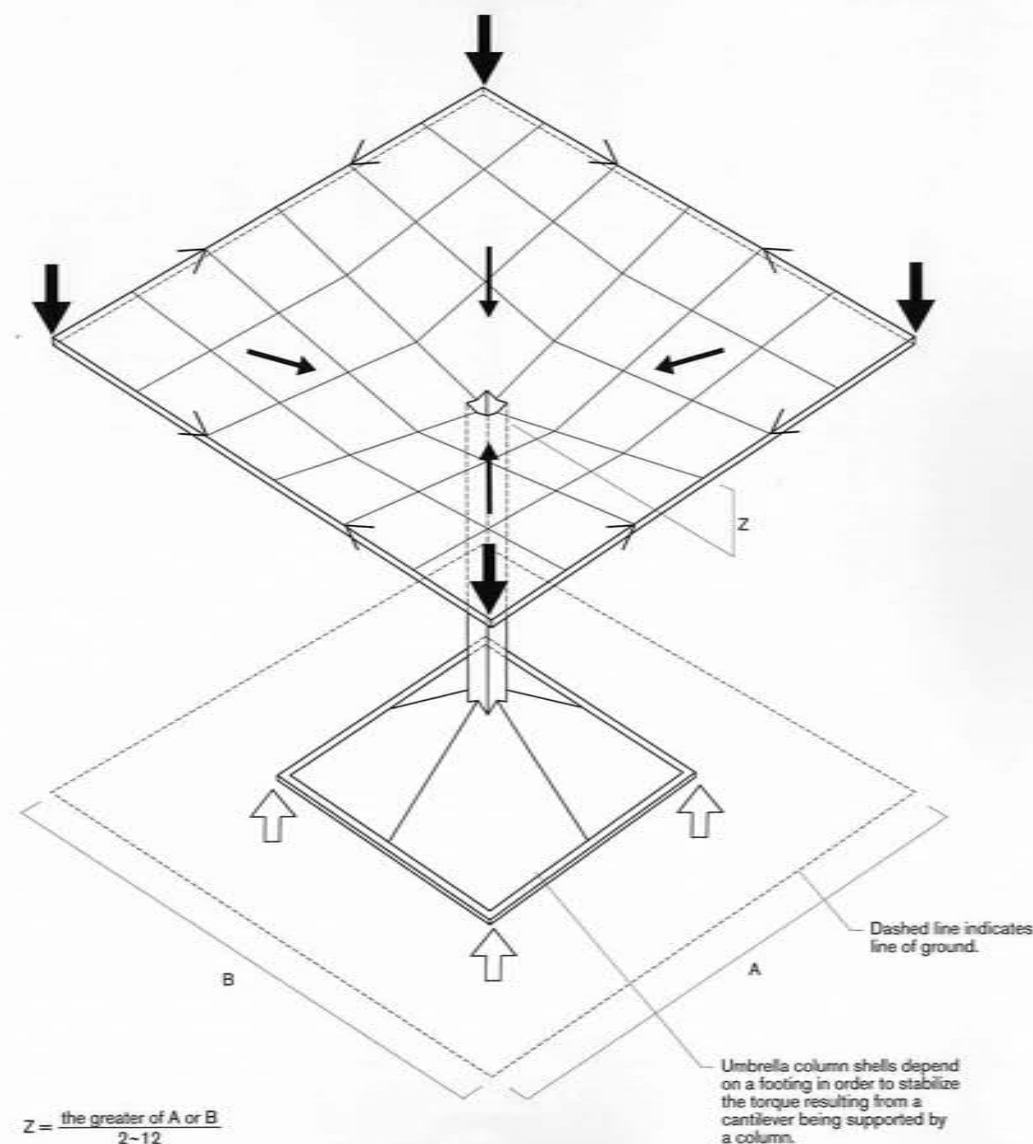
**The base unit of a hyper-curved umbrella column shell** is composed of surfaces, usually four, which are derived from the extension of the faces of a column that is polygonal in plan. Hyper-curved umbrella column shells direct the primary bending moments through their surfaces, along multiple axes, transferring the forces from the horizontally spanning hyper-surfaces to the vertical faces of the column. Hyper-curved umbrella column shells can be made of reinforced concrete, although in some instances terracotta bricks are incorporated to reduce the overall weight, or glass-block bricks to bring light in. The distribution of loads in a hyper-curved umbrella column shell embeds it with an optical affective property of slanting and linearity that remains consistent within any space it defines. The concave surfaces of the umbrella shell may promote focusing or specularity, depending upon the expanse and radius of curvature of the surfaces.

Hyper-curved umbrella column shells are flexible in several ways:

**Plan:** Hyper-curved columns can tessellate horizontally along straight or curved lines of growth to produce primarily horizontal structures, or sheds.

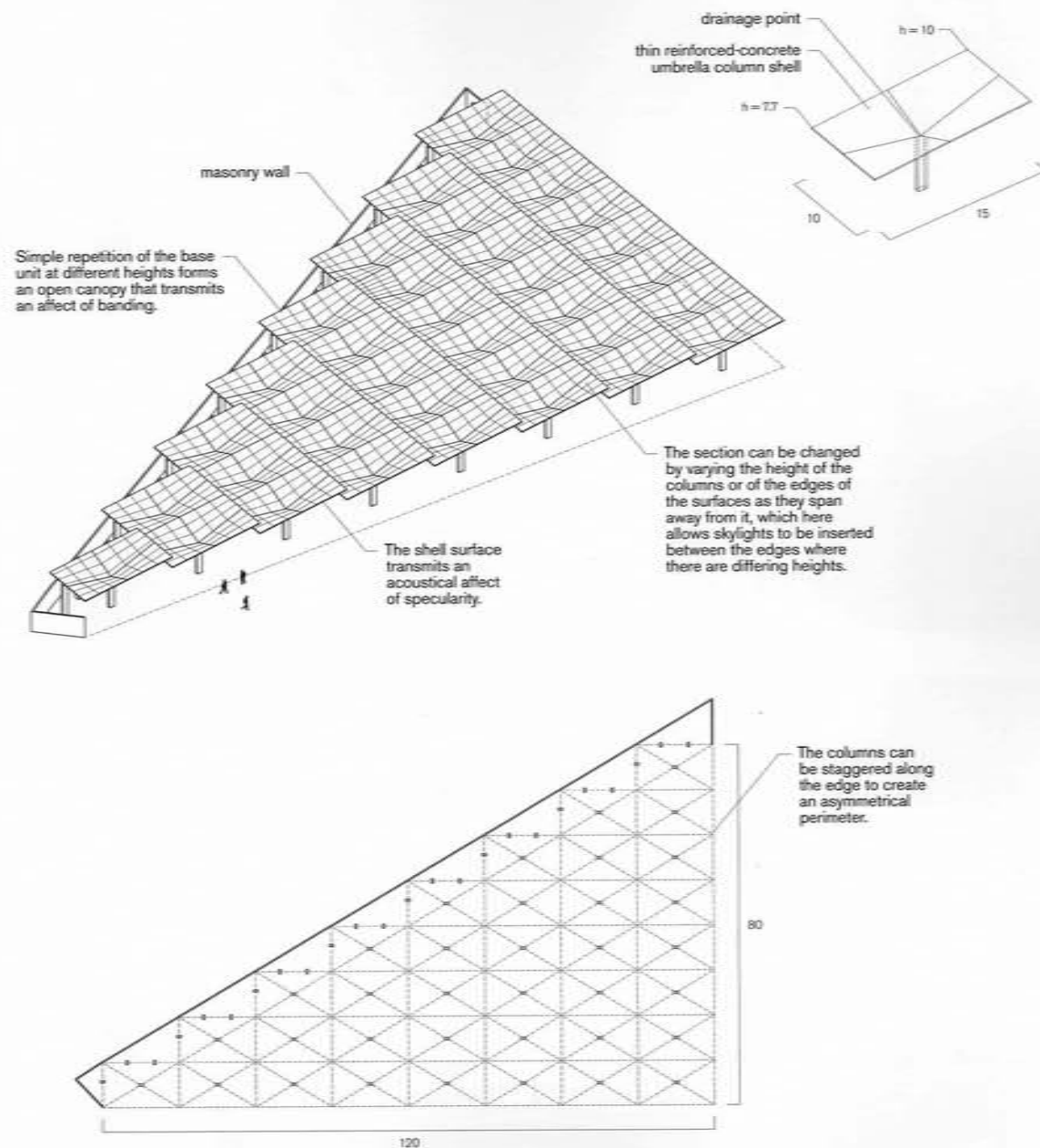
**Profile:** The protogeometry of hyper-curved umbrella column shells allows them to be flexible in the section of the surfaces springing from the column, and also in the height of the column itself.

**Affect:** The optical affect of a hyper-curved umbrella column shell can be multiplied when the base unit imbricates or intertwines with external factors, such as asymmetries that respond to the physical constraints of the site, environmental considerations, programmatic concerns, etc. As a result, in addition to slanting and linearity, a structure made of hyper-curved umbrella column shells can transmit other affects, including folding, tenting, axially, hyper-curving, focusing, specularity. The acoustical affect of umbrella shells can be diffusion or specularity.





RIO WAREHOUSE F. CANDELA, A. SÁENZ DE LA CALZADA MEXICO CITY, MEXICO 1953-54



The Rio Warehouse is produced by the tessellation of an umbrella column shell base unit, to create a series of bays in which the shells span outwards from columns symmetrically positioned along the central axis of each bay. The elevations between the surfaces can be changed by gradually changing the height of each of their faces, and the overall height of the column can also vary. Gradual changes to the overall section, in terms of both the shell surfaces and the height of the columns, can change the volume of the space as well as the amount of natural light, allowing it to respond to programmatic needs and environmental conditions. The Rio Warehouse transmits an optical affect of banding, and an acoustical affect of specularity.





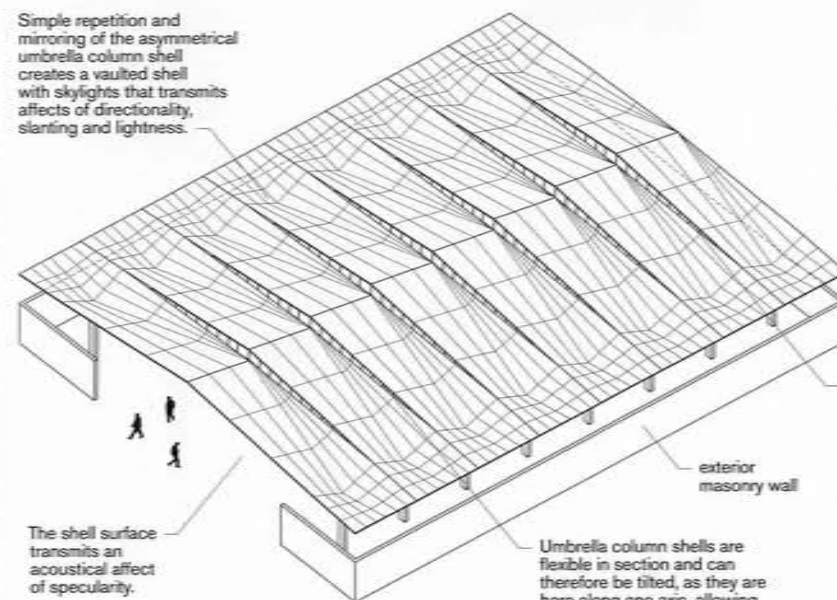
HERNAIZ WAREHOUSE

F. CANDELA

MEXICO CITY, MEXICO

1956

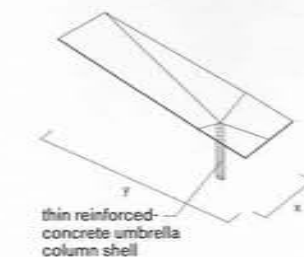
Simple repetition and mirroring of the asymmetrical umbrella column shell creates a vaulted shell with skylights that transmits affects of directionality, slanting and lightness.



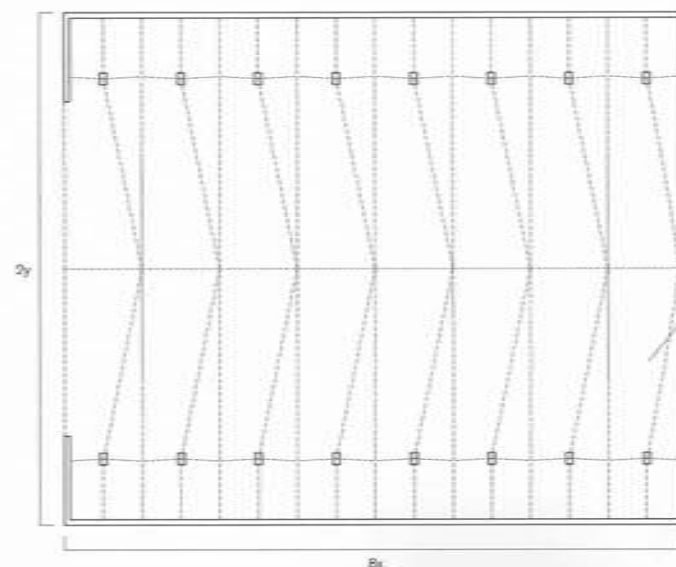
The shell surface transmits an acoustical affect of specularity.

Umbrella column shells are flexible in section and can therefore be tilted, as they are here along one axis, allowing clerestory lighting to be introduced.

exterior masonry wall

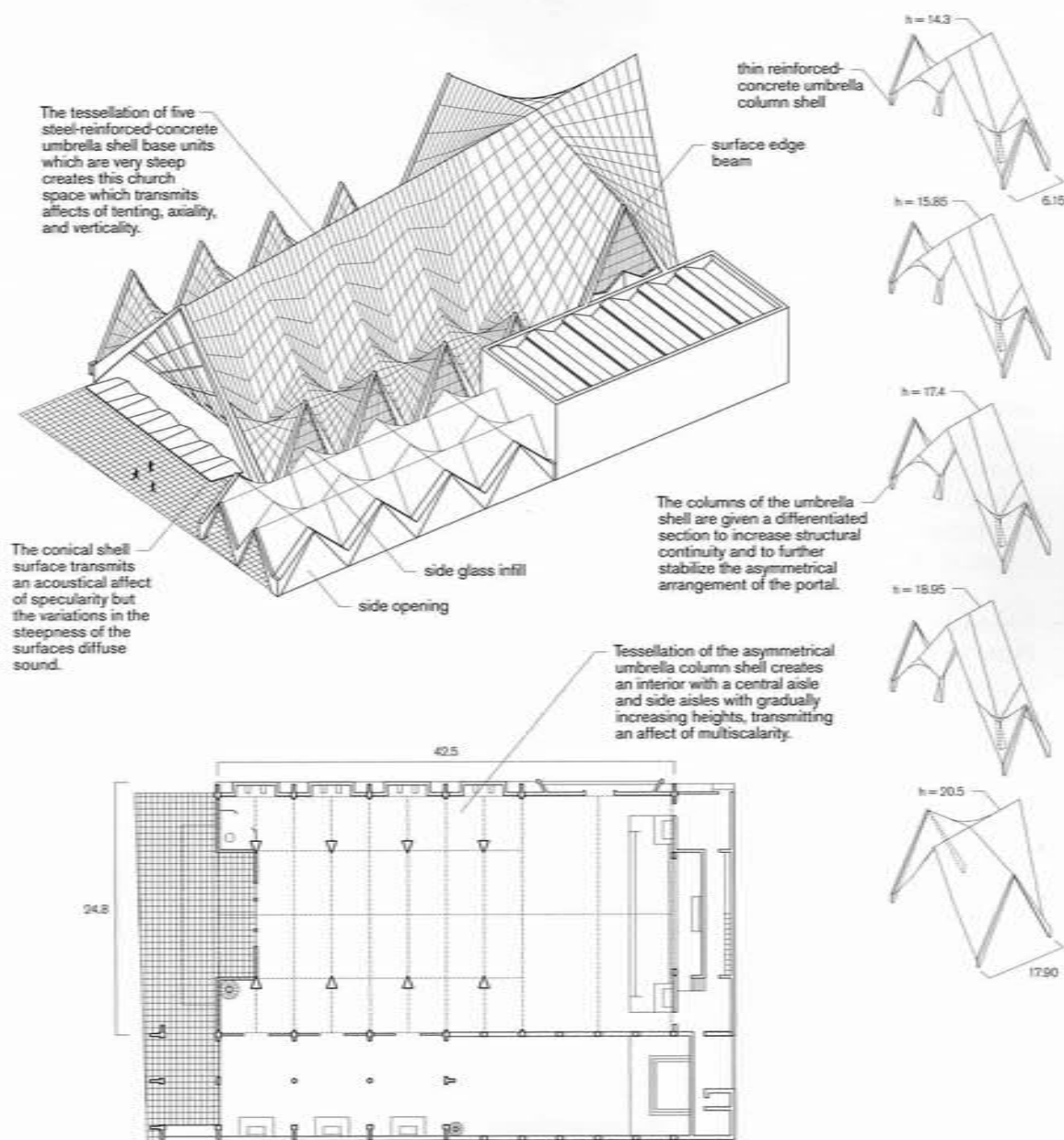


The section can be changed by varying the height of the columns or of the edges of the surfaces as they span away from it, which here allows skylights to be inserted between the edges where there are differing heights.



Tessellation of the umbrella column shell base unit transmits an affect of axiality.

The Hernaiz Warehouse is produced by the tessellation of an umbrella column shell base unit to create a central bay and two smaller side aisles, with the shells spanning outward from a set of columns located asymmetrically along the central axis of each bay. Here the umbrella column shells work in pairs to create a single bay. A gradual increase in height of the apex can vary the section from one bay to the next, increasing or decreasing its height in response to programmatic or environmental needs. The Hernaiz Warehouse transmits an optical affect of directionality, slanting, axiality and lightness, and an acoustical affect of specularity.



The church of Our Lady of the Miraculous Medal is produced by the tessellation of an umbrella column shell base unit to create a central bay composed of five variations of the base unit and two smaller side aisles, with the shells spanning outward from a set of columns located asymmetrically along the central axis of each bay. The umbrella column shells work in pairs to create a single bay. The height of the section is increased by a gradual increase in the height of the base unit as it repeats. The height of the columns is also reduced gradually, and in the final bay they disappear altogether, leaving the upper surface of the shell free-standing. These adjustments to the section, which alter not only the height of the structure but also the elevations, enable it to respond to both programmatic and environmental needs. The church of Our Lady of the Miraculous Medal transmits an optical affect of tenting, axiality, and verticality, and acoustical affects of specularity and diffusion.

**The base unit of a three-pointed hyper-curved shell** is composed of a hyper-surface spanning in two directions, which rests on three vertices. Three-pointed hyper-curved shells the primary loads through the section of the shell. The geometry of the shell is determined by the nature and magnitude of the loads it will resist. For predominantly uniformly distributed loads the (ie if the shells self weight governs as is the case in long span roofs) the curvature will be close to spherical. Hyper-curve shells can be made of thin-shell reinforced concrete spanning very great distances. The distribution of loads along the hyper-surfaces of a three-pointed hyper-curved shell embeds it with an optical affective property of lightness and radiating that remains consistent within any space it defines.

The acoustical affect of a shell is determined by the curvature of its surface. Consequently, a concave shell has an affect of focusing near the center of curvature, and a convex one has an affect of diffusion.

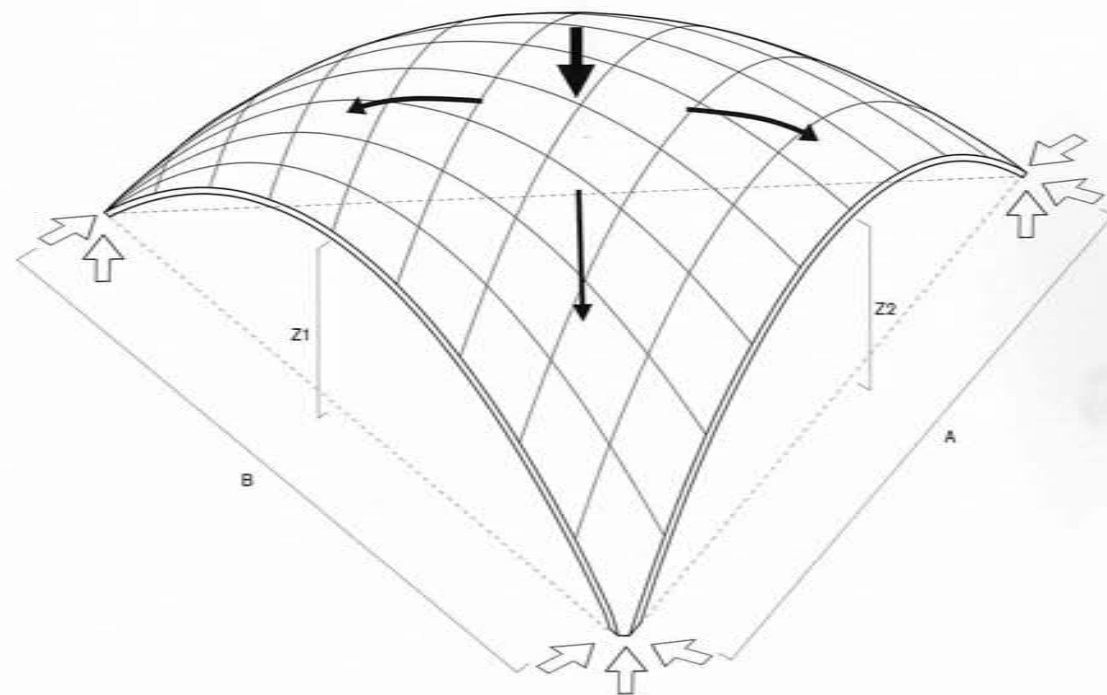
At a distance from the center of a concave shell, or in the case of a concave shell with a shallow curvature, the shell has an affect of specularity.

Three-pointed hyper-curved shells are flexible in several ways:

**Plan:** Three-pointed hyper-curved shells can tessellate horizontally along straight or curved lines of growth to produce primarily horizontal or curved structures.

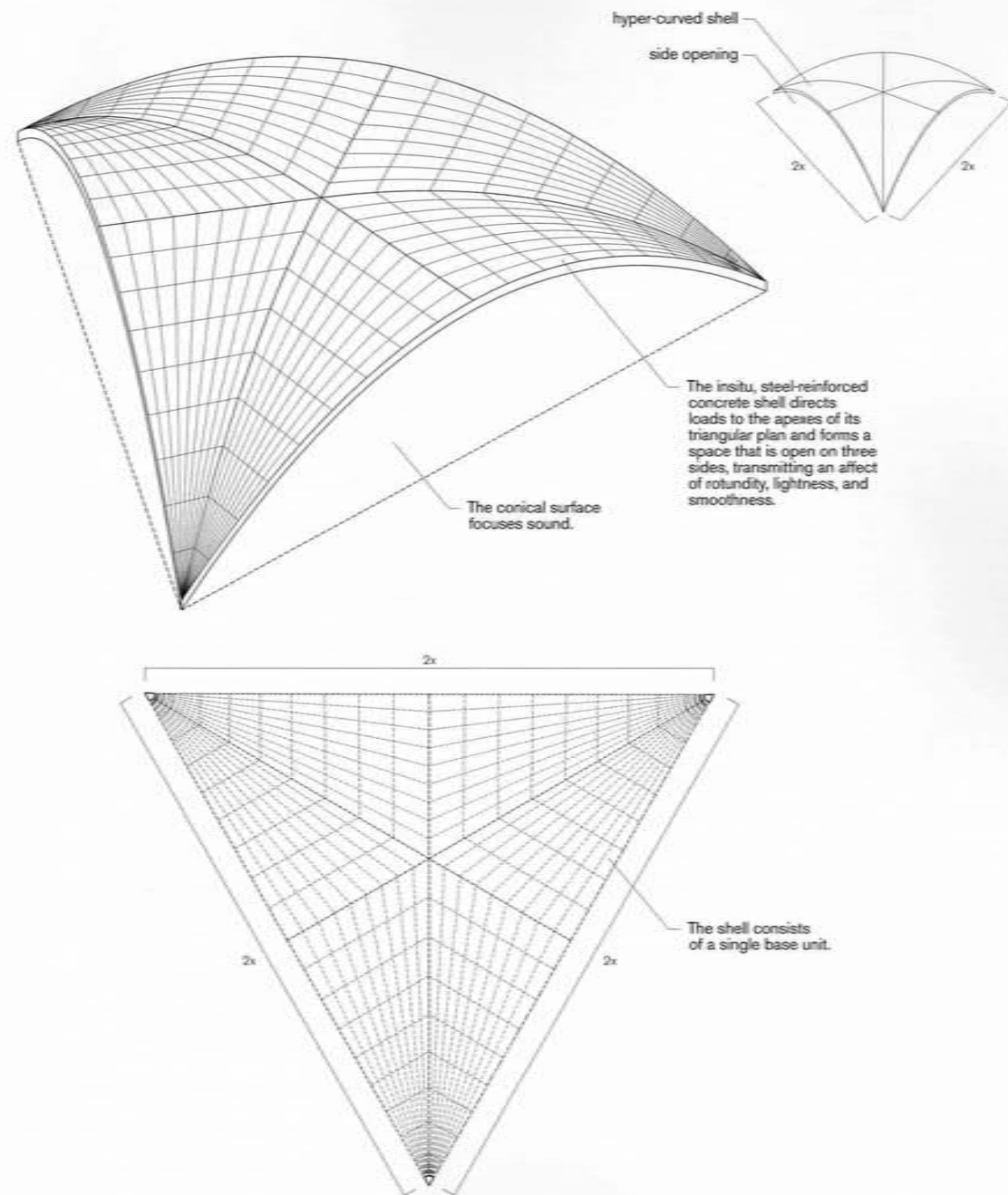
**Profile:** The protogeometry of a three-pointed hyper-curved shell allows it to be flexible in the range of curvature given to the surface and the curvature of the edges, which can form an arched opening in a wide range of widths. The curvature of the shell's surface can also vary, resulting in a wide range of profiles.

**Affect:** The optical affective property of a three-pointed hyper-curved shell can be multiplied when the base unit imbricates or intertwines with external factors, such as asymmetries that respond to the physical constraints of the site, environmental considerations, programmatic concerns, etc. As a result, in addition to lightness and radiating, a structure made of a three-pointed hyper-curved shell can transmit other affects, including rotundity, attenuation, thinness, pleating, enclosure, triangularity, slitting, tapering, scalloping, flaring, pleating, torquing. The acoustical affect of a hyper-curved shell can be focusing or specularity.



$$Z1 = \frac{B}{2-12}$$

$$Z2 = \frac{A}{2-12}$$

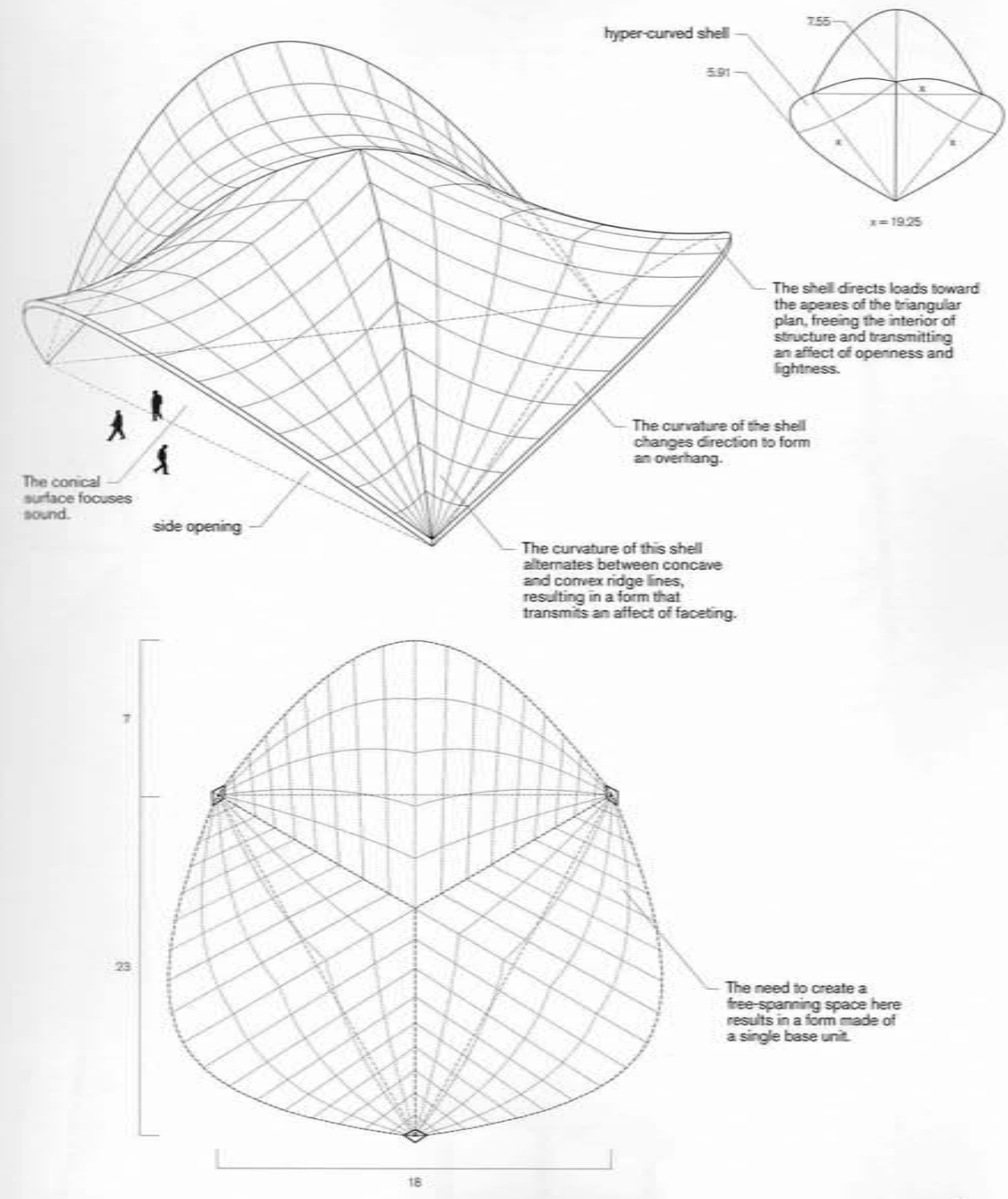


This horizontal form is produced by a hyper-curved shell base unit. This type of assemblage is flexible in the changes that can be made to the curvature of the arch in elevation and to the section as the surface of the shell is developed. Gradual changes in the curvature of the arches that form the three elevations, together with changes in the height of the central apex, enable the form to respond to programmatic and environmental needs. This form transmits an optical affect of rotundity, lightness and smoothness, and an acoustical affect of focusing.





LA JACARANDA NIGHTCLUB F. CANDELA, J. SORDO ACAPULCO, MEXICO 1957



The La Jacaranda Club is produced by a hyper-curved shell base unit. This type of assemblage is flexible in the changes that can be made to the curvature of the arch in elevation and to the section as the surface of the shell is developed. Gradual changes in the curvature of the arches that form the three elevations, together with changes in the height of the central apex, enable the form to respond to programmatic and environmental needs. The La Jacaranda Club transmits an optical affect of centeredness, lightness and smoothness, and an acoustical affect of focusing.

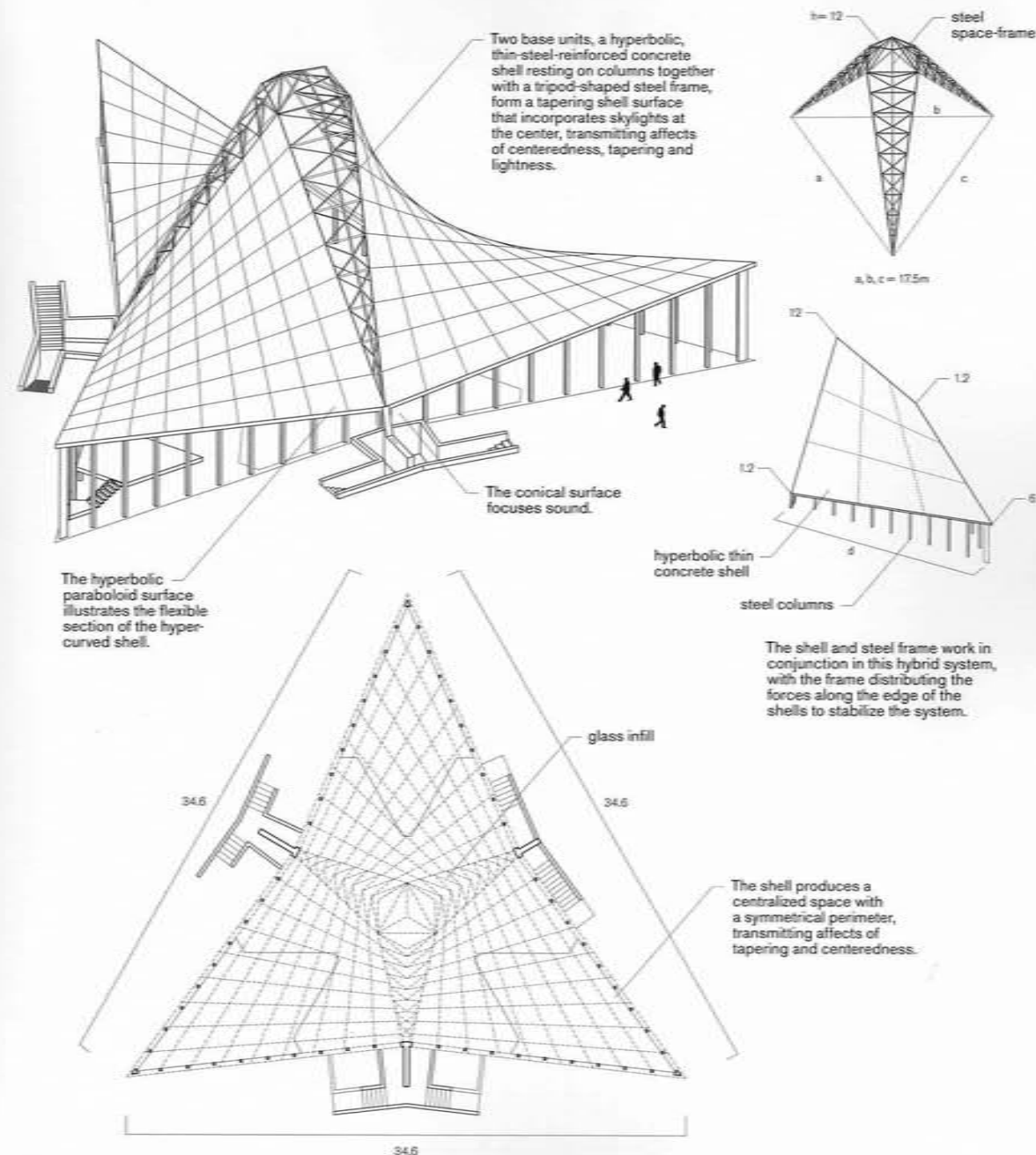


ST. VINCENT DE PAUL CHAPEL

F. CANDELA, E. DE LA MORA, A. LÓPEZ CARDONA

MEXICO CITY, MEXICO

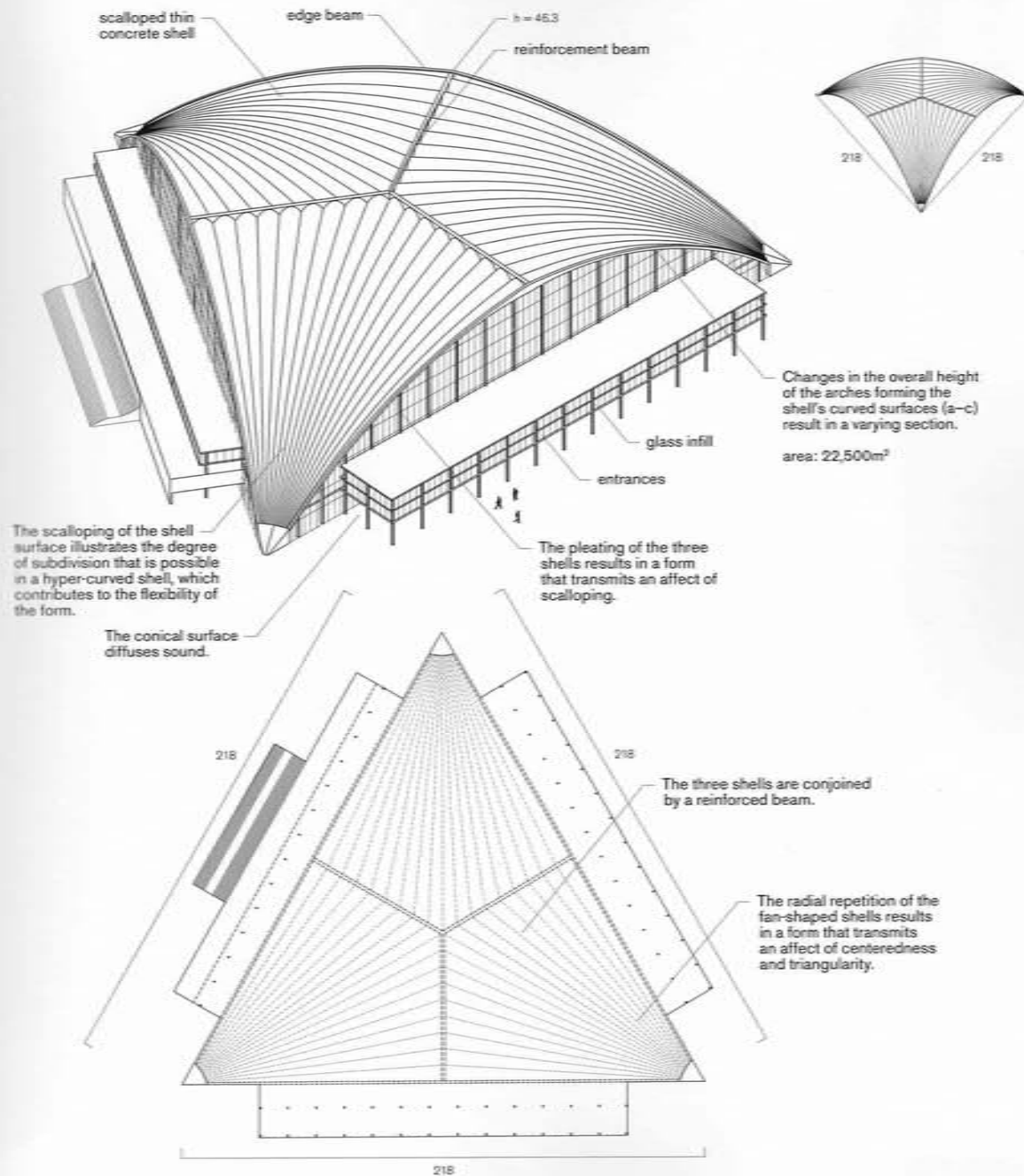
1958-59



The St. Vincent de Paul Chapel is a hybrid form produced by the tessellation of a hyper-curved shell working in conjunction with a steel space frame. Three shells are supported at their centers by a space frame, a tripod made of open steel trusses. Gradual changes in the height of the apexes of the shells changes their sections and elevations. Higher apexes increase the area of the side elevation. In this type of form more than three surfaces can meet at the central tripod to create enclosed space in a variety of shapes, such as pyramidal or rectangular or linear. The St. Vincent de Paul Chapel transmits an optical affect of centeredness, tapering and lightness, and an acoustical affect of specularity.



CNIT BUILDING R. CAMELOT, J. DE MAILLY, B. ZEHRFUSS, P.L. NERVI, J. PROUVÉ, N. ESQUILLAN PARIS, FRANCE 1958



CNIT building is the largest concrete shell in the world in terms of the ratio between the supports and the floor area covered. It is formed by three scalloped hyper-curved shells that intersect at a central point. The individual shells are not autonomous, but depend on one another to form the base unit. The flexibility of the design lies in the changes which can be made to the curvature of the arch in elevation, and the changes in section, as the surface of the shell is developed. The CNIT building transmits an optical affect of centeredness, triangularity and scalloping, and an acoustical affect of diffusion.

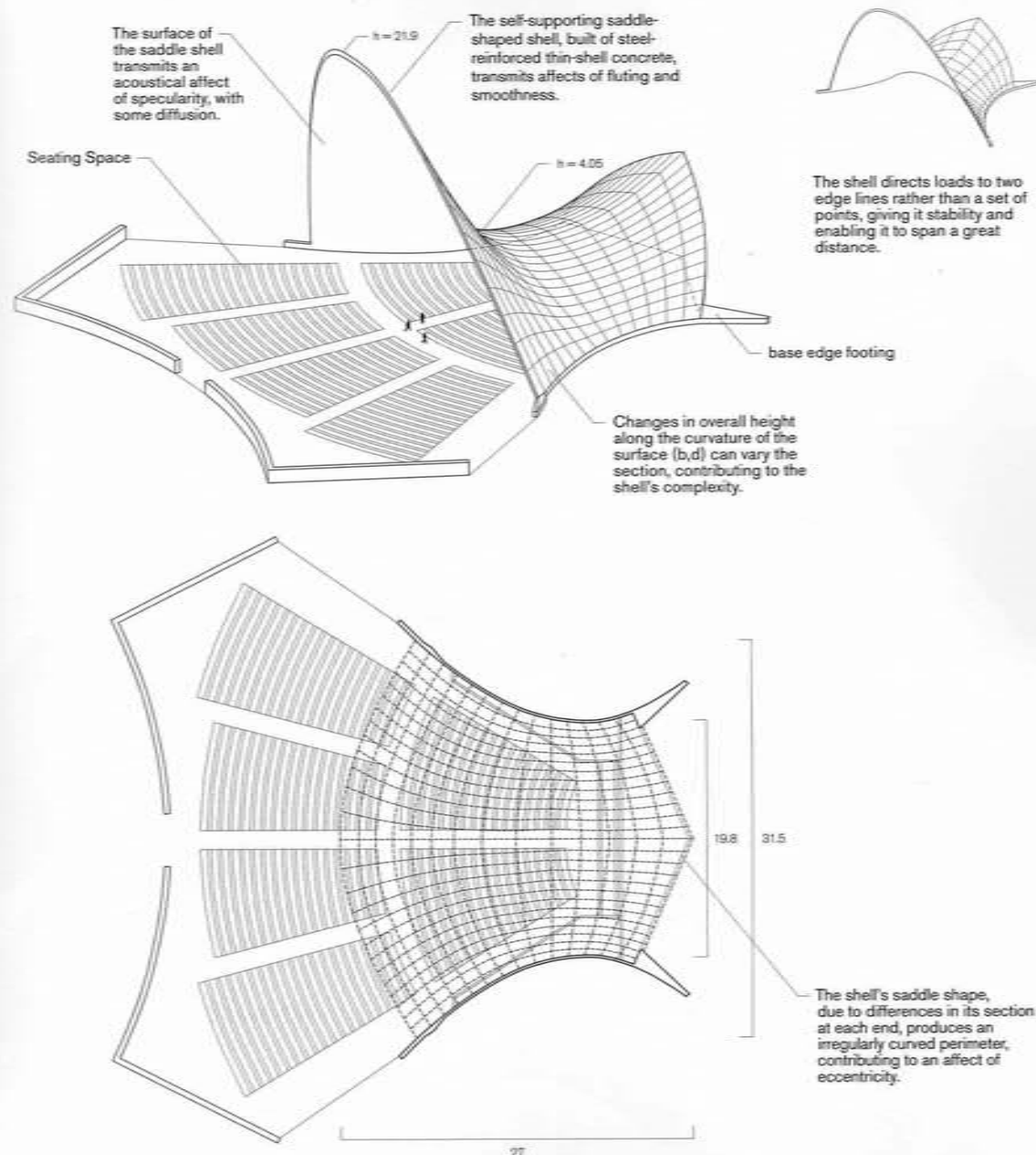


LOMAS DE CUERNAVACA CHAPEL

F. CANDELA, G. ROSELL, M. LARROSA

CUERNAVACA, MEXICO

1958



The Lomas de Cuernavaca Chapel is produced by a hyper-curved base unit, which comprises a single paraboloid shell, saddle-shaped and self-supporting. The curvature of the shell can be changed by modifying the radii of the curves that define the plan, while changes in the width or steepness of the shell's curvature can also change its form, to enable this type of shell to adapt to programmatic needs such as acoustical properties, or environmental requirements such as the introduction of natural light to the interior. The Lomas de Cuernavaca Chapel transmits an optical affect of fluting, smoothness, complexity and eccentricity, and an acoustical affect of specularity and diffusion.



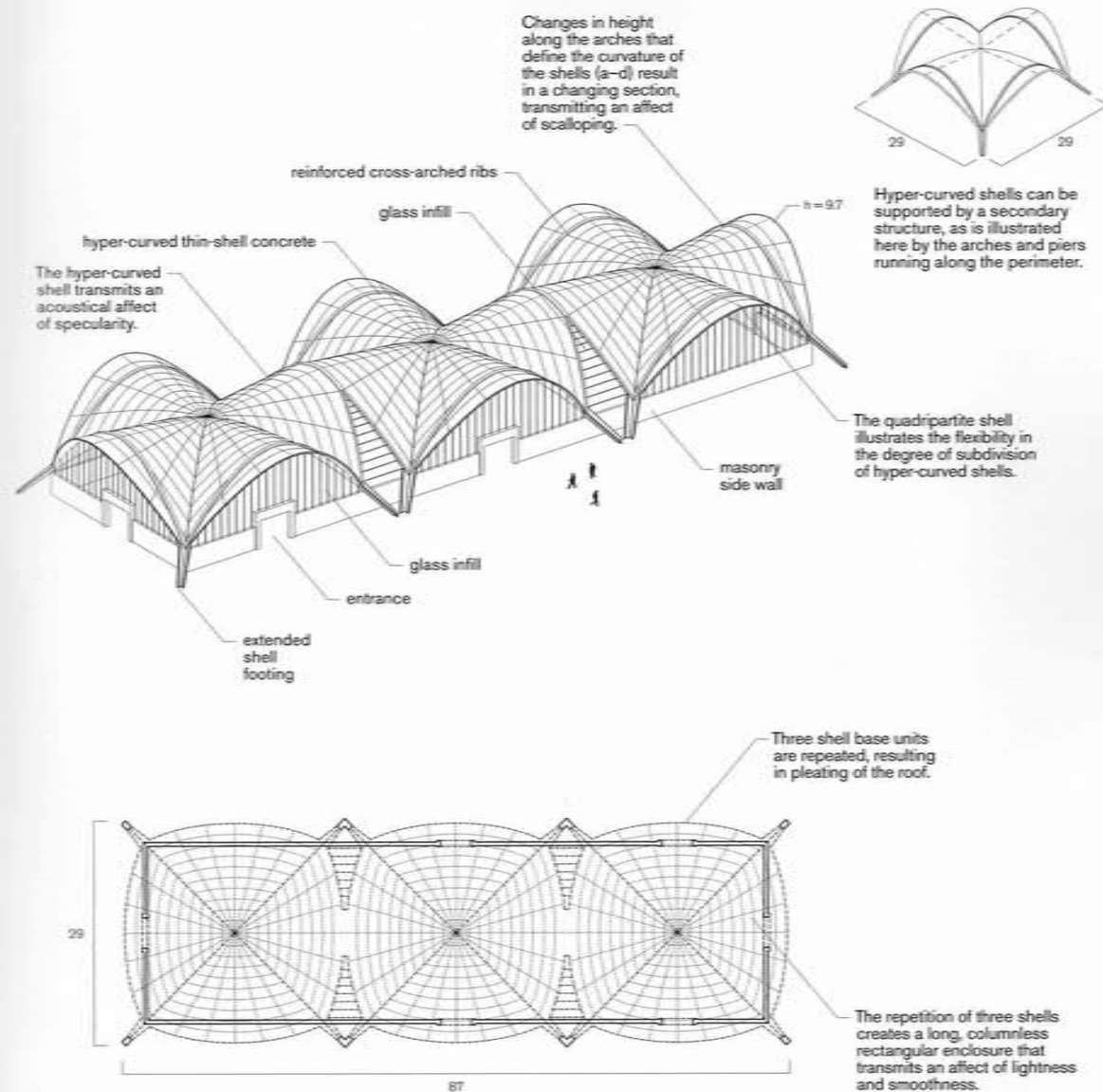


BACARDI BOTTLING PLANT

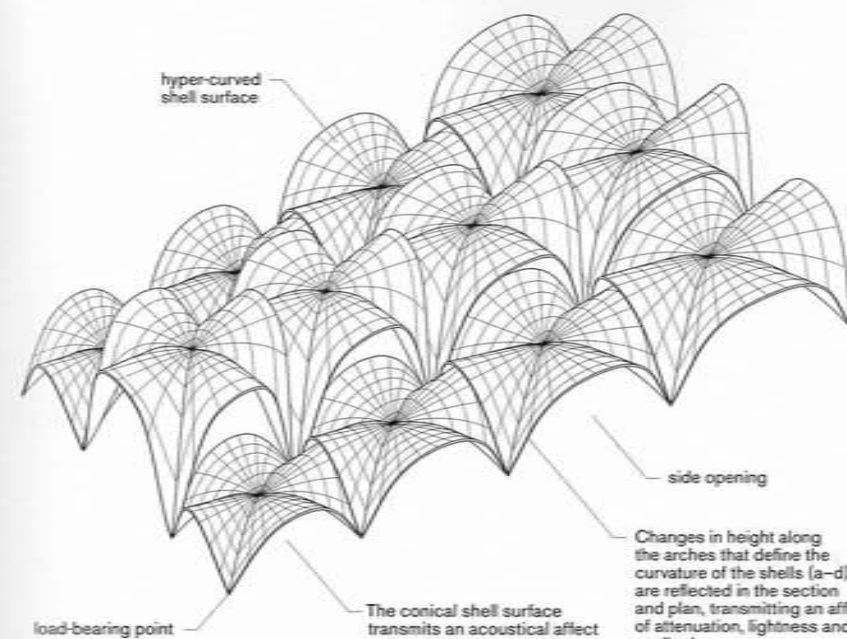
F. CANDELA, A. SÁENZ DE LA CALZADA,  
CANCIO-MARTÍN, ÁLVAREZ AND GUTIÉRREZ

CUAUTITLÁN IZCALLI, MEXICO

1960

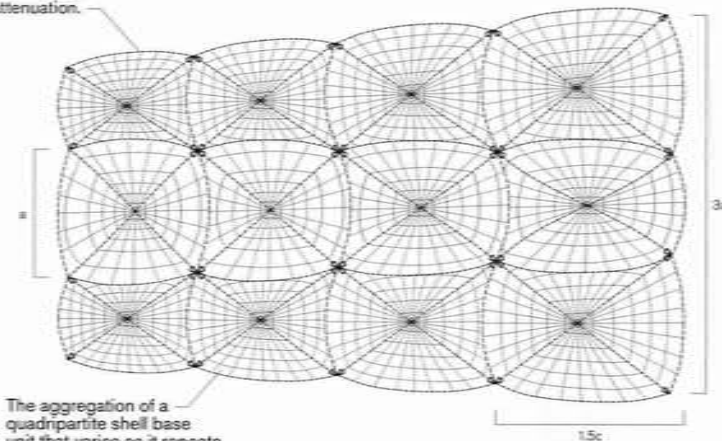


The Bacardi Bottling Plant is produced by a hyper-curved concrete shell base units. Shells intersect to form a cross-vault with glass and masonry infill. The plan and section can be changed by increasing or decreasing the radii of the curves that define the arches in order to change their height, or the area of the glass and masonry infill can be extended, to allow the structure to adapt to programmatic or environmental requirements such as the volume of the space or the amount of natural light. The Bacardi Bottling Plant transmits an optical affect of scalloping, pleating, lightness and smoothness, and an acoustical affect of specularity.



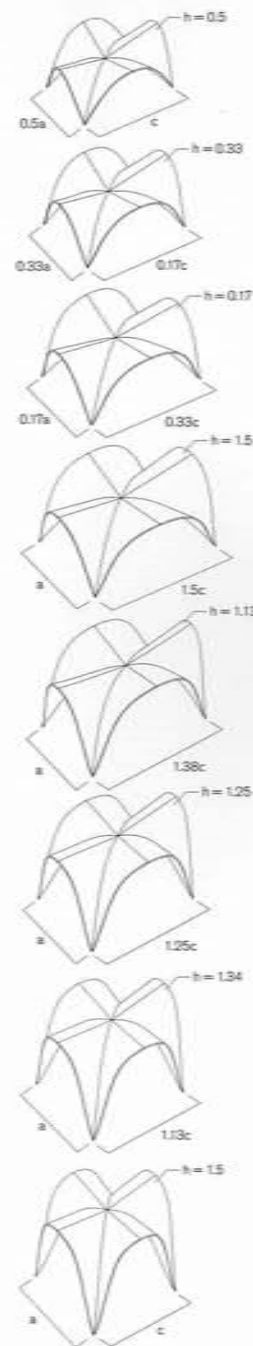
The conical shell surface transmits an acoustical effect of specularity which may, however, be overwhelmed by the diffusion resulting from the aggregation of multiple shell surfaces.

The changes in section allow for a variety of heights in the elevations and an increase in the amount of surface overhang, transmitting an affect of attenuation.

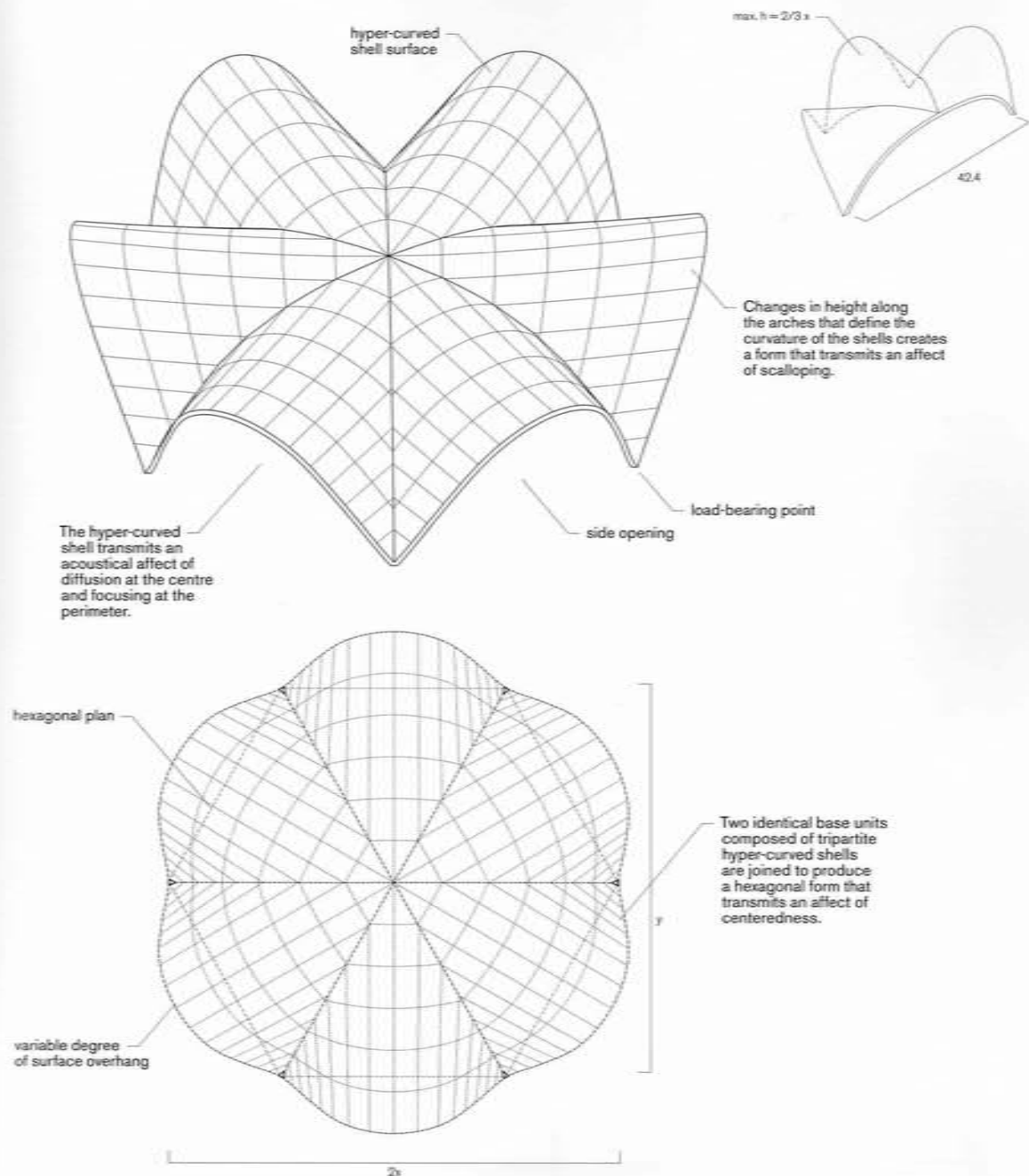
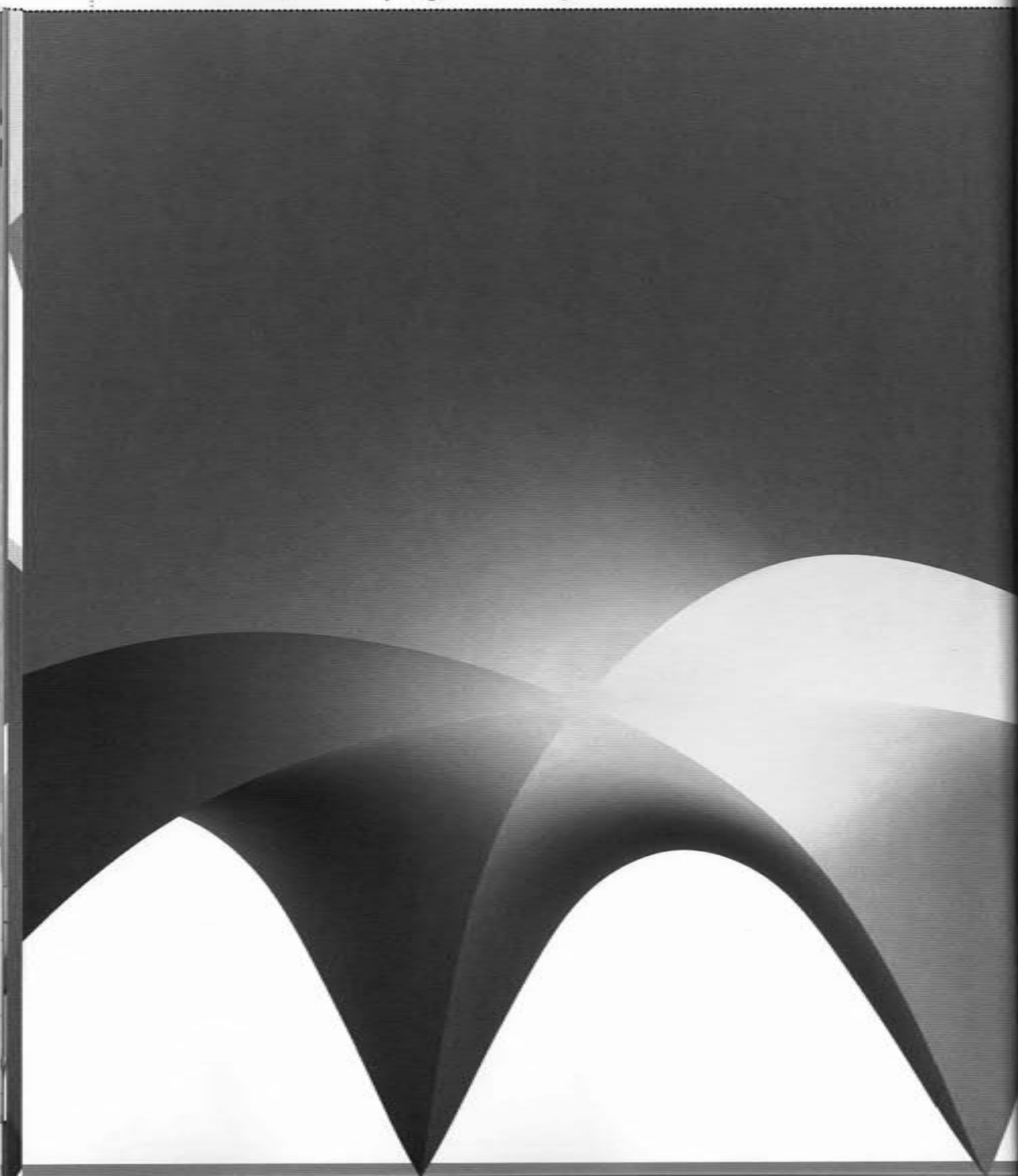


The aggregation of a quadripartite shell base unit that varies as it repeats produces a perimeter in the form of a tapering rectangle with varying degrees of scalloping.

Changes in height along the arches that define the curvature of the shells (a-d) are reflected in the section and plan, transmitting an affect of attenuation, lightness and scalloping.



This horizontal form is produced by the tessellation of a hyper-curved concrete shell base unit, forming three irregular bays, with the width of each bay gradually tapering longitudinally. The height of the shells in the central aisle is greater than that of the two side aisles, allowing for openings in the resulting elevations. This assemblage transmits an optical affect of attenuation, lightness and scalloping, and an acoustical affect of specularity and diffusion.



This form is produced by a single base unit comprising three intersecting single-curved shells arranged around a central point repeated once to form a hexagonal plan. The flexibility of the base unit lies in the changes that can be made to the radius of the curvature that defines the surfaces in section, changes to the extent of surface overhang of each shell on the perimeter, and changes to the height of the central point around which the shells are arranged. By changing the height of the arches that define the curvature, the base unit can increase or decrease the interior volume that it defines while simultaneously increasing or decreasing the area of its exterior elevation, enabling it to adapt to programmatic or environmental requirements. This form transmits an optical affect of centeredness, scalloping and faceting, and acoustical affects of focusing and diffusion.





LOS MANANTIALES RESTAURANT

F. CANDELA, J. ÁLVAREZ ORDÓÑEZ

MEXICO CITY, MEXICO

1958

The surface of the shell is divided into eight identical regions, illustrating the degree of subdivision that is possible on a hyper-curved shell.

hyper-curved shell surface



overall plan array = 8 x  
range of heights = 5.84 - 9.93m

Changes in height along the arches that define the curvature of the shells (a-h) are reflected in the section, transmitting an affect of scalloping.

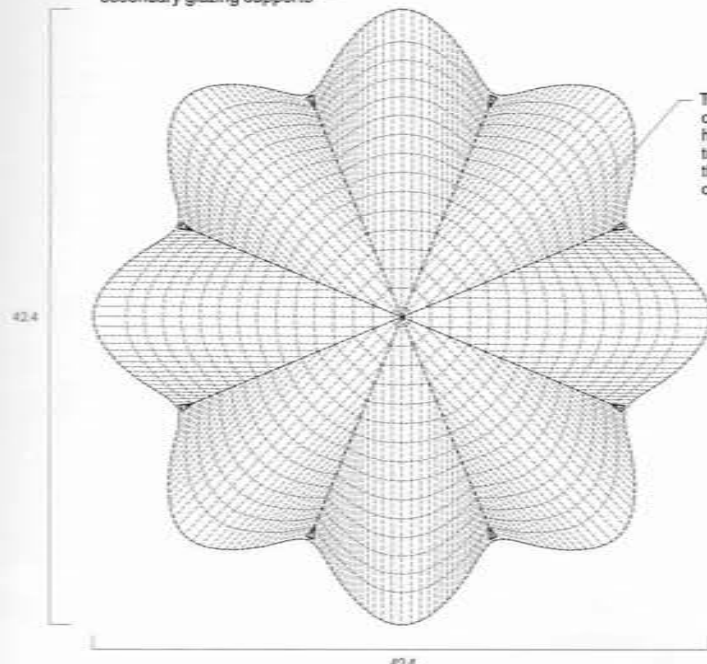
load-bearing point

The hyper-curved shell surface focuses sound.

glass infill

groin seam

secondary glazing supports



Two identical base units composed of quadripartite hyper-curved shells are joined to produce an octagonal form that transmits an affect of centeredness and scalloping.

Hyper-curved shells can be supported by a secondary structure, as is illustrated here by a ring of side columns and the central ring that acts as a supporting beam.

The Los Manantiales restaurant is produced by a base unit comprising four intersecting hyper-curved concrete shells arranged around a central point, repeated once to form an octagonal plan. The flexibility of this base unit lies in the changes that can be made to the radius of the curvature that defines the surfaces in section, changes to the extent of surface overhang of each shell on the perimeter, and changes to the height of the central point around which the shells are arranged. By changing the height of the arches that define the curvature, the base unit can increase or decrease the interior volume while simultaneously increasing or decreasing the area of its exterior elevation, enabling it to adapt to programmatic or environmental requirements. The interior surfaces are outlined by the edges of the eight groins, reinforcing the areas where the stresses converge, while the exterior surface of the shell appears as a continuous surface. The Los Manantiales restaurant transmits an optical affect of centeredness and scalloping, and an acoustical affect of focusing.



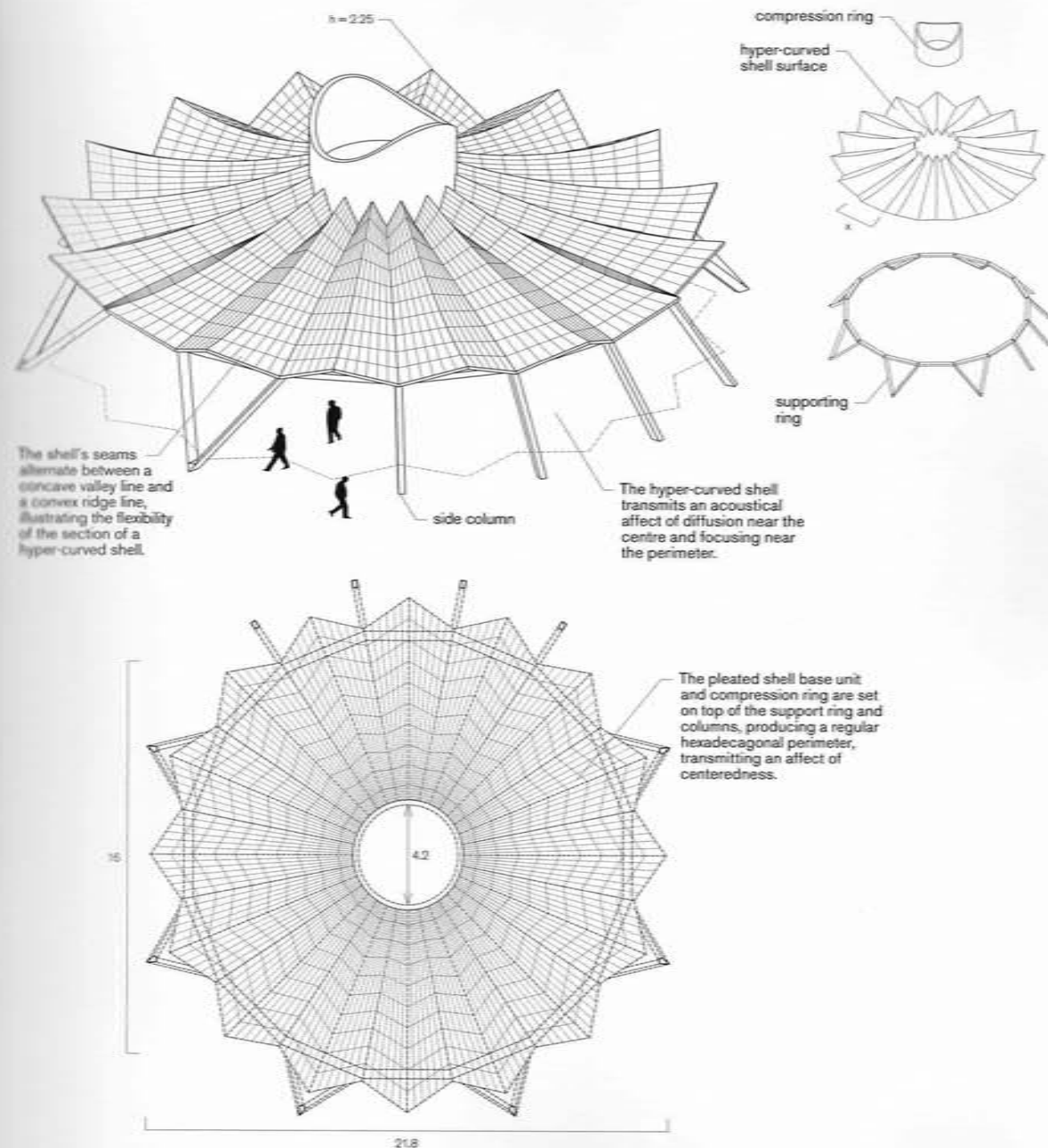


LOMAS DE CUERNAVACA BAZAAR

F. CANDELA, G. ROSELL, M. LARROSA

CUERNAVACA, MEXICO

1958



The Lomas de Cuernavaca Bazaar is produced by a single base unit comprising sixteen folded hyper-curved concrete shells arranged around a central compression ring in the form of a tube. The flexibility of this base unit is determined by several characteristics: the height of the apexes of each of the shells as they span outward from the central tube can be changed to increase the structural depth, the depth of the folds that form each of the shells can be changed to increase their strength against bending moments, and the location of the compression ring can be shifted from the center to produce an asymmetrical plan. The Lomas de Cuernavaca Bazaar transmits an optical affect of centeredness and pleating, and an acoustical affect of specularity and diffusion.

## Tenting, Torquing, Smoothness, Lightness, Specularity, Diffusion



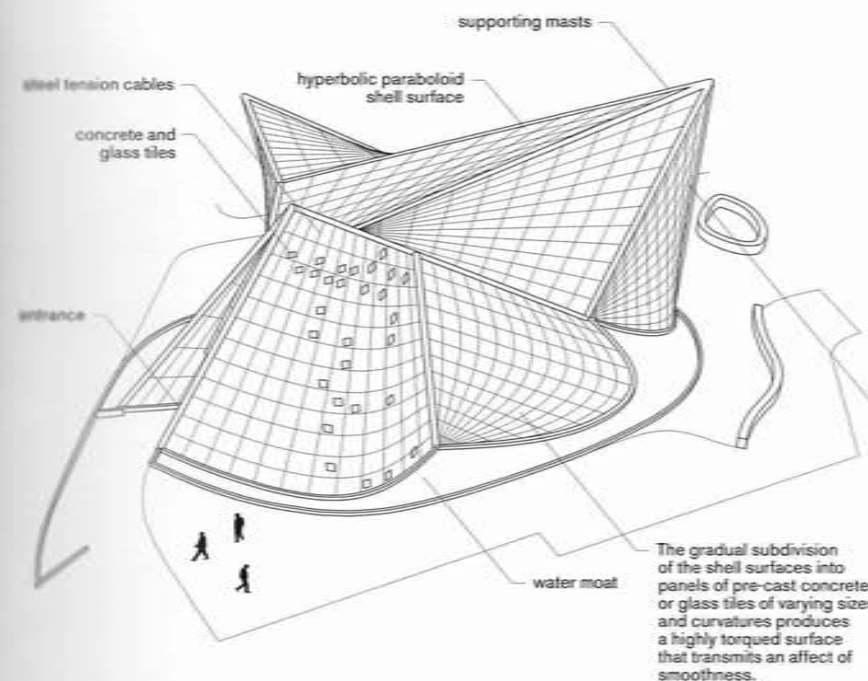
## Curved / Hyper-Curved Shell and Tensile Membrane

PHILIPS PAVILION

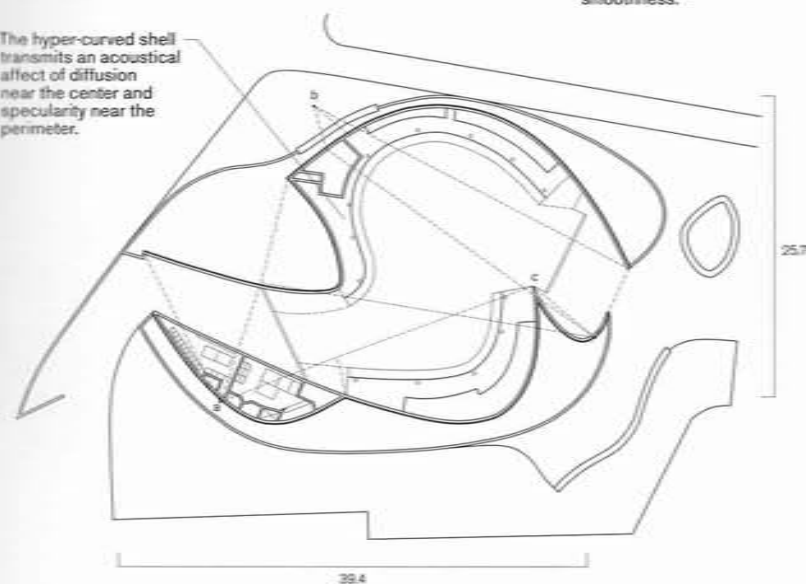
LE CORBUSIER, I. XENAKIS

BRUSSELS, BELGIUM

1958



The hyper-curved shell transmits an acoustical affect of diffusion near the center and specularity near the perimeter.



The Philips Pavilion is produced by the tessellation of a hyperbolic paraboloid base unit repeated asymmetrically to create a dynamically angled space that begins as a series of curves in plan and transforms into a number of apex points. The surfaces are made of steel tension cables and precast concrete and glass tiles. A large-scale steel structure controls the regular distribution of cables that give shape to the ruled surfaces of the shells. The flexibility of this base unit is determined by several characteristics that enable it to adapt to changing programmatic requirements: changes can be made in the curvature of the perimeter in plan, in the height of the apex points of the tubular structure, and in the scale of subdivision, which can be generated by the cable grid. The Philips Pavilion transmits an optical affect of tenting, torquing, smoothness and lightness, and an acoustical affect of specularity and diffusion.

