Design and Applications of Ultra-thin Free-form Shell Structures

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EXTENDED ABSTRACT

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ABSTRACT

As part of the research "Design and Performance of Ultra-Thin Concrete Shells", the proposed study seeks to explore the architectural dimension of an ultra-thin free-form shell structure. By applying spatio-functional analytic methods, its performance was evaluated in different real situations (natural and urban environments), studying how the visual fields, spatial movements and the shade produced, would be affected in the chosen site. Thus it was sought to identify and validate with concrete hypothesis, different implantation layouts of the several possibilities introduced. Through the study of the historical evolution of shells and the existing technology and construction methods, it was intended to highlight the importance and advantages given of using this type of structures. Their natural form, associated to the development of new materials and prefabrication technology, transform this shell into a promising opportunity of future development. This work seeks to make part of that future, contributing for the understanding of the multifaceted spatio-functional dimension of these structures and their inseparable architectural component.

Key-words: Ultra-thin free-form shell structures, space-functional requirements, field of vision, isovists, space syntax, layouts.

1. INTRODUCTION

The development of shell structures in the early 20th century was originated by the need to cover large spans in an economical way, using reinforced concrete as the building material. This type of structure requires the design and structural project to converge into the same object, creating a three-dimensional surface element described by a curved surface, in which one dimension (thickness) is significantly smaller than the other two [1]. In this case, the studied structure is an ultra-thin free-form shell structure, corresponding to a curved surface without mathematical or geometrical representation, of optimized structural behaviour [2]. Through membrane action¹ developed on their surface, shell structures can carry high loads with a very small thickness, making it a tool and criteria when defining a space [2].

Shell structures existence dates back to ancient Egyptian and Assyrian civilizations, developing later in the Roman period until the beginning of the 20th century. In the next decades there were several historical situations that led to both its development and extinction, converging now in a period of new technical and computational advances. This progression has encouraged several professionals to search for more complex and abstract shapes, which can allow a faster construction and economy, providing a new opportunity to explore thin-shells. The chances of prefabrication offered by new materials such as Ultra-high Performance Fibre Reinforced Concrete (UHPFRC), allow using all the potential and versatility of shell structures.

This dissertation aims to explore the application of a free-form shell structure developed as part of the research project "Design and Performance of Ultra-thin Concrete Shells". Through analysing the functional polyvalence of the space defined by a shell, two case studies were chosen. It is intended to characterize functional programs, identify space-functional requirements and explore different layouts that meet pre-established objectives.

2. METHODOLOGY AND STRUCTURE

The methodology used for this study is divided in two main parts, a theoretical research and the development of the two case studies.

¹ General state of stress which consists of in-plane normal and shear stress resultants only [3].
The first part is based on the research and analysis of existing information related to thin-shells, focusing on three different subjects: their evolution; shape and surface classification; design and construction elements of thin shells.

The second includes a series of procedures needed for the development of the case studies. First there is a research and observation phase of the chosen site, as well as its morphological and environmental characterization, analyzing the existent activities in terms of the type of occupation, frequency, duration and the approximate number of users (the Herbert Jacobs method was used). Next, the respective space-functional requirements are defined and several exploratory layouts for the implantation of the shell are made, obtaining a wide range of possible scenarios. The layouts are then analysed in two ways: 1) exploring visual fields using Space Syntax methodology [4]; and 2) the geometry of the shade produced using 3D modelling. The final phase consists of the selection of the layout that best suits and fulfils the pre-established requirements, producing realistic views of the shell structure implantation on the site.

The syntactic model used for analysing visual fields establishes that space has a syntax defined according to: the social organization of the groups that inhabit it, the relations of co-presence, and the interactions intended for the system to enable or inhibit. The Visibility Graph Analysis (VGA) method proposed by Turner et al. (2001) [5] using Benedikt’s isovist model, considers global relational measures between all points of a space. Allowing to define the topological properties of space systems according to a continuum. To generate a visibility graph, the software UCL Depthmap (version 10.15.00r) was used, establishing a regular grid (variable) where each space represents a node, and the vertex between nodes represents connections between spaces. From the VGA, spatial properties can be analysed and quantified such as connectivity² and integration³. Also isovists properties are considered, representing the set of all points visible from a given point in space with respect to an environment [5]. Since they represent a defined visual surface, some geometric properties can be quantified (area, perimeter, compactness⁴, occlusivity⁵ and maximum and minimum radial distance⁶). Apart from VGA and isovists, also axial maps were used. Included in the same Space Syntax methodology, it uses axial lines⁷ to understand which lines of vision, rather than areas, connect to more points and provide more visual links. The lines were drawn using the same software, generating an intersection matrix from which the average integration values of the site are obtained [6].

3. EVOLUTION OF SHELL STRUCTURES

Since ancient times extraordinary examples of rudimentary shell technology have been constructed, e.g. the Pantheon in Rome and the Hagia Sophia in Istanbul. Roman times gave way to the development of domes and vaults in the Gothic and Renaissance period, only to be forgotten until the 20th century. At this point, the will to create open spaces and the development of the new reinforced concrete gave the ideal conditions for shell structures to flourish.

With the construction of the first shell structure for the Zeiss planetarium in Germany in 1925, Franz Dischinger and Ulrich Finsterwalder marked the beginning of the new era of shell construction. This led to many other structures using the same system, and expanded thin shells throughout Europe and America. Anton Tedesco is considered the first shell constructor in the US with the Hayden Planetarium (1932, New York). During the next three decades, several architects

² Connectivity of a node (space) x: is the number of nodes (spaces) connected directly to x.
³ Integration of a node (space) x: is the average distance of x to all other nodes in the graph (system).
⁴ Compactness: ratio between the average and maximum distance of each point. Varies between 0 and 1, if it tends to 0 shapes are linear, thin, and less compact. High values compact circular shapes [7].
⁵ Occlusivity: proportion of the perimeter lying on the solid boundary of the environment [5].
⁶ It refers to the maximum and minimum distance that can be seen from the point x [7].
⁷ Axial lines: largest straight lines able of covering all the system.
and engineers as Bernard Laffaille (1900-1955), Pier Luigi Nervi (1891-1979) and Eduardo Torroja (1899-1961), where among the first shell constructors, introducing new projects and techniques. They created a variety of iconic structures, as the grandstand of the municipal stadium in Florence (1932, Nervi), or the basketball stadium Fronton Recoletos in Madrid (1936, Torroja).

With the beginning of World War II there was an interruption in construction. Many structures were destroyed and new projects were rejected. Only in the US and South America construction continued developing, highlighting the work of Oscar Niemeyer (1907-2012) e.g. the Pampulha Church of São Francisco de Assis (1943). But the war had two sides, on one hand it destroyed and stopped shell development, on the other it gave way to a post-war reconstruction period with low labour costs and the need for new buildings, representing shell structures the best solution. Nervi, Torroja and Tedesko continued their work alongside Nicolas Esquillan, Felix Candela, Eladio Dieste and Heinz Isler, guiding the blooming period of shells between 1950 and 1970 [3].

At the end of the 1970s shells suddenly disappeared. Constant increases in labour costs, high material prices, associated with the complex design of shells, made them only available to a few specialists and limited drastically their construction. But after a few years, new developments started to emerge, as membrane structures and grid shells became the new tendency in the 1980s. Since the 1990s, natural free-form shapes and blobs attract more attention [3]. With new computer and software developments innovative possibilities are given, eliminating the constraints of regular forms and exploring new methods of form-finding8 and morphogenesis9. Also combining the recent developments in concrete technology with ultra-high performance fibre reinforced concretes and pre-fabrication opportunities, is possible to revive thin shells construction.

4. CLASSIFICATION OF SHELL SURFACES

Structure represents one of the most important components in construction. In shell structures it is fundamental that the spatial curve develops membrane behaviour, making the geometrical shape dependent on the force flows and determining the behaviour of the structure. For shells, classification through their surface is crucial and can be reached in several ways: considering their Gaussian curvature10 or how the shape is generated (geometrical or non-geometrical). The Gaussian curvature values can be zero (monoclastic11), positive (synclastic12) or negative (anticlastic13). A monoclastic shape represents a simple curvature, considering the generated surface to be developable, what allows the shape to be altered into a plane without cutting or stretching the original surface. Surfaces where all points have a positive or negative Gaussian curvature are considered non-developable, since they can’t be transformed into a planar element without any alteration. Non-developable shapes are known to be stronger and more resistant, once there is more external energy needed for buckling to occur.

Geometric generated shells are defined by mathematical functions, allowing an easy analysis and a simple way of describing surfaces. It can be divided into: surfaces of revolution (rotating a plane curve around an axis); translational surfaces (sliding a plane curve through another); ruled surfaces (sliding the two ends of a straight line - parallel to a given direction - between two curves); and complex surfaces (combination of revolution, translational and ruled surfaces).

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8 Form-finding is the process of defining a geometry of a structure according to the desired final behaviour.
9 Morphogenesis is a biological process who originates the shape of a living organism [8].
10 The Gaussian curvature of a three-dimensional surface is the product of the main curvatures, which are defined as the maximum and minimum curvature of a certain surface.
11 Circular or non circular cylinders, cones or translational shells.
12 Spherical or elliptical domes, ellipsoids or revolution paraboloids.
13 Hyperbolic paraboloids.
Non-geometrical surface generation defines shapes through form-finding methods. Form-finding is a process that by controlling some parameters, the ideal shape of a structure is found, assuring its static equilibrium. Form-finding methods can be divided into experimental and numerical. **Experimental methods** generate surfaces through physical models where their shape derives from the existent forces. The best known are hanging structures, shapes created by the plasticizing of fabrics and pneumatic created shapes. **Numerical methods** are computational modelling techniques that base structural efficiency on aesthetic and spatial functionality. They simulate physical processes in a virtual environment, that generates surfaces without real models. Allowing total freedom when creating shapes, it uses CAD and CAM technology to become a faster, economical and real scale modelling method. The most used numerical methods are Force Density Method (FDM), Dynamic Relaxation Method (DRM) and Particle-Spring System (PS).

Optimization is also an important part of surface generation. It is a process that seeks a better adaptation of form-finding parameters to an ideal geometry, minimizing a specific function or an adaptability criterion. Some of its objectives are: minimizing material usage, weight, deviations or dynamic vibrations, or maximizing the load bearing ability of a structure. Structure optimization is connected to morphogenesis and genetic algorithms, being able to formulate functions independent of structural performance. Through exploring evolutionary algorithms, several possibilities can be created, and exploiting them will assure that the best solutions are generated.

5. DESIGN OF SHELL STRUCTURES

Structural design is the iterative process of projecting an efficient structural system. In shell structures, optimal design provides an advantageous geometrical and structural interaction which results in membrane stress field allowing an efficient load bearing system [3]. When designing concrete shells, some factors should be considered and will be presented ahead.

The span and scale of a shell are chosen according to the function it should serve. Candela established, following structural, functional and economical parameters, that the ideal span for thin concrete shells would be 30m. Higher spans increase proportionally the height of the structure, needing special formwork, becoming expensive, and risking not achieving the desired shape. A good design would be a compromise between complexity (economizing material) and simplicity (overall economy). **Thickness** is also fundamental, meaning a superior dead weight when not correctly dimensioned, and allowing a better development of membrane behaviour with inferior thicknesses. If bending moments appear, it is possible to increase it locally.

**Ribbed** shells were a solution developed to find a different way of obtaining bigger spans without having to distribute the material throughout the whole surface. Makes it possible to stiffen the structures and get better buckling resistance. **Prestress** is another way of increasing spans, assuring that tensile stresses were prevented or reduced by introducing compressive stresses in the structure. It is considered that only spans above 30m need prestress. Some of its advantages include: crack control; control on the influences of shrinkage, temperature and bending moments; assures compression; and makes it easier to remove the formwork. Another alteration in shell design was the desire to show spectacular thin cross-sections of shells, originating **free edge** shells. To remove the supported boundaries other solutions had to be found, e.g. introducing an edge ring beam or a tension cord, or thickening locally the shell supports. **Materials** also play an important role being fundamental to know beforehand the properties of the one chosen. Some of the most used in shell structures are: masonry, used a lot in domes and vaults; iron, later developed into several types of steel; ferrocement used by Nervi for prefabricated shells; ceramic tiles combined with concrete; plastics; and concrete, which made possible amazing developments in construction continuing to be a research subject (e.g. ultra-high performance...

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14 Computer-Aided Design.
15 Computer-Aided Manufacturing.
fibre-reinforced concrete). Supports design should also not be forgotten, being essential to assure its correct fixation. Possible movements could lead to disturbances in the membrane stress field, increased deflections or in-extensional deformations [3]. Also the type of loads supported by the shell should be considered, being grouped according to their time variation: permanent (dead weight); variable (climatological conditions as wind and snow); accidental; and time dependent loads (creep, shrinkage and temperature gradients).

And finally, all these characteristics converge into the overall economy of the structure. If traditional techniques are used, a lot of labour work will be needed implying high costs. Methods which require less manpower will allow more economical options and renew shell construction.

5. CONSTRUCTION OF SHELL STRUCTURES

Shell construction involves several parts, each affecting the structure in a different way. Therefore the following construction elements were considered: formwork and framework, reinforcement, placement of concrete, finishing and prefabrication.

Formwork and framework are two of the biggest difficulties in shell structures and represent the major constraint on their economical construction. Several professionals tried to reduce costs in three ways: improving traditional wood formwork, using standardized measures, and through implementing new construction techniques. Thus, formwork can be divided into: conventional formwork, which is extremely time consuming and expensive, but allows any shape to be constructed; prefabricated moulds, e.g. ferrocement moulds used by Nervi (permanent formwork) or Cornshell system (uses a reinforced steel base that works as formwork and reinforcement); airform shells, with MINI, BINI and Monolithic Dome techniques (using air inflated membranes); and stressed membranes (using prestress to place the membrane into the desired shape).

Reinforcement is what allows the transference of tensile stresses from bending, membrane action and transverse and membrane shear [3]. There are different types of reinforcement for each construction technique. In shells the most used ones are: conventional reinforcement (one or two layers of steel rebar or wire mesh); airform moulds, using MINI or BINI systems (reinforcement is arranged before inflation), and Monolithic Dome (steel rebars are fixated to the interior). The most important placement of concrete techniques in shell construction can also be separated into conventional placement and sprayed concrete. The first technique uses a skip and a tower crane with a jib, starting from the supports to the top, assuring the coverage of all reinforcement. Sprayed concrete consists on spraying a mortar or concrete mixture with air pressure [3].

Surface treatment is not normally used in shell structures, once an appropriated concrete with the adequate cement content is durable and impermeable enough [3] to resist climate attack.

With prefabrication, shells are divided into parts and assembled after their production, connecting them on site. Structures can be prefabricated has a whole (only small shells), in small pieces (too many components) or in big pieces (in-between solution). Overall, the choice is made according to the desired objective, considering the transportation and erection, but also a question of tolerances and the joints to be made [3].

6. CASE STUDIES

For the two case studies presented, the shell H800N3 developed within the research project which includes this thesis will be used. The shell was created considering some key criteria: area, number of supports, maximum height and edge’s height; originating a 25m diameter triangular shape, with 8m height and with 1m width on the supports. The possibility of prefabrication, separation of its shape into parts, the absence of an occupational program, and its inherent properties, transform this structure into an ideal research element.
6.1. Case Study 1: Keil do Amaral Amphitheatre

The first chosen site was Keil do Amaral Amphitheatre, located east from Montes Claros on the South hill of Monsanto Forest. The specific approach to this case study involved a direct and indirect observation of the activities occurred and exploration of the preferential location for the shell to be placed. The primordial objective is to provide climate protection respecting special requirements such as: the structure should not be imposing on the site; ensuring the continuity of the usual occupations; preserving existent visual frameworks; and allow user mobility in space.

Activities as geocaching, hiking, climbing, running, BTT, horse riding, bird watching, cicloturism, picnics, among many others are some of the activities that take place in this area. The wide range of activities made it necessary to group them in four main groups: small sport activities, diverse leisure activities, promotional or musical events, and start/end point of events. Small sports activities can include outdoor yoga classes or football games, with approximately 20 participants or less at the time (Fig. 1 - a), occupying mostly the plain area of the amphitheatre. With leisure activities (Fig. 1 - b) as hiking, resting, enjoying the view, the used area concentrates mostly on the sitting areas. Promotional or musical events (Fig. 1 - c) are related with e.g. Red Bull Silent Garden, or Meo Out Jazz (activities that take place in this amphitheatre every year), occupying all the amphitheatre area, both plain (where the “show” takes place) and sitting area (extending to all areas nearby). For start/end of events (Fig. 1 - d) most activities that take place are races (e.g. Ajuda race, Tree race, Chestnut race), now concentrating on the existent pedestrian path and the nearby areas.

After analysing the existing uses, different implantations for the structure were studied, considering the most occupied areas, where shading is more needed and following the previous requirements established. Firstly, the ideal number of shells to use was considered, testing layouts with: one shell, locating it on the different sitting areas; two shells, combining the protection of different sitting areas and the plain “stage” region; and three or more shells, covering all the sitting and “stage” area. The chosen layout used two shells, combining a shell in the sitting area near the “stage”, and another on the plain area itself.

Once the number of shells and where they should be located was established, it was important to find out in which position they should be implanted. For that, visibility graphs and isovists properties were analysed in four different situations, rotating first one shell and then the other, as well as the geometry of the provided shade.

The chosen layout (Fig. 2 - a) was consequence of analysing the previous layouts, obtaining the best situation possible. It allows great connectivity values (Fig. 2 - b) on the whole area (red and orange), being the most affected is a small part of the sitting area; the integration (Fig. 2 - c) shows a greater probability of movement on the plain area of the stage, having an overall free reading of the space; compactness (Fig. 2 - d) values even though they are still close to 0, indicate a tendency of the isovists shape to evolve to more regular and symmetrical shapes; with the occlusivity (Fig. 2 - e) can be seen the inexistence of red areas, which indicates low hidden areas.
The data obtained on each critical point of the sitting area allows to better quantify the appreciations made through the graphs. It can be seen that the area and perimeter of the isovists are very different, which supposes a more regular visual field, without many interruptions (also verified by the compactness values). The hidden area is also not significant compared to the total.

Table 1 - Data from the analysis of the isovists on the three chosen points.

<table>
<thead>
<tr>
<th>Point</th>
<th>Area</th>
<th>Perimeter</th>
<th>Compactness</th>
<th>Occlusivity</th>
<th>Max. Dist.</th>
<th>Min. Dist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>6995,38</td>
<td>605,58</td>
<td>0,24</td>
<td>331,67</td>
<td>97,68</td>
<td>3,62</td>
</tr>
<tr>
<td>Point 2</td>
<td>8222,47</td>
<td>804,12</td>
<td>0,16</td>
<td>518,56</td>
<td>112,66</td>
<td>3,31</td>
</tr>
<tr>
<td>Point 3</td>
<td>8780,76</td>
<td>789,20</td>
<td>0,18</td>
<td>489,20</td>
<td>120,64</td>
<td>3,67</td>
</tr>
</tbody>
</table>

The geometry of the shade was also explored on all the situations, using six different times and events of some of the activities studied. Here only four of them will be shown, representing the most extreme situations. Even though it does not have a proficient behaviour at all times, those bad behaviour hours are between 8h and 10h, when the sun is not very strong, and from 17h when it comes down. The rest of the time, it allows a perfect protection, and even on those extreme times, the area covered is still significant.

Considering all the specifications and needs of this site, the best configuration and implantation of the structure was explored. Introducing these shells would solve the excessive sun exposure, protect the most occupied areas on the most critical hours, and allow to use this space at anytime. With their organic shape and thin section, these structures do not disrupt the natural environment or visual frames, and allow a free and uninterrupted movement.
6.2. Case Study 2: Fátima Sanctuary

The second case study is located in Cova da Iria, on Fátima Sanctuary precinct, which is one of the most important marian sanctuaries in the world. For this site, indirect observation through research and document analysis were made, allowing to understand how religious ceremonies happen and what are the necessary conditions for them to occur. From the data obtained different solutions were explored. The main objective for the shell(s) is to provide climate protection in the open terrain of the sanctuary, creating also a new celebration exterior area, introducing new programmatic opportunities. In this case some particularities must be considered. The site is defined through strong axes that conform the space and introduce a volumetric symmetry between the built masses. Analysing the axes will determine the most suitable implantation places for the shells. The main axis (E1) organizes all the area, creating symmetry between buildings, accesses, and green areas (Fig. 5). The two other axes are introduced by the Chapel of the Apparitions, creating new defining lines, both longitudinally (E2) and across it (E3).

Figure 5 - Illustrative schemes of the existent axes on site.

Also the existent activities were analysed since it is one of the most visited sacred places in the world. Everyday people can attend a mass from 8h to 21h30 every hour, with a special program on Sundays. From May to October on the 12th and 13th there are very large pilgrimages. Considering this, activities were divided into: daily use (Fig. 6-a); Sunday mass (Fig. 6-b), and special events (Fig. 6-c). Overlapping the activity schemes (Fig. 6 - d), the most used areas can be seen: sitting areas (1), Chapel of the Apparitions (2) and in front of the Basilica of Rosário (3).

Figure 6 - Illustrative scheme of occupation of the site by a) daily use; b) Sunday mass; c) special events; d) overlapping of the activity schemes.

After analysing the existing activities, different implantations for the structure were studied, considering the axis system and the most used areas. As in the first case study, the ideal number and compositions of shells were tested. One shell, located on different parts of the axes; two shells, combining them into one single area or using them separately; and three or more shells, also combining them or not. The chosen layout used three or more shells, giving a better protection and allowing a more comfortable exterior altar area. For the next analysis, two hypothesis were considered, one with seven shells and other with five, both analysed according axial maps, visibility graphs, and geometry of the provided shade. The chosen layout (Fig. 7-a) allows special relations and visual frames with diverse existent elements in a simple and direct way. The shells were located in two separate places: the volume introduced by the Chapel is compensated in front of it by combining two shells into a single one, and the rest is positioned following the axis E2. With the axial analysis the influence of the shells can be evaluated through visual and physical accessibility lines. With this hypothesis the general integration of the area diminishes in relation to the original situation (Table 2), still maintaining good overall values (Fig. 7-c). Shells also help homogenizing the overall integration, once the difference between the
maximum and minimum integration values is inferior to the original situation (Table 2). The data obtained from the visibility graph analysis helps to understand how the presence of the shells changes the general perception of the area. The north area is the one with less connectivity (Fig. 7 - d) and integration (Fig. 7 - e) values, being more obstructed and with less movement potential, but allowing in general a free connected area. The compactness (Fig. 7 - f) has very low values, indicating very complex and asymmetrical isovists, giving a very interrupted visual field (Table 3).

As for the occlusivity (Fig. 7 - g) values, the most unobstructed area is through the main axis.

Table 2 - Data from the axial analysis of the average, minimum and maximum integration values.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Average Integration</th>
<th>Min. Integration</th>
<th>Max. Integration</th>
<th>Max. I. - Min. I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>24.03</td>
<td>5.75</td>
<td>41.90</td>
<td>36.15</td>
</tr>
<tr>
<td>Hip. 1</td>
<td>21.60</td>
<td>6.30</td>
<td>38.94</td>
<td>32.64</td>
</tr>
</tbody>
</table>

Table 3 - Data from the analysis of the isovists on the three chosen points.

<table>
<thead>
<tr>
<th>Point</th>
<th>Area</th>
<th>Perimeter</th>
<th>Compactness</th>
<th>Occlusivity</th>
<th>Max. Dist.</th>
<th>Min. Dist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>62456.1</td>
<td>8208.92</td>
<td>0.01</td>
<td>7159.29</td>
<td>348.33</td>
<td>22.78</td>
</tr>
<tr>
<td>Point 2</td>
<td>71569.4</td>
<td>8013.65</td>
<td>0.01</td>
<td>6725.59</td>
<td>266.53</td>
<td>9.23</td>
</tr>
<tr>
<td>Point 3</td>
<td>84415.2</td>
<td>8049.33</td>
<td>0.02</td>
<td>6882.62</td>
<td>276.22</td>
<td>26.28</td>
</tr>
</tbody>
</table>

The geometry of the shade was also explored on both situations at several different hours through the day. In summer, when it is more important to have an adequate shading system, it protects a considerable area, and in winter its performance is diminished in the morning and evening.

For this specific case study, a program for the secondary exterior altar was also developed, testing different layouts and how the program can work in the structures and what is the best place for it. After several considerations, it was chosen to locate the altar on an 2.5m elevated platform, increasing its visibility to and from it. Next, digital images were produced to understand how the shells would work on the area and several layouts were developed, exploring the views from and to the platform, choosing the ones that give a better access and greater visual field, introducing a new diversity to the existing area and allowing new functional possibilities. Also the organization of the different areas on the platform where slightly explored, studying several ways to access the platform (the example chosen is accessed by three ramps) and defining different areas: altar, tribune, lectern and a sitting area (for bigger celebrations with more clerics).
8. CONCLUSION

The developed work had the main objective of studying the architectonical dimension of a shell structure created on the research project “Design and Performance of Ultra-Thin Concrete Shells”. By studying their historical evolution and construction, it was intended to highlight the importance and advantage of using this typology of structures. Through functional exploration of the space, its behaviour was analysed in very different situations, studying how the chosen site would be affected, and obtaining good and several valid options for each study. With the case studies it was demonstrated that this structure can receive several different functions, proving its functional polyvalence (works on both in a very undefined situation, and with very specific function relating to other existing elements in an urban context). The functional flexibility of H800N3 shell was explored according to extensibility criteria (expansion possibility), convertibility (internal organization modifications), and versatility (polyvalence of spaces). Using the developed work as a base, it would be interesting to explore some further points: new scenarios and case studies, demonstrating and validating with other real situations the possibilities introduced for this shell; other space syntax properties, as Choice (identifies the most probable preferential movement directions) in axial analysis, or Clustering Coefficient (how the visual information changes inside a system), Step Depth (number of barriers to cross from one point to another), Control (areas that can be easily seen) and Controllability (contrary to control) in visibility graph analysis. The current technological means are promising to the future implementation and dissemination of these structures extending its benefits and minimizing its drawbacks. Their natural form associated to the development of new materials and prefabrication technology, transform this shell into a promising opportunity of future development. This work seeks to make part of that future, contributing for the understanding of the multifaceted spatial-functional dimension of these structures and their indispensable architectural component.

9. REFERENCES