Nexus Network Journal (2022) 24:913–934
https://doi.org/10.1007/s00004-022-00590-3

NEXUS NETWORK JOURNAL
Architecture and Mathematics

RESEARCH

Check for updates

Reconstructing Pérez Piñero's Anoeta Velodrome

Federico Luis del Blanco García[1]

Accepted: 22 January 2022 / Published online: 14 February 2022

Abstract

The 1972 dome to cover the Anoeta Velodrome is the product of the experiences up to that date of the architects Emilio Pérez Piñero and Félix Candela, specialists, respectively, in the design of deployable reticular structures and thin concrete shells using hyperbolic paraboloids. It is a very relevant project in the careers of both architects, as the Anoeta dome was Pérez Piñero's last project, and also the last of the domes in which Candela participated since 1965. Pérez Piñero's death in 1972 marked the end of a phase in Candela's life. This paper describes the virtual reconstruction of a variation of the project and analyses its geometry, based on the subdivision of the sphere into polygons onto which hyperbolic paraboloids were then inserted. New documentation is provided which offers context for the evolution of Candela's work, linking this project to his previous major work: the Palacio de los Deportes built for the 1968 Mexico Olympics.

Keywords Emilio Pérez Piñero · Félix Candela · Anoeta Velodrome · Sphere tessellations · Hypars · Domes · Virtual reconstruction

Introduction

The design of the preliminary project submitted to the competition for the Anoeta Velodrome was done by Pérez Piñero alone. After his death, Candela would be in charge of carrying it out.

During the 1950s and 1960s, Félix Candela became one of the most important international architects for the design of thin concrete shells (Faber 1963), building more than 800 projects, most of which were based on the geometry of the hyperbolic paraboloid (hypar).

After the decline of this type of structures, which happened very fast in Mexico after 1964, Candela was not involved in building many more projects (del Cueto 2010). The dome for the Palacio de los Deportes for the 1968 Mexico Olympics

✉ Federico Luis del Blanco García
federicoluis.delblanco@upm.es

[1] School of Architecture, Polytechnic University of Madrid, Madrid, Spain

Birkhäuser

was to become his last great work, a project quite different from the thin concrete shells that had earned him international prestige (del Blanco and García 2018).

Research into Candela's unbuilt architecture shows that from 1965 to 1972 Candela entered a new world of structures designed to span huge distances, over 150 m. In this period Emilio Pérez Piñero was a major influence on Candela, who worked on four projects using large domes with an enclosure generated by his already iconic hypars.

The last of these projects, the 1972 design for a dome to cover the old Anoeta Velodrome in San Sebastián (Spain), was the culmination of this stage. The design for the preliminary project was made by Pérez Piñero. After the architect's death, Candela was commissioned to carry it out.

This project brought together the solutions that had been worked on by Candela and Pérez Piñero, with the former specialising in thin concrete shells using hypars and the latter in structures of metal and deployable mechanisms (Seguí 2004).

Ultimately never built, this was nevertheless an emblematic project. The Anoeta dome was to be Pérez Piñero's last project, and was also the last dome of this type in which Candela would participate. The premature death of Pérez Piñero in 1972 closed a chapter in Candela's life.

The geometry of the dome designed by Pérez Piñero is based on the subdivision of a sphere into hexagons and triangles using arches that share the centre with the sphere, which was then finished off with a diamond-shaped structure. Drawings of variations of the project with a hypar enclosure are included in the documentation preserved in the University of Columbia. In the words of Salvador Dalí (1972), the project looked like a flock of seagulls about to take off (Fig. 1).

During this period Candela already enjoyed international prestige (Cassinello 2010), but in the later stages of his life he hardly built any projects (Del Blanco 2021). The company Cubiertas Ala, founded by Candela, was starting to have problems building its iconic thin concrete shells (del Blanco and Ríos 2016), as new regulations and disruption in the construction industry made it more expensive to make the manually-built formworks needed. In Mexico in 1964 minimum wages were established for the first time for professions and labour costs for construction workers rose; the minimum wage increased from 17.50 pesos in 1962 to 32 pesos in 1970 (Cárdenas et al. 2008). After this, thin concrete shells ceased to be viable (Arup 1963). New forestry measures to increase protection for Mexico's forests had already been passed in 1960, making it harder to fell trees and, indirectly, making the hand-built wooden formworks required for the construction of the concrete shells more expensive (Basterra 1998). Further, the more complex auxiliary measures required by laws on safety in the workplace, and much more stringent fire prevention regulations (Garlock and Billington 2008). All of this had disastrous consequences for Cubiertas Ala.

The decline of the thin concrete shells was by no means restricted to Mexico, but was a global phenomenon. Proof of this can be seen in the fact that in 1970 the "International Association for Shell Structures" was renamed "International

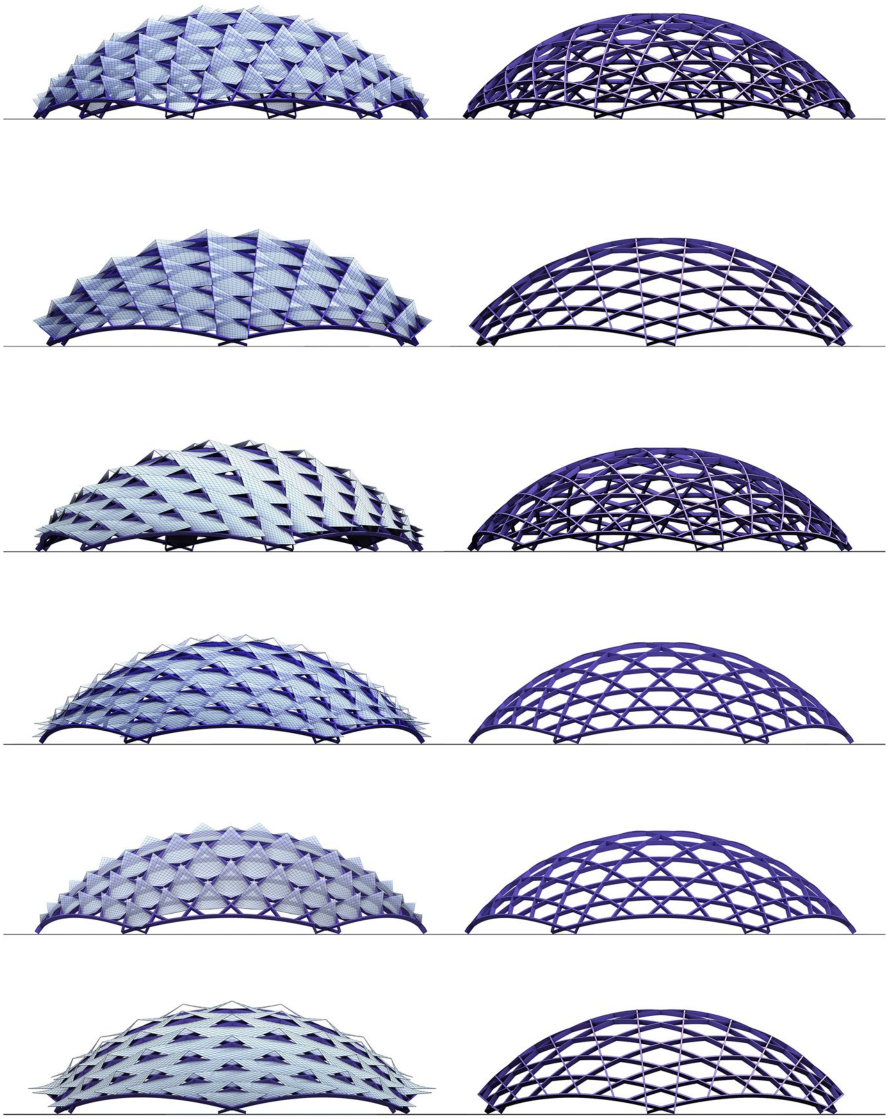

Fig. 1 Virtual reconstruction of the Anoeta Velodrome roof with the hypars variation. Orthogonal views of enclosure (left) and structure (right)

Association for Shell and Spatial Structures", keeping its acronym IASS but now covering all kinds of spatial structures (García 2007).

In 1969, the year he left his company *Cubiertas Ala* and a year after the construction of the emblematic Palacio de los Deportes for the Mexico Olympics, and twenty years on from the building of his first thin concrete shell structure, Candela gave a speech in the Kresge Auditorium at MIT entitled "The Architect of the Future", ending with these words:

> The truth is that I am as lost and disoriented as you are. I am nearly sixty years old, and I have spent twenty of these as a designer and builder of structures. I know the traditional trade of the architect reasonably well, and yet I can find neither a market nor any use for these skills that I have spent many years learning. I feel out of place in the world today and I do not know what to do or indeed whether I am any good for anything (Candela 1969: 51, my trans.).

These words were the fruit of Candela's frustration in the face of the difficulties that he faced in continuing to build his thin concrete shell structures, which just a few years earlier were being built by the hundred.

But then new influences and the partnerships Candela formed, above all with Pérez Piñero and Praeger–Kavanagh–Waterbury, resulted in four projects which used domes to span long distances (del Blanco et al. 2017b). This was to be the start of the lesser-known phase of Félix Candela's architecture.

A New Collaboration Between Candela and Pérez Piñero

The first contact between Candela and Pérez Piñero took place in July 1961. Candela went to London for the Union Internationale des Architectes (UIA) congress, where he was awarded the Auguste Perret Prize. Taking advantage of the trip, he was appointed member of a jury for a student competition to design a pop-up theatre, as part of an initiative to spark architects' interest in structures. The jury was made up of Candela and the engineers Ove Arup and Buckminster Fuller (De Miguel 1961).

In Candela's words, "among the many projects presented, there was a really extraordinary one, and of course we awarded it the prize without much discussion. The author was Emilio Pérez Piñero, at the time a student at the Madrid School" (Candela 1972: 9, my trans.). Pérez Piñero presented a transportable theatre which could be folded up by means of a dome, following a system of his own invention (Ródenas et al. 2020).

Emilio Pérez Piñero, from Calasparra (Murcia, Spain) was a "promising Spanish architect known for his work on deployable, and in some cases mobile, reticular structures" (Candela and Pérez Piñero 1984). He died in a car accident at age 37, after having dedicated his professional life almost exclusively to the study and research of this type of structures.

The complexity of these structures, together with the non-existence of precise calculation methods at that time, led Pérez Piñero to make scale models of his own. The information contained in plans is scarce, however, the study of his designs can be done with the scale models. Several of them were disassembled to reuse the material (Puertas 1989).

Due to the singular character of his solutions, Pérez Piñero instructed a group of craftsmen in Calasparra for the implementation of his domes. He built few projects, always using his characteristic spatial structures. The first project he built was a folding structure to house exhibitions in Nuevos Ministerios Madrid (1964).

Continuing his explorations in deployable structures, he built a transportable theater for festivals in Calasparra (1966) and the following year (1967) the Cinerama screening room, which included a crane for its assembly. In 1971 Salvador Dalí commissioned him to build the dome for Dali's Theatre-Museum in Figueras and that same year he began the roof to cover the excavations in a paleochristian cemetery in Tarragona. His last two projects were finished by his brother due to the untimely death of the architect (Puertas 1989).

Pérez Piñero's case is unusual, he had no support from others since his designs were new (Puertas 1990). He developed his work alone, protecting his findings with patents and trying to commercialize his structures. In his own words:

> Everyone knows that trying to investigate or progress in a field as complex as Physics – specifically the structures that are part of it – is not conceivable, as I said, unless it is in a Laboratory. Anyone who has obtained one of these prizes ... be it Frey, be it Nervi, are in Laboratories or in Institutes more or less like that of Torroja; and I, quite simply, have not had any of these means, but I have done everything a bit on my kitchen table. That is how I have been making the models and calculations, and the scale models that I have needed (Castro 1972: 26, my trans.).

In a short period of time, Pérez Piñero accumulated several awards for the development of deployable bar structures. Despite his being a student, the UIA congress considered the solution of the transportable theater to be a first-rate technical contribution in the field of spatial structures. In the same year he was awarded the Gold Medal of the Biennial of Architecture. The following year he won the Gold Medal at the International Patent Exhibition in Brussels. In 1962 he finished his architectural degree in Madrid as number one in his class (Puertas 1996).

After 10 years dedicated to the development of deployable structures, in 1972 the UIA awarded Pérez Piñero the Auguste Perret Prize. "With an award of such indisputable prestige within the profession, which automatically removes the 'simplistic' character that is normally given to things in Spain, I stopped being a 'more or less exotic man' in Calasparra and became a true authority on structures" (Castro 1972: 26, my trans.).

During those years, Candela and Pérez Piñero maintained contact by correspondence, until in 1968 Pérez Piñero decided to visit Candela, with the excuse of the inauguration of the Palacio de los Deportes for the Olympics in Mexico City. Candela wrote that because Pérez Piñero "did not bother to announce his trip to me" (Candela 1972: 9, my trans.) he had left the country to attend a number of conferences and to get away from the turbulent political situation in Mexico. Candela's return to Mexico, however, was to herald the start of a close collaboration between the two, culminating in the project for the Anoeta Velodrome.

The reasons for this visit was to try to commercialize Pérez Piñero's patents in the United States. The U.S. Navy showed interest in the patents for the construction of a base of operations in Antarctica with scientific-military applications. For its part, NASA considered one of its projects as suitable for the construction of a greenhouse on the Moon. Candela visited NASA's facilities where they provided him with the maps of the Moon so that Pérez Piñero could cover a crater. In the end, none of these projects came to fruition. In his posthumous tribute to Pérez Piñero, Candela stated: "It would have been great if the first structure erected on the Moon had been built in Calasparra, but again we ran up against the impenetrable barrier of the organization" (Candela 1972: 11, my trans.).

The Competition for the Roof of the Anoeta Velodrome

Pérez Piñero initiated the process for the open competition on 18 June 1971, after a telephone conversation with the directors of the company Arregui Constructores. The architect from Calasparra based his design on variations on the idea of a dome the structure of which would be formed by spherical arches generating a hexagonal mesh enclosed by a warped diamond shaped structure (Fig. 2).

These are some of the technical premises established by Pérez Piñero in his proposal for the project (1972: 16, my trans.):

- The current structure of the Velodrome would remain untouched.
- All cement work would be carried out on the outside of the current building to avoid any interruptions in its use during this phase.
- Prefabrication of the roof to enable very fast mounting once outside cement work was completed.
- Minimum surface area for the facade (that is, the roof itself forms the facade).
- Complete autonomy of the structure.
- Plan for modifiable supports and compressed cement work, adjustable by steering and linking rings.
- Flexibility and lightness of structure.

A few days before the final deadline for the competition, the construction company, Arregui Constructores, asked Pérez Piñero to suspend the studies he was carrying out for the competition. The architect, however, decided not to abandon the competition. Having already made the models and with the plans in hand, he turned up at the College of Architects of Vizcaya to take part in the competition as a sole architect, without the backing of a construction company. At his request, the competition jury gave him twenty days to re-present his proposal in accordance with the competition rules, using a new construction company (Pérez Almagro 2013).

Despite Pérez Piñero's attempts, his proposal did not win the competition, but his premature death that same year resulted in a decision to build the dome in homage to the architect from Calasparra, thanks to an intervention by Salvador Dalí:

> … I would like to appeal to the nobility and generosity of all Spanish architects, and whenever geodesic roofs and domes are required they have recourse to the solutions devised by our very own genius, Piñero, who is the most legitimate representative of this type of architecture. And as we have the good fortune that my great friend Candela is coming to Madrid, he

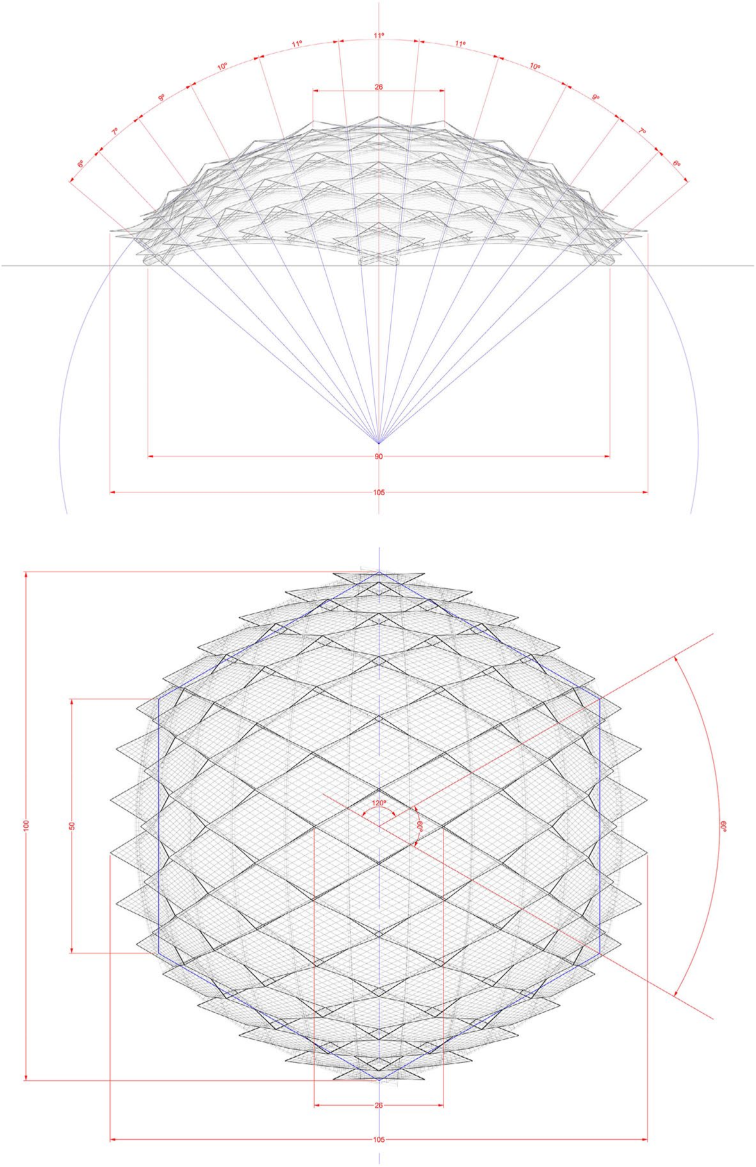

Fig. 2 Reconstruction of the dome of Anoeta Velodrome with the hypars variation. Plan and front view

> could … provide general direction and supervision for new structures of this type (Dalí 1972: 5, my trans.).

Salvador Dalí was not the only one to support the building of the dome. After the decision on the preliminary project, Encio Cortázar, the technical director for town planning, made public his support for Pérez Piñero's proposal and openly criticised the other proposals, describing them as “architecture of the last century” lacking the profile required for a city like San Sebastián.

It was finally decided that Félix Candela, working with the construction company Dragados, would build the dome. However, after examining the documentation, Candela concluded that the project could not be built in its current condition, as it was incomplete and exceeded the construction company’s budget.

All of this was carried out by correspondence, since by this time Candela had already moved to Illinois. In addition to the construction company Dragados, Candela exchanged letters with Rafael de la Hoz, at that time Director General of Architecture, via Carlos de Miguel, director of the journal *Revista Nacional de Arquitectura*.

In the end Dragados rejected Candela’s proposal, claiming that it could not be carried out within the projected period of ten and a half months. The budget was still higher than that of the proposal that was finally brought to fruition.

Original Documentation

The original documentation for the competition and the correspondence between Candela and Pérez Piñero during the years before are kept in the Avery Architectural & Fine Arts Library at Columbia University and at the Emilio Pérez Piñero Foundation in Murcia.

There is no detailed documentation, as the project was never built and the construction company Dragados rejected the proposal before it was finalized. There are different variations on the concept of the segmentation of the sphere and its enclosure.

The final model submitted by Pérez Piñero for the competition is kept at Columbia University, to which it was donated by Candela. After his death, it was sent from Spain to Illinois for Candela to study. Candela did not make any more models; he only made models when his clients required them, as he did not consider them to be helpful for his designs (de Garay 1994).

Among Pérez Piñero’s documentation there are images of a scale model that was made of strainers placed on hexagonal polygons, referred to as a *cúpula de cupulines* (dome of little domes). This model was published in the magazine *Nueva Forma* and was dismantled in order to reuse the materials.

Several approximate models were made for the project at a later date. One of these, made by students at the University of Alicante, was donated to the Emilio Pérez Piñero Foundation, and another was created for the exhibition “Arquitecturas Ausentes del siglo XX” at Madrid in 2005 (Rispa 2005).

Antecedents of the Anoeta Velodrome: Three Domes (1965–1969)

The only large dome built by Candela was the Palacio Olímpico for the 1968 Mexico Olympics. This project has been considered the culmination of the great architect’s career, but Candela’s intention was to begin a new phase away from thin concrete shells. Pérez Piñero was influenced by Candela's domes for the design of the preliminary project of Anoeta. Before the Anoeta Velodrome, Pérez Piñero had already built metal-framed domes using deployable structures, however, this project was more closely related to Candela's previous domes than to his own designs, showing their mutual influences.

When Candela was asked why he had not used a concrete shell for the Olympic stadium, the answer was simple: "the limitations of the material generally make it unsuitable for spans of this size" (Candela 1985).

From 1965 to 1969 Candela undertook three projects with large-scale domes, enclosed by hyperbolic paraboloid surfaces.

– Sports facilities for Brown University, Rhode Island, 1965–1972.
– Competition for the Palacio de los Deportes for the Mexico Olympics, 1968.
– Competition for the Kuwait Sports Centre, 1969.

Of these projects, only the Palacio de los Deportes was actually built. The projects revolve around the search for an efficient subdivision of the sphere into polygons, which would later generate an enclosure using hypars. The function of the hypars is only secondary, and they no longer form the main structure. Each dome presents a different solution, including some of the solutions that Candela had already used in thin concrete shell structures in earlier years.

Some of the letters exchanged between Candela and Pérez Piñero were compiled by Miguel Seguí (2004: 31, my trans.):

> … the solution for the Palacio de los Deportes seems to have been influenced by an idea expressed by Emilio Pérez Piñero, who pointed out to Candela the opportunity to have the containing planes of the arches pass through the pole rather than through the centre of the sphere. This enables a greater slope in the dome (optimisation of this shape as a structure; minimising the transmission of horizontal force to the ground or to intermediate elements)…

However, an analysis of the geometry of the Candela domes shows that the Palacio de los Deportes project for the Mexico Olympics does not follow this solution (Fig. 3). The information provided by Seguí is correct, but Candela used

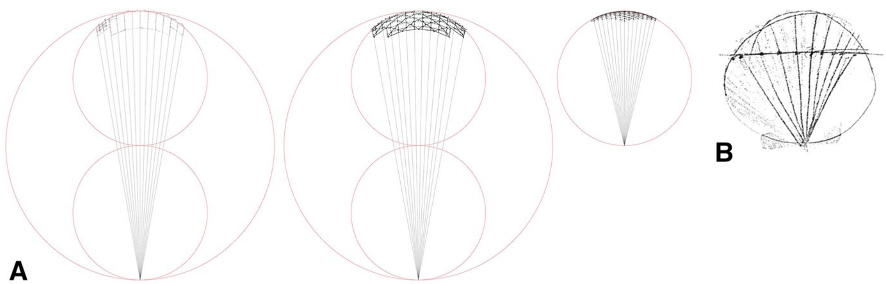

Fig. 3 **A** Centres of initial proposals for Brown University; **B** Geometry attributed to the Palacio de Deportes in Mexico City

this geometry for another earlier project that was never built: one of the proposals for the sports facilities at Brown University (1965). In all subsequent projects the containing planes of the arches intersected at the centre of the sphere.

The lack of reach of this phase of Candela's work has led to misinterpretations of his geometric solutions, which even today remain unclear. Subsequent publications that have studied the Palacio de Deportes have repeated this confusion, and in the most recent exhibitions held on the occasion of Candela's centenary in 2010, the same errors were repeated in the geometry of the domes.

Geometry and Structure

The geometry of the dome for Anoeta is based on the subdivision of a sphere into hexagons and triangles on top of which a diamond-shaped enclosure is erected. The architect described it in this way:

> On the base of a network formed by hexagons and triangles within the classic networks, rises a roof that breaks with the central symmetry that makes these solutions so monotonous. Instead it chooses to go off in a direction parallel to the mountain in a series of crossed rhombuses which also serve as gutters to drain away surface water. This avoids having to waterproof such a large surface area and creates a continuous line of skylights mirroring the toothed ridge of the mountains and ensuring uniform lighting in the whole of the interior space (Pérez Piñero 1972: 18, my trans.).

To generate the structural arches, the sphere is sectioned by three families of planes, the intersections of which generate the arch structure. Each of these three families of planes shares the same diameter as the sphere, with 60° angles between them. In this way, all the planes have a single point in common, the centre of the sphere (Fig. 4).

Deformation in the hexagons and triangles increases as they move away from the apex of the dome, and is at its maximum at the perimeter of the cap. The top

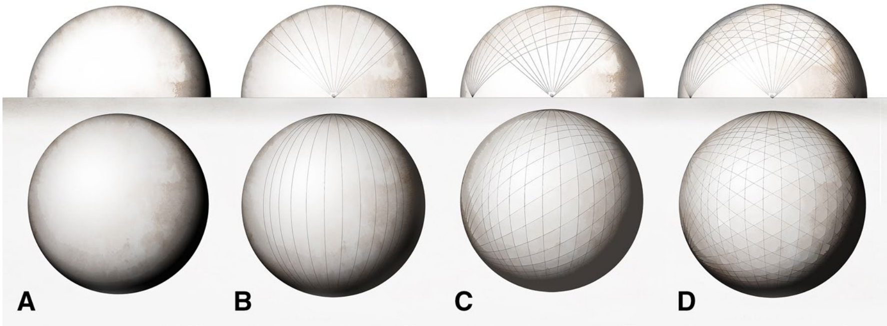

Fig. 4 **A** Initial sphere; **B** First family of arches intersecting in the diameter of sphere; **C** Second family of arches forming 60°; **D** Segmentation of sphere in hexagons and triangles

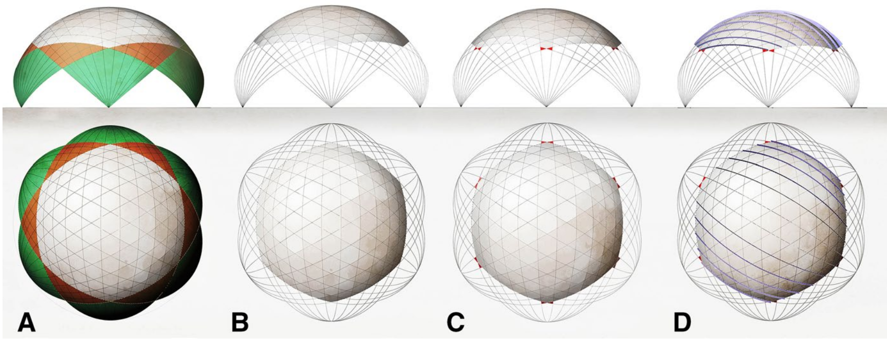

Fig. 5 **A** Division of sphere into fragments; **B** Obtaining cap of dome; **C** Supports follow subdivision of arches; **D** Thickness of arches oriented towards centre of sphere

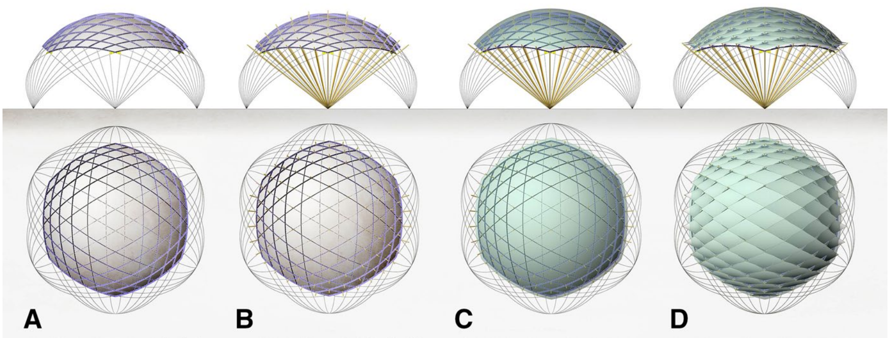

Fig. 6 **A** Three families of arches define the main structure; **B** Vertices of enclosure hypars to be set in segments linking centre of sphere with intersections of arches; **C** Second concentric sphere defines length of radii; **D** Enclosure hypars to be set between two spheres

hexagon at the apex of the sphere is the only regular polygon to be found in the project. The sides of the remaining hexagons are of different lengths, and their deformation increases the farther they go from the regular hexagon. The cap of the dome, along with its supports, is defined in accordance with the contour of the perimeter polygons, which in turn form the structural arches (Fig. 5).

The thickness of the structural arches is oriented towards the centre of the dome. As it is a symmetrical structure, the horizontal forces cancel each other out.

A second, larger concentric sphere establishes the position of the enclosing hypars. Linking the centre of the sphere with each of the intersections that form the arches obtains the radii of the sphere, which will determine the position of the upper vertices of the hypars. The length of these radii is determined by the second sphere concentric to the original one (Fig. 6).

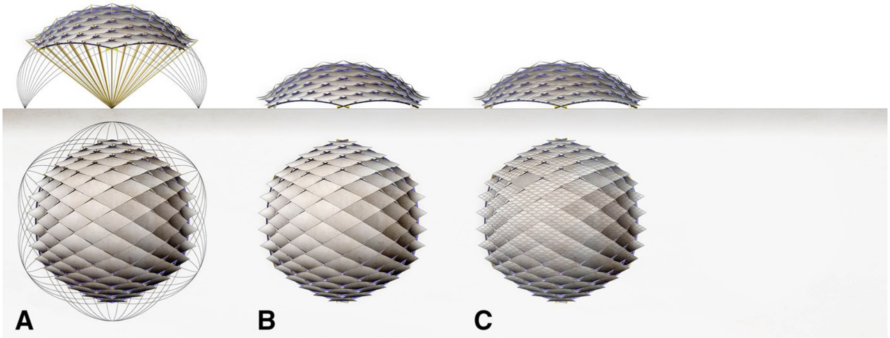

Fig. 7 **A** Full geometry of roof, including auxiliaries; **B** Resulting dome; **C** Generators of hypars

Each hypar is generated from four vertices: the two upper ends, the intersection of the radii that intersect with the larger sphere, and the two lower ends, located at the base of each hexagon (Fig. 7).

The geometric subdivision of this sphere is the same as the one that Candela used in the dome for the Kuwait Sports Centre, the main difference being that in the Anoeta Velodrome the subdivisions are larger, generating a larger number of enclosure modules with more homogeneous polygons. For the solution used by Candela in Kuwait, he relied on Pérez Piñero's advice, obtained via correspondence.

While the idea of subdivision into triangles and hexagons is maintained throughout the project, different solutions introduce variations in frequency (density of the pattern of the arches) and slope of the arches. There are also variations in the way the hyperbolic paraboloids are distributed over the sphere and at the edge of the spherical cap.

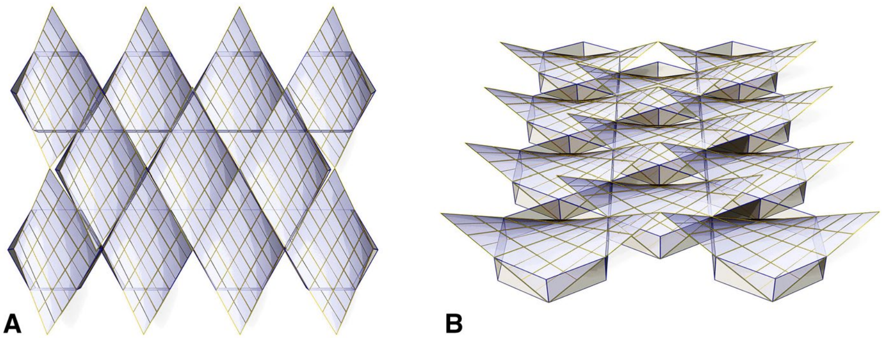

Fig. 8 Openings between enclosure modules: **A** View from above; **B** Front view

Geometry on a Single Plane

Viewing the geometry on one horizontal plane enables us to obtain a simplified map of the dome (Fig. 8). This eliminates the variables caused by the curvature of the sphere, and allows a better understanding of the modulation and enclosure of the project. All hexagons and triangles would be the same size and regular in form. The sphere is a non-developable double-curved surface, so this operation implies a modification of both the elements and the locations where they meet (Figs. 9, 10).

This is a common operation that simplifies the geometry. Candela had already carried out in previous projects, such as the sports facilities in Kuwait, where the same geometric solution was used for flat and spherical roofs (del Blanco et al. 2017a). On the other hand, several of the enclosure hypars that he used for the domes had previously been employed as thin concrete shells on a horizontal floor.

Columbia University documentation shows a more complex variation for the enclosure of the Anoeta roof. Each hypar is reduced in size and each module is oriented in three different directions. This new solution is organised on the same mesh of hexagons and triangles with two possible variations in each hexagonal module (Fig. 11). The hypars on the left show the straight lines generators of the surface (Fig. 11A), completely defining the geometry of the hypar and allowing to calculate the rest of its elements (axis, vertex…). For this reason, Candela used to include the generators in the drawings of his thin concrete shells.

The vertices of the hypars connect to each other in two different ways. An auxiliary bar structure is required to hold up the upper vertices, so each hexagon is divided into six triangles, and from the centre of each hexagon rise six bars that support the upper vertices of the hypar (Fig. 12).

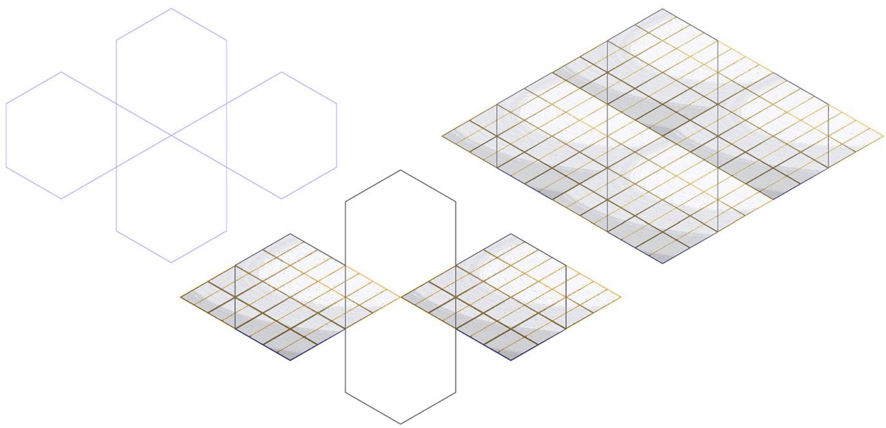

Fig. 9 Hypar module on mesh of polygons. The generators of the hypars are parallel to the straight edges of the surface

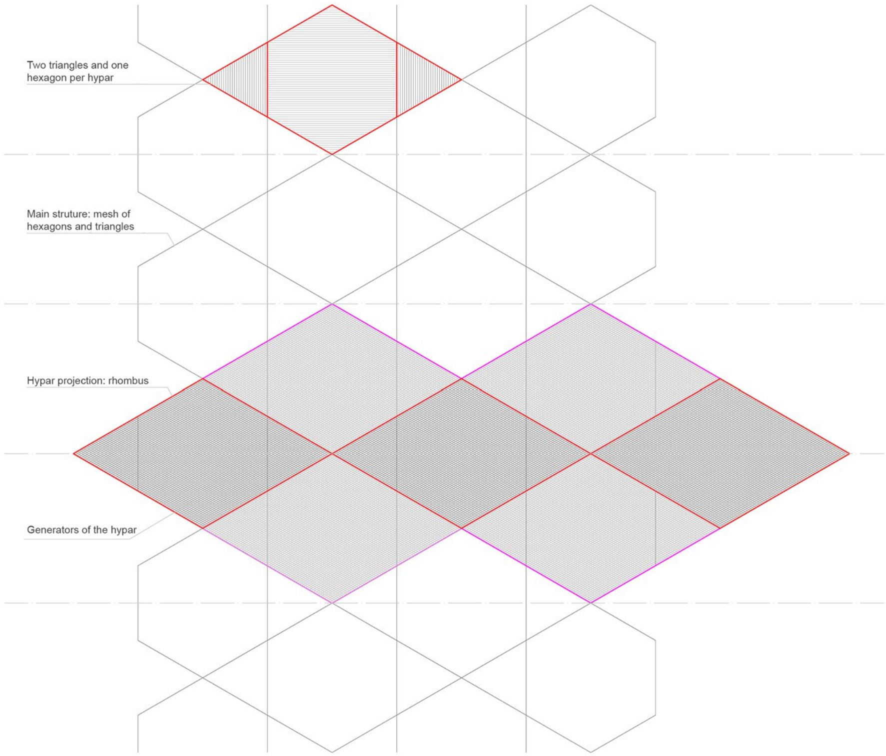

Fig. 10 Geometry of hypars on a horizontal plane. Initial proposal presented for the competition

Enclosure Modules

The original scale model made by Pérez Piñero for the preliminary project shows an enclosure formed by rhomboids that are distributed over the mesh of hexagons and triangles. Drawings and diagrams show straight-edged hypars for the closure of the dome (Figs. 11A, 13A).

It is the simplest form in which a hypar can appear, with the generators parallel to the edges. Candela had already used this geometric solution in a number of projects as a thin concrete shell structure, but in this project it has undergone a change of scale.

If this module were projected onto a horizontal plane, a rhombus with two pairs of parallel sides would be obtained. If a hexagon with two equilateral triangles is then juxtaposed onto this, the resulting figure would also be a rhombus, and a radial projection of the edges of the hypar towards the centre of the sphere would coincide with the arched structure of the dome (Fig. 13).

The edges of the arches of the dome are used to generate the module, with hexagonal-based prisms. The two lower vertices of the hypar are in contact with two lower and opposite vertices of the hexagonal prism, while the upper

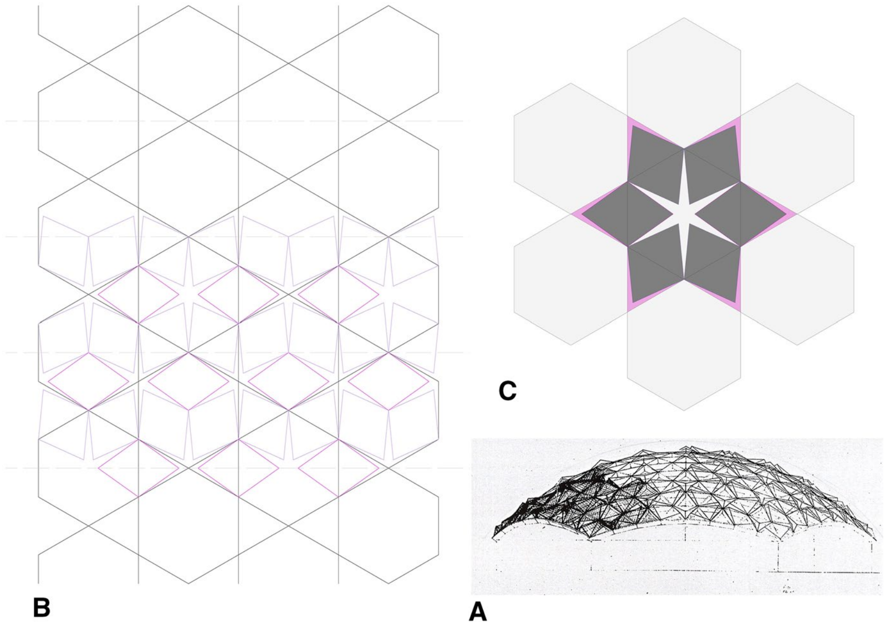

Fig. 11 Variation on the enclosure modules. **A** Front view of dome, original drawing kept at the University of Columbia. The hypars on the left show the generators of the surface; **B** Geometry of hypars on a horizontal plane; **C** Hypars (dark grey) on mesh of hexagons (light grey) and triangles (magenta)

vertices of the paraboloid are cantilevered. One of the proposed variants added an auxiliary structure of bars, avoiding the cantilevered structure. These common vertices are the ones that would be projected onto the triangles.

The enclosure structure employs a solution which is redolent in geometric terms of the Palacio de los Deportes in Mexico City. The hexagons have replaced the four-sided polygons, and the hermetic enclosure is opened up, allowing in natural light. Scale is clearly a matter of great interest. In the distance there is a large spherical dome, and as we approach it the monotony is broken by the detail provided by the small hypars (de Garay 1994).

If the enclosure modules are deployed on a horizontal plane, the top view would show a hermetic structure. However, the difference in height of the vertices of the hypar allows skylights to be generated, which allow light to enter. The juxtaposition of the modules follows the mesh of hexagons and triangles that, indirectly, make up the rhombuses on which the hyperbolic paraboloids fit. Two perfectly-matching rows of rhombuses are created, due to the fact that they have parallel sides (Fig. 14).

In each row, the rhombuses share the vertex belonging to the main axis, so that when the hypar modules are set in, they will all share a common vertex. In this geometric distribution, the hexagonal prisms remain totally watertight, while the triangular prisms form the skylights through which sunlight penetrates.

This geometric distribution is simple when viewed on a horizontal plane, but it does lead to inconveniences and inaccuracies on a sphere. In three-dimensional reconstruction on surfaces without thickness, the vertices of the hypar are tangent.

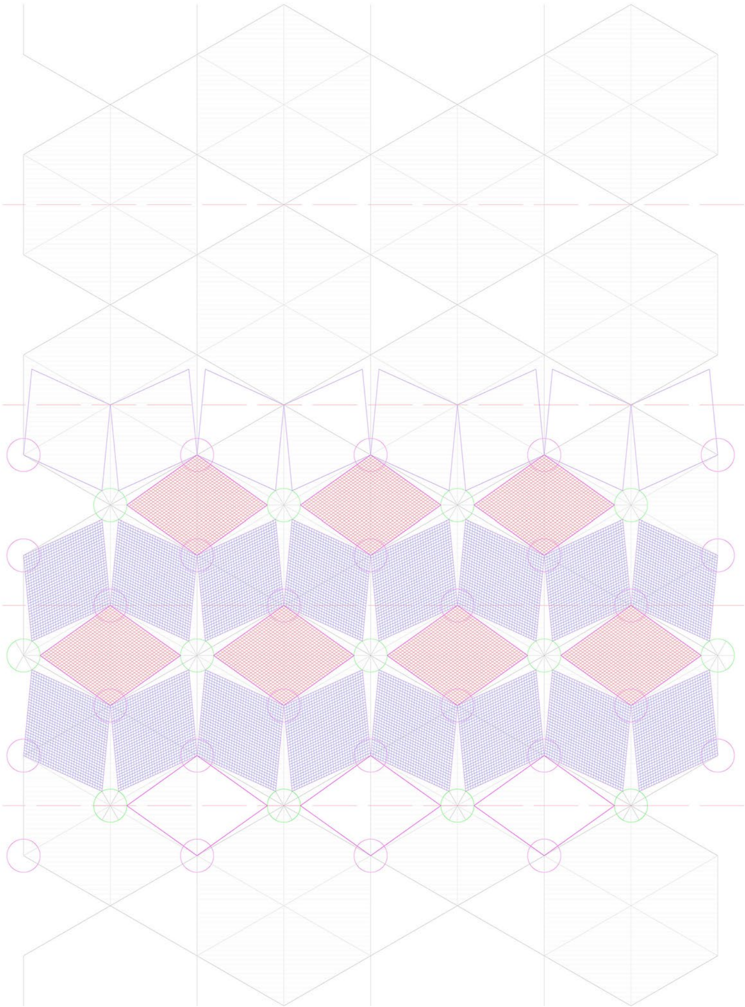

Fig. 12 Organisation of hypars on a horizontal plane with secondary structure of bars. Green circles indicate length of bars supporting upper vertices of hypars

However, when thickness is added to the surfaces and arches, there start to be different possible construction solutions that are not described in the original documentation.

Natural Lighting

Pérez Piñero's preliminary project included natural lighting, and all subsequent variations maintained this premise. Natural lighting was an essential consideration for Candela when he was building his thin concrete shells in their

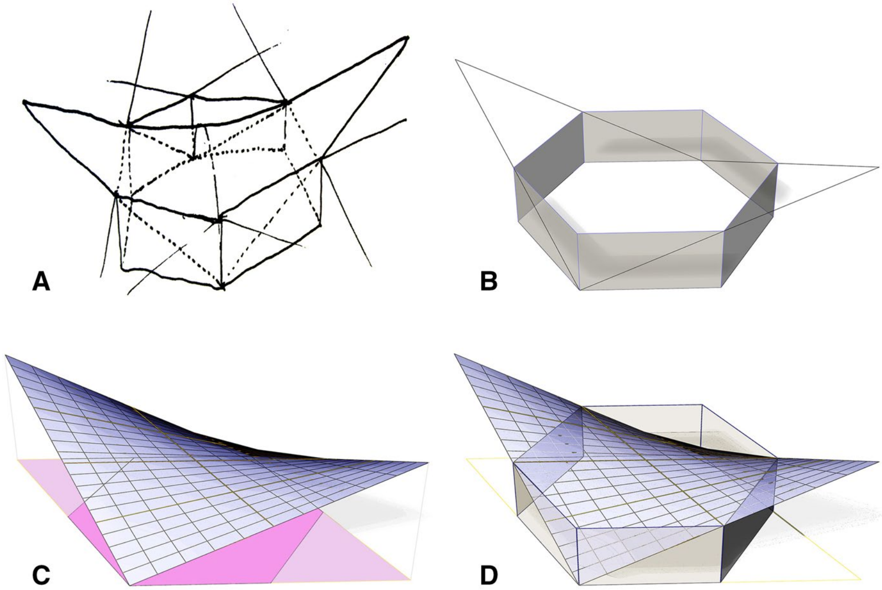

Fig. 13 Enclosure module. **A** Original sketch kept at the University of Columbia; **B** Hexagonal prism supporting the hypar; **C** Projections of hypar; **D** Complete module showing the generators of the hypar

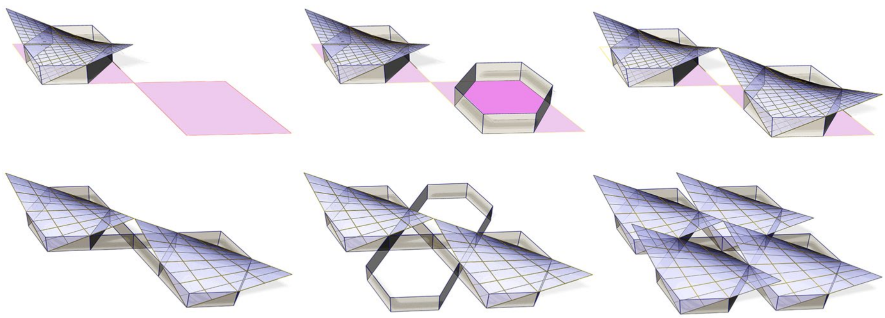

Fig. 14 Diagram of juxtaposition of enclosure modules

heyday. The cuts in the geometry, the configuration of the hypar or the method used for juxtaposing the concrete sheets offered innumerable variations which allowed light to enter. However, in the previous domes that Candela designed lighting was not taken into account, and there was no place for natural light. The enclosure modules created a hermetic wrapping that did not allow light rays to pass through the cap of the sphere.

From a geometric point of view, the dome for the Anoeta Velodrome does not represent an important advance on the previous domes designed by Candela, and its greatest contribution is the introduction of natural lighting.

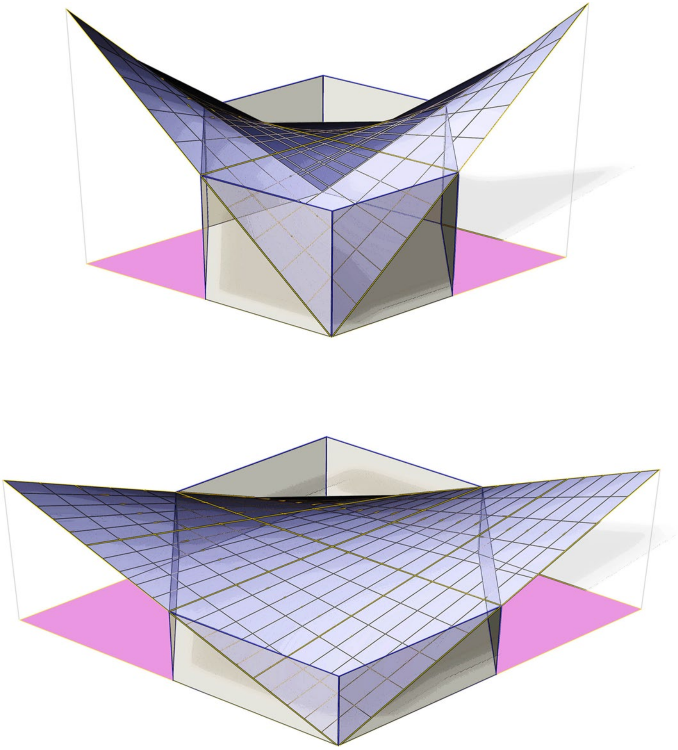

Fig. 15 Variations in slope according to thickness of arches

The different variations presented for this project all generated different types or sizes of skylight, but at no time was natural lighting discarded. Depending on the thickness of the arches, the hypar would have been set at a different slope, which would have allowed more or less light to enter (Fig. 15).

The hypar modules take advantage of the height difference of their vertices to create an enclosure that is permeable to light. It should be pointed out that the layout of the hypars (or the rhombuses) entailed complications for the drainage of surface water, making this more expensive. This was indeed one of the reasons why the construction company Dragados were not interested in going ahead with the project.

As has already been mentioned, the structural arches of the dome generate a mesh of hexagons and triangles on which the hypar enclosure modules are based. The hexagonal prisms are completely sealed, while the triangular ones allow sunlight to enter (Fig. 16).

The arrangement of the enclosure modules is the main conditioning factor in the different variations proposed for the project, not only in terms of their size, but also in their orientation. From the outside, sunlight would glide across the smooth surfaces of the hypar, avoiding hard angles, and the only hard shadows would be those cast by the upper vertices of the hypar on adjoining modules.

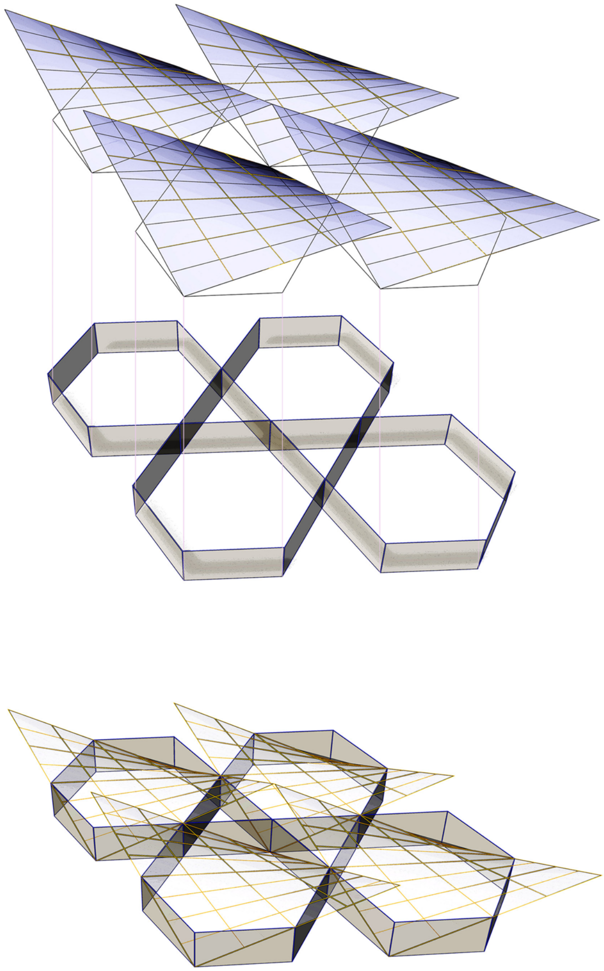

Fig. 16 Hypars on structural mesh, diagram on a horizontal plane. The triangles allow natural light to enter

Conclusions

The initial design for the preliminary project of the Anoeta Velodrome was made by Pérez Piñero. Its analysis and comparison with Candela's previous domes shows their similarity and the influence they had on him. On the other hand, the influence of Pérez Piñero in this new phase of Candela is clear, and the Anoeta Velodrome could be considered as the culmination of their joint experiences.

The scale model of the preliminary project presented by Pérez Piñero showed a diamond-shaped enclosure. It is not clear whether the final solution would have included hypars. He did not mention the use of hypars for the project, but rather warped rhombuses. However, there are drawings that show the use of hypars for the enclosure. The question remains as to whether the final project would have been executed using hypars or another type of warped surface. The incorporation of Candela into the project suggests that the generic warped rhombuses would have been hypars. It would not affect the solution of the main structure, since a different diamond warped surface could share the same four vertices of the hypar.

The analysis of Candela's unbuilt domes has allowed us to deepen our knowledge of the architect and of his development—incomplete if we take into account only the projects he actually built—and to provide context for his last great work, the Palacio de los Deportes for the Mexico Olympics in 1968.

All of Candela's projects involving domes in these years are designed for sports facilities. While in previous years thin concrete shells were concentrated in industrial architecture (mainly using the inverted umbrella structure), and to a lesser extent in religious architecture (especially based on vaults built from hypars).

Candela's previous thin concrete shells were highly effective at spanning distances of up to 30 m. With the need to cover spans of over 150 m, the dome structure came into its own. Pérez Piñero's influence and advice played an important role in Candela's new phase. The question does arise, though, as to what extent was Candela really interested in creating sports facilities, or was he only looking for projects that would allow him to cover large spans?

Acknowledgements This research has been made possible thanks to the archives preserved in the Columbia University, the Emilio Pérez Piñero Foundation and the Colleges of Architects of Madrid and Barcelona. I would also like to thank Miguel Seguí, curator of the exhibition "Arquitecturas Ausentes del siglo XX", for his help in the early stages of the research. The family of Pérez Piñero has clarified the architect's authorship of the design submitted to the competition; Candela's participation occurred after the death of the former to try to build it.

All images are by the author unless otherwise noted.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

References

Arup, Ove. 1963. Foreword. In: Colin Faber, *Candela: The Shell Builder*. London: Architectural Press.

Basterra Otero, Alfonso. 1998. Las estructuras arquitectónicas de Félix Candela: una revisión actual. PhD Diss, ETSAV, University of Valladolid.

Candela, Félix. 1969. El arquitecto del futuro. *Arquitectura: Revista del Colegio Oficial de Arquitectos de Madrid (COAM)* 130: 48–51.

Candela, Félix. 1972. Emilio Pérez Piñero. *Arquitectura: Revista del Colegio Oficial de Arquitectos de Madrid (COAM)* 163: 9–13.

Candela, Félix. 1985. Divagaciones estructurales entorno al estilo. In: Félix Candela, *En defensa del formalismo y otros escritos*, pp. 37. Bilbao: Xarait.

Candela, Félix and Emilio Pérez Piñero. 1984. Félix Candela architectural records and papers, 1950–1984. *Avery Drawings & Archives Collections*. https://findingaids.library.columbia.edu/ead/nnc-a/ldpd_3464748. Accessed Oct 2021

Cárdenas Ojeda, Mauro Ernesto, Carlos Peralta Alamilla and Mauro Cárdenas Hernández. 2008. Salario mínimo en México. insyde.org.mx/pdf/seguridad-y-reforma/salario_minimo_en_mexico.pdf

Cassinello, Pepa. 2010. *Félix Candela centenario. La conquista de la esbeltez*: Fundación Juanello Turriano.

Castro, Carmen. 1972. Entrevista a Emilio Pérez Piñero. *Arquitectura: Revista Del Colegio Oficial de Arquitectos de Madrid (COAM)* 163: 25–28.

Dalí, Salvador. 1972. Sobre la obra de Emilio Pérez Piñero, el pensamiento de Salvador Dalí. *Arquitectura: Revista del Colegio Oficial de Arquitectos de Madrid (COAM)* 163: 5–8.

De Garay, Gabriela. 1994. *La entrevista a Félix Candela. Raleigh 1994.* Audio file. 1994.

De Miguel, Carlos. 1961. Teatro ambulante. *Arquitectura: Revista Del Colegio Oficial de Arquitectos de Madrid (COAM)* 30: 27–35.

Del Blanco García, Federico Luis and Ismael García Ríos. 2016. De las estructuras laminares a las estructuras metálicas en la arquitectura de Félix Candela. Análisis y reconstitución de la sala de exposiciones para el concurso del Palacio Olímpico de los Deportes, México 1968. *Rita Revista Indexada de Textos Academicos,* 5: 98–105. https://doi.org/10.24192/2386-7027(2016)(v5)(05)

Del Blanco García, Federico Luis and Laura Pérez Lupi. 2017a. Estructuralismo y renovación: la invitación a Félix Candela, Kenzo Tange, Frei Otto. *P+C: proyecto y ciudad: revista de temas de arquitectura* 8: 228–239.

Del Blanco García, Federico Luis and Ismael García Ríos. 2017b. *Las cúpulas de Félix Candela. Análisis y reconstitución de las instalaciones deportivas de la Universidad Brown, 1965–1972*. *EGA Expresión Gráfica Arquitectónica, 22(*29): 228–239. https://doi.org/10.4995/ega.2017.7358

Del Blanco García, Federico Luis and Ismael García Ríos. 2018. Fernando Higueras y Félix Candela en un retorno a la geometría de paraguas invertidos. Análisis y reconstitución gráfica del aeropuerto de Murcia, 1983. *EGA Expresión Gráfica Arquitectónica, 23*(32): 232–243. https://doi.org/10.4995/ega.2018.9813

Del Cueto Ruiz-Funes, Juan Ignacio. 2010. *Félix Candela 1910–2010*. Valencia: IVAM, SECC.

Del Blanco García, Federico Luis. 2021. Virtual reconstruction and geometric analysis of Félix Candela's inverted umbrellas for The Villahermosa Cathedral. *Disegnarecon*, 14(27):1–14. https://doi.org/10.20365/disegnarecon.27.2021.10.

Faber, Colin. 1963. *Candela: The shell builder*. London: Architectural Press.

García García, Rafael. 2007. Láminas plegadas de hormigón armado. Realizaciones en España. *Actas del quinto congreso nacional de historia de la construcción*, pp. 1.

Garlock, Maria E. Moreyra and David P. Billington. 2008. *Felix Candela: Engineer, Builder, Structural Artist*. Princeton University Art Museum.

Pérez Almagro, Carmen. 2013. Estudio y normalización de la colección museográfica y del archivo de la Fundación Emilio Pérez Piñero. PhD Diss. University of Murcia.

Pérez Piñero, Emilio. 1972. Anteproyecto de cubrición del Velódromo Anoeta de San Sebastián. *Arquitectura: Revista del Colegio Oficial de Arquitectos de Madrid (COAM)*, no. 163, pp. 16–19.

Puertas del Río, Lina. 1989. *Estructuras espaciales desmontables y desplegables. Estudio de la obra del arquitecto Emilio Pérez Piñero*. Phd diss, University of Murcia.

Puertas del Río, Lina. 1990. Estructuras espaciales desmontables y desplegables. *Informes de La Construcción*, *42*(409), 43–53.

Puertas del Río, Lina. 1996. Primeras propuestas en España de estructuras desplegables de barras. *RE: Revista de Edificación*, *23*(05), 48–53.

Rispa, Raúl. 2005. *Arquitecturas Ausentes del siglo XX*. S.l. Madrid: Fundacíon Barrié.

Ródenas-López, Manuel Alejandro, Martino Peña Fernández-Serrano, Pedro Miguel Jiménez-Vicario, Pedro García Martínez and Adolfo Pérez Egea. 2020. Geometric Evaluation of Deployable Structures Using Parametric Modelling. *Nexus Network Journal* 22, 247–270. https://doi.org/https://doi.org/10.1007/s00004-019-00432-9

Seguí, Miguel. 2004. *Un diálogo imaginal: proyecto para el concurso del velódromo de Anoeta (1972).* Madrid: Editorial Rueda.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Federico Luis del Blanco García is an architect with a Cum Laude degree from the Universidad Politécnica de Madrid. He has a Masters in Analysis, Theory and History of Architecture (UPM) and Postgraduate Studies in Multimedia Design (UPM). He specializes in the use of digital tools and new technologies. He is an Assistant Professor at the Escuela Técnica Superior de Arquitectura de Madrid, and Coordinator of the Masters in Computational Design and also responsible for the instrumentation module of the Masters in Architectural Communications. He has been invited to deliver lectures at the Architectural Association in London, the Universidad Federal in Río de Janeiro and the Universities of Alcalá, Seville, Alicante and Valencia. He also teaches master's degree courses at the Escuela Superior de Diseño in Barcelona. At a professional level he has worked on projects with companies and organizations such as Toyo Ito & Associates, NH Hotels and the Madrid regional government.