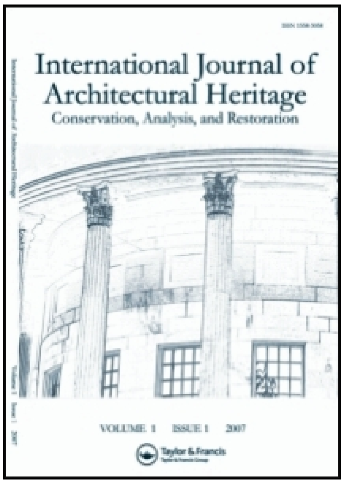

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EVOLUTION OF THE FORMWORK USED IN THE TEMPLE OF THE SAGRADA FAMÍLIA

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The Sagrada Família is Gaudi's unfinished work, to which he exclusively dedicated his last years of life. Even though he only got to build a small part of the total, he defined the rest through models and photographs. Gaudi's design for the inside of the Temple was based on a new geometric architecture that made extensive use of ruled surfaces (paraboloids, hyperboloids, ellipsoids), opening a new field which later architects have followed. The following article aims at showing the construction complexity of these structures, especially in relation to the set-up of their formwork. The vaults, which cover the naves at 30, 45, and 60 m heights, will be discussed. This discussion will show how the construction method, and in consequence the formwork, is adapted to the construction needs according to the geometric shape, size, position, material, and repetitions of each vault.

KEY WORDS: Gaudi, Sagrada Família, geometric architecture, formwork, molds

1. INTRODUCTION

The Temple of the Sagrada Família is the last Cathedral to which the classic concept of an evolutive construction process, of over a century in duration, can be applied. As a consequence, although Gaudi's initial philosophy is maintained, the construction process must change accordingly to the evolution of the time's building technology. Therefore, the evolution of its construction process closely mirrors that of the general building techniques of the epoch.

Nevertheless, Gaudi's design proposal appears to be surprisingly up-to-date:

> Gaudi's precision has allowed a new geometric, powerful and accurate architecture to appear. This architecture can be found nowadays both in structural meshes and in architecture such as that of Calatrava, Isozaki . . . (Buxadé 2006, p. 150)

The use of this geometry, which results in various aspects such as the importance of the number 12 or the repetition of different elements (Alsina and Gómez-Serrano 2002), leads to the use of multiple and varied ruled surfaces, such as hyperboloids, paraboloids, and ellipsoids. Although technically viable, these surfaces demand in

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practice complex construction processes, especially in terms of formwork. As an additional condition, the evolution of labor, both in costs and in experience, has to be taken into account.

The present article, aims to show the evolution of the ways of solving the construction of this sort of formwork during the years. This article is a continuation of a previous article (3) oriented to describe the evolution of the use of concrete in Gaudi's Sagrada Família.

In 1914, Gaudi's works were being criticized in the *"Noucentista"* cultural scene because of their cost and lack of adaptation to modernity.[1] At the same time, Gaudi (working exclusively on the Sagrada Família Temple), starts a new architecture, based on geometry and ruled surfaces. He will satisfactorily solve the Temple's project by means of various scale models. Lacking economic resources, Gaudi will only be able to build the 17-m tall pinnacle for the Nativity facade towers. The rest of his work remains represented in models and photographs that his collaborators rescued from destruction, allowing them to continue the construction process.

This new architecture, based on the precision of geometry, can be effectively adapted to the new graphic and building technologies. As a consequence, the quality of the works in the Sagrada Família increases clearly as the construction processes technology is improved. This project is therefore advanced for its time and is also very suitable to the technologies of the twentieth and twenty-first centuries.

2. SITUATION OF THE RULED STRUCTURES

The Temple of the Sagrada Família is a basilical, Latin cross plan building, with five longitudinal naves and three more naves forming the transept (Figure 1a). It is surrounded by a rectangular cloister, with 12 perimetral towers, symbolizing the Apostles, 95 to 115 meters high, and six large towers in the inside. The central tower, measuring 170 m, represents Jesus Christ and is surrounded by the four 125-m tall Evangelists towers and the tower of the Virgin Mary, 120 m tall and located on top of the apse. These symbolize the Eternal City, which transcends the Apocalypse, as narrated by St John (Ap. 21.10–27), which Gaudi wanted to symbolize in some parts. The tallest towers are situated in the center of the transept and on top of the apse, solving the maximum difficulty for the Renaissance architects, while the naves do not need buttresses, surpassing Gothic architecture (García Gabarró 2002) by means of a static load equilibrium in its design.

In 1914, Gaudi designed a new space for the inside of the temple, with a new architecture based on ruled and other geometries (Figure 1b). These structures, designed according to antifunicular load equilibriums, substitute the buttresses in their role of transmitting vertical loads to the foundations. These surfaces are also introduced in the design so as to give more light to the lower part of the temple.

In the final project, the columns will be double-turn helicoids, the roofing will be formed by paraboloids and the interior part of the vaults will consist on hyperboloids overlapping transition paraboloids. Their complex assembly was clearly defined in the 1/10-scale models and in their photographs. In 1936 Gaudi's workshop burnt down,

[1] *Noucentisme* was an architectonic style quite in fashion in Catalonia between the 1910s and 1930s, which was based on the use of classic orders.

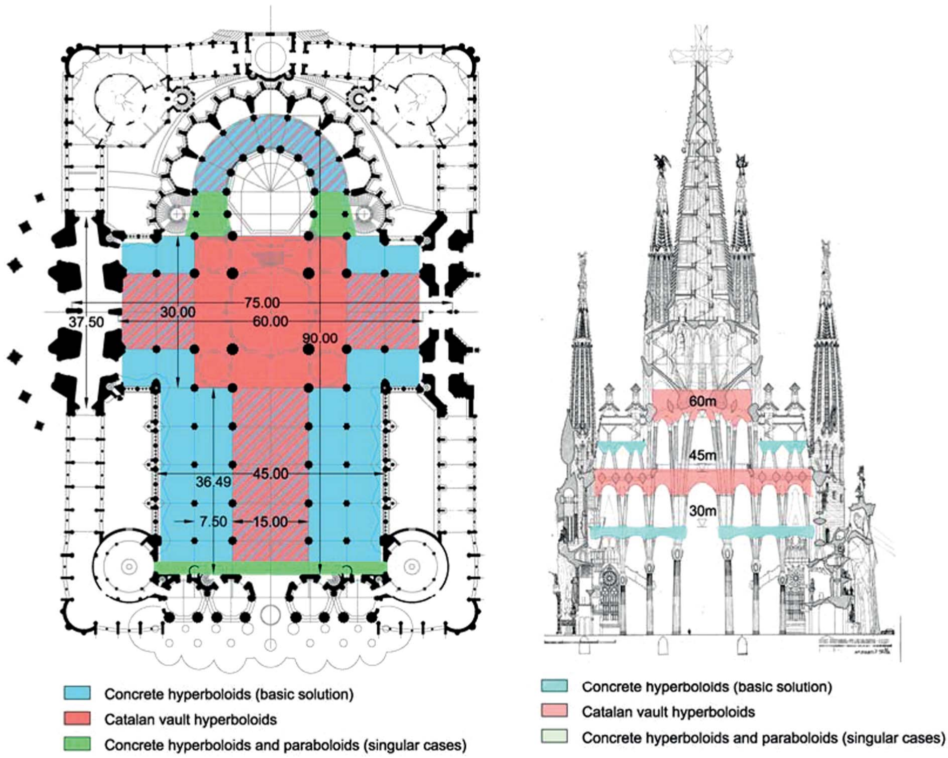

Figure 1. Plan (left) and cross-section (right) of the Temple of the Sagrada Família, showing the naves dimensions and the location of the various types of vaults. Source: Arxiu del Temple Expiatori de la Sagrada Família (ATESF) (figure is provided in color online).

but the models survived because they were made of clay, thus resisting fire, allowing his followers to rebuild some of them.

The vaults at 30 m are generally built of concrete, as Gaudi had suggested (Sugranyes 1923). The hyperbolic vaults at 45 m or higher up are being built using ceramic materials, as Gaudi had foreseen and as his collaborator and biographer Joan Bergós (1953) has written in his works.

Building aspects related to the use of concrete and precast concrete are also important. After his intense and dedicated work for the temple, Gaudi designs and builds the pinnacles for the Nativity facade towers, and he defines the rest of the temple in scale models. Gaudi had already used precast concrete and cemented agglomerates on previous occasions, for example, in the Casa Calvet, Parc Güell, and the church of the Colònia Güell. But in his last work, the pinnacle for the Sagrada Família, cast in situ concrete and the prefabrication of the formwork with Murano glass make it clear that concrete and its formwork were essential to the design (Grima 2004). Gaudi's collaborators had also written, while he was still directing the work, that Gaudi would use concrete structures to obtain a good bonding and because of the building economy they offered (Sugranyes 1923).

From a geometric point of view, the application of computer graphics to the ruled surfaces has allowed to design them more accurately and to make the construction of other parts of the vaults viable, defining Gaudi's geometry and modulation, as well as their mechanical and resistance conditions. As a result of continuous work since 1992, it has been possible to carry out a set-up of all the ceiling of the Temple, which might be finished in 2 years' time (Gomez Serrano et al. 1996). This work is the result of all the studies, experience, and used methodologies.

This geometric approach allows, in great measure, the construction process to continue naturally. Gaudi reacts to the increase in labor costs inherent to Modernism with ruled surfaces or repetitive geometries that can be partly industrialized in the building site to reduce costs. The columns, in which he combines the turns of squares and pentagons (apart from using their basic shapes and triangles and hexagons) to obtain these rigorous but nonetheless visually impacting shapes, can be included in this geometric approach (Figure 2).

However, Gaudi does not only solve a problem: he also gives the solutions to the whole, forming a rational building system, the outcome of which can be observed both in the particular solutions and in their union zones. A clear example of these intermediate zones joining partial systems is the union of a column with its upper pillars, simulating human bones: they are joined using an imitation of a kneecap, which he solves with great geometric elegance by using an ellipsoid (Figure 3).

Nevertheless, the best example of this is the union of the spatial elements that constitute the slabs: hyperboloids and paraboloids. Gaudi creates intersections in which the end of one of the structures corresponds to the beginning of another,

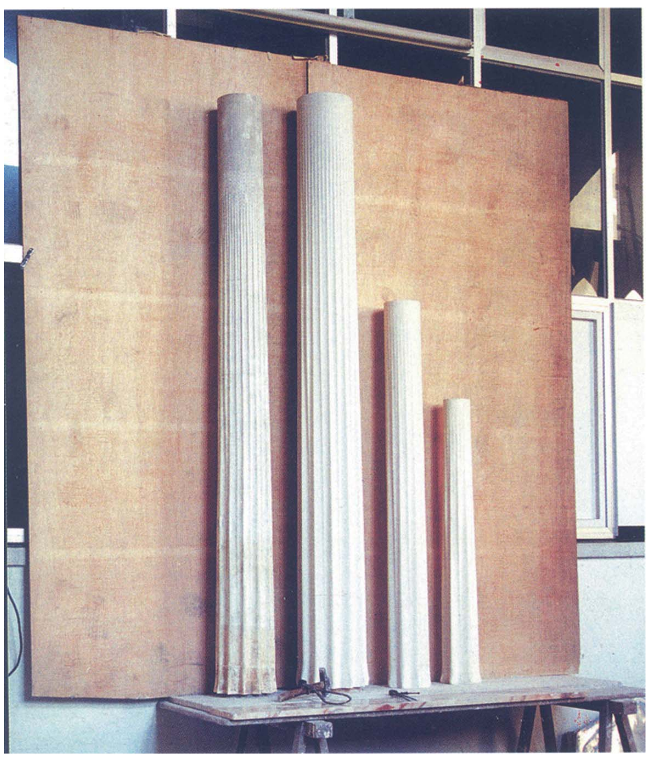

Figure 2. Photograph of models of different columns, as the result of the turning of basic geometric solutions (figure is provided in color online).

Figure 3. Photograph of an ellipsoid as a solution to the union of subsystems (figure is provided in color online).

integrating them in a very natural manner, which can easily pass unseen even to the expert (Figures 4 and 5).

Some of these intersections are emphasized by the interweaving of the structures and allowing flanges such as those in Figures 4 and 5, reminiscent of two hands in a position of prayer or meditation, to appear. Just another detail from the architect, who tries to strengthen the structure's function through the whole of it, including the details, something which is not commonly done today.

3. EVOLUTION OF THE RULED STRUCTURES' BUILDING TECHNIQUES

3.1. General Aspects

The Sagrada Família's construction process is and has always been challenging, due to its peculiarity and complex shapes. Because this building process was started many years ago, very different processes have been used, from traditional technologies

Figure 4. Photograph of the intersection between hyperboloids and paraboloids (figure is provided in color online).

Figure 5. Photograph of detail of an intersection between hyperboloids and paraboloids (figure is provided in color online).

to state-of-the-art modern tools. The change has been especially noticeable because building construction, like many other sciences, did not start to evolve in such a revolutionary way until the beginning of the twentieth century. The Sagrada Família has witnessed the change in structural materials from masonry to reinforced concrete. The tools which have been used during this process range from the same chisels, punches, and stonemason hammer's, besides others, which have been in use for millennia, to sophisticated numerically controlled diamond wire machines.

However, the most noticeable changes are those that have been made possible thanks to the significant improvements in building technologies. Gaudi used inverted arches made of stone blocks as foundations; today a new system based on pilotis is used. The stability of the pilotis is greater than that of the stone foundations, thanks to the great depth that the pilotis can reach and the friction they cause in contact with the ground. As one of Gaudi's collaborators said:

> [Gaudi believed] that this new organic architecture which he had designed and which used inclined columns, would be much easier to build in a self-supporting material — he referred to "concreted" [2] structures — because a lot less scaffolding would be needed. (Sugranyes 1923, p. 12)

The scaffolding of Gothic cathedrals could not be removed until the vaults were completed, because the whole structure was designed to work under compression. This limitation has long since been overcome, so it was greatly helpful to be able to build the central nave with one provisional working platform at 40 m while removing all scaffolding from beneath it.

Gaudi did not have the opportunity to build the ruled surfaces at 30 and 45 m in height, so he did not have to confront the construction issues that they cause in the Sagrada Família, even though he had clearly decided they would be used, as an easy and cheap option (García Gabarró 2002). Nevertheless, he had used them in some other works, such as the Parc Güell (hyperboloids) and the Colònia Güell church (paraboloids), even though that was in a less explicit form in the whole of the structure.

These surfaces, especially hyperboloids, have various functions: transmitting the vertical loads to the pillars with the minimum weight, allowing light to enter the temple, giving monolithism and transversal rigidity. They substitute for the Gothic amphorae in their role of lightweight filling for the roof.

These surfaces have to be made of high-performance materials, given their small thickness. Concrete can fulfill this demand, so it is the material that has been used in the paraboloids. However, each of the solutions for different paraboloids varies, for aesthetic, economic, or other reasons.

The use of precast concrete sections has also been challenging. Gaudi started to use them in the spheres atop the pinnacles and other elements in the Nativity facade that made in the workshop and then lifted to their final position. Today this system is being greatly promoted, so it is possible to build increasingly larger and higher quality precast elements. This process is also possible thanks to the six powerful cranes and hydraulic lift tables that are used in the Temple.

The amount of technology present in the various conventional workshops of the Temple, ranging from carpentry to metalworking or model-making makes it increasingly easier to construct a building of this scale. Normally the pure standard solutions are difficult to apply to the work, so new solutions are found, relying on the resourcefulness and creativity of the workers. This is why we believe the Temple of the Sagrada Família is one of the greatest permanent construction laboratories in the world.

3.2. First Basic Formwork Solution for the Building of Gaudi's Project

The concrete vaults that represent hyperboloids, located at 30 m over ground level, can be built using molds as formwork, due to the fact that there is a great number

[2] Note that the term *concrete* is not used today to refer to that material in Catalan, the term *formigó* is used instead. Gaudí's use of the word *concrete*, derived from English, shows to what extent it was still a very new material at the time, as there was no specific word for it in Catalan yet.

Figure 6. Photograph of polyester molds (figure is provided in color online).

of a repeated element (20). This use of molds is called the *basic solution*. This solution is introduced in 1993, as an adaptation of shipbuilding techniques to architectural needs.

In this solution, the molds are built by means of a first real-scale plaster model, produced by the Temple's model-makers, on top of which polyester molds are made (Figure 6). These molds are considerably big, so it is important to design them in a manner, which allows easy assembly and removal.

As a consequence, it was decided to cut the polyester molds so as to make them more comfortable to use and to make their removal easier. The molds are not always cut at the same point, because they can adapt to different positions and because their dimensions have to be proportionate. Therefore, a certain level of craftsmanship is still necessary even though the rest of the process has been greatly industrialized.

Once the molds have been placed, a first layer, 10 to 12 cm thick, of mortar and white cement is shotcreted onto the molds (see Figure 7). If the reinforcing bars were placed before shotcreting, there could be visual problems in the finish, such as dark areas in the fair-faced concrete, behind the bars, as a result of the accumulation of sand in some zones or because of a deficient blending of the mortar.

After this, a second layer of concrete made with gray Portland cement is sprayed on top. Next, the reinforcing bars are placed and the chambers are prepared. Initially, this layer was done spraying concrete or a coarse aggregate mortar. This method has since been abandoned, though, because of problems related to the aggregate rebounding (making it difficult to remove afterwards, and so increasing the weight), apart from reflections of dark areas, caused by concrete spraying problems or other issues, on the first layer.

As a substitution, a core mold is also used to give shape to the inside of the chambers. This mold is made of low-density expanded polystyrene (EPS) (Figure 8). This makes the construction of elements that connect to the hyperboloids (such as pillars, beams, slabs) easier (Figure 9). The EPS is shaped by cutting it with a fire-heated wire. Later, a plastic wrapper is used to stop the EPS from disaggregating. To stop this

Figure 7. Photograph of concrete spraying (figure is provided in color online).

Figure 8. Photograph of EPS mold (figure is provided in color online).

core mold from floating on the fresh concrete, it is fastened in position by means of a fixing cage. The concrete is compacted with a vibrator.

The concrete spraying-based solution implied a greater thickness of these sheets, increasing the structure's weight. For this reason, the EPS lighter solution is used whenever the volumes to fill are not too large.

Figure 9. Photograph of connection elements (figure is provided in color online).

The only inconvenience of this solution is the difficulty in moving the formwork, given its large surface and relief. The formwork's manipulation is complicated because of the weight of the polyester and that of the metallic structure that reinforces it. This situation is complicated even more because of the formwork's unstable shape. As a result, both the placing and uncasing of the formwork are complicated procedures.

3.3. Catalan Vault: Second Solution, Main Solution at the 45 m Ceilings

Catalan vault is traditional building technique that is very commonly used in Catalonia to cover spaces and build staircases which consists of two or three layers of tiles or bricks mortared together, creating a very resistant whole. At the Temple of the Sagrada Família, this solution is used for the first time in 1998, coinciding with the change of the main crane. They are basically located at the 45 m high vaults, both in the main nave and in the transept, at the 60 m vaults in the crossing, and in some zones of the 30 and 45 m vaults in the apse.

On the Temple's vaults, the solution that is used for the molds is to prepare the hyperboloids with hencoop mesh covered steel bars to create a continuous surface (Figure 10). The first layer of tiles follows the straight lines of the hyperboloids (Figure 11). The empty spaces left by the lines of tiles are filled with decorative

Figure 10. Photograph of the preparation of the hyperboloids (figure is provided in color online).

Figure 11. Photograph of the details of the first layer of tiles (figure is provided in color online).

triangular elements, made of green- and golden-colored glass (their dimensions having previously been calculated in a computer drawing). These triangles represent the palm tree leafs that Gaudi wanted to express on the vaults. Construction and decoration follow geometry, turning the plane brick vaults into an element of the inside aspect.

A fast cement, placed by lateral contact, is used in the first layer. In the other two, a standard Portland cement mortar is used. A stainless steel soldered net is placed as a frame, to increase the unification of the whole (Figure 12). Every time a new layer of tiles is built, the previous one is wetted (Figure 13), so as to strengthen their union.

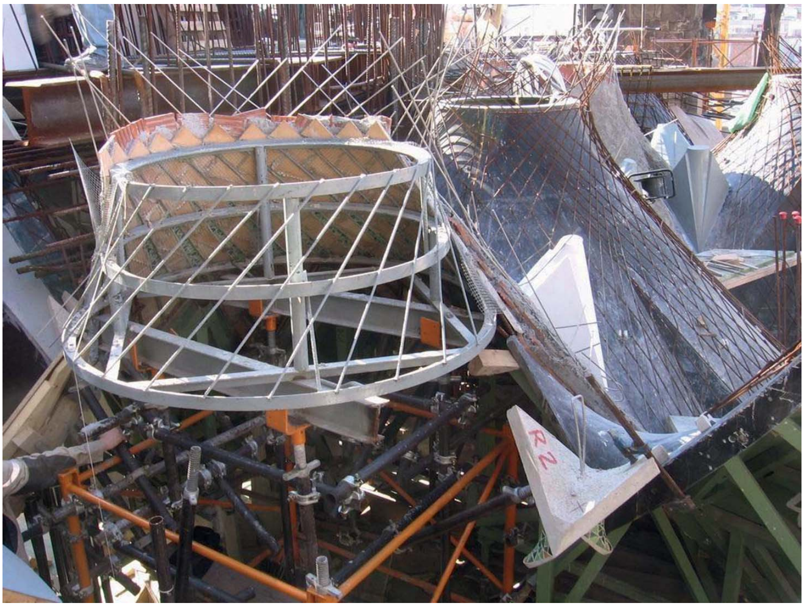

Figure 12. Photograph of a stainless steel soldered net during placement as a frame for the hyperboloids (figure is provided in color online).

Figure 13. Photograph of the details of the first layer of tiles (figure is provided in color online).

The direction of the following layers is different from that of the first one. The final layer follows the meridians of the vault. The whole process lasts 3 weeks.

3.4. Single Formwork Concrete Vaults, Applied Single Solution

This formwork is used in vault modules, which will only be built once, so it is only intended for one use. Its low cost and construction easiness are essential in its application. These vaults are basically located where the apse and the nave meet, and in the inside of the Glory facade. The structures are, in this case, mainly hyperboloids that can be applied both to the capitals or in different zones of the vaults. This solution's main problem is its slowness. Every geometrical element has to be treated with a different technique, rendering the process very slow and needing great coordination efforts between the various crafts that intervene in its setup and assembly. For example, making the edges of a totally wooden hyperboloid coincide perfectly with those of a paraboloid with a metallic base can be a complex and slow process. Different materials are used for each situation, according to the shape and dimensions of the pieces, as noted the following text.

3.4.1. Flat sections of formwork Flat sections of formwork, given their simple shape, are made of phenolic board, cut out of a triangular template. The dark area molding is included in the formwork. The board's surface and a good vibration of the concrete ensure its correct finish.

3.4.2. Parabolic formwork pieces The parabolic formwork pieces can be differentiated according to their dimensions.

3.4.2.1. Large pieces The largest ones are built with metallic corrugated bars soldered forming the exterior perimeter of four sides in space and one of the directions of the generatrices. These bars are separated 5–10 cm from each other and are covered by a "tablex" board painted with latex (a coating of water and acrylic), which adapts its shape to that of the paraboloid's curved surface in a day's time and can be tied to the metallic generatrices by means of wires (Figure 14). The formwork's inside surface is

Figure 14. Photograph of the formwork adaptation of its shape to that of the paraboloid's curve (figure is provided in color online).

Figure 15. Photographs showing the contrast of different surface finishes (figure is provided in color online).

painted with red lead to avoid it being porous. It is normally bush-hammered, to give it a better finish and to avoid imperfections (Figure 15), even though a very smooth surface is obtained on the pillars by hammering them by hand or using a pneumatic drill. This bush-hammered surface can be made to contrast with other finishes (such as smooth finishes) to mark the difference between them.

Large parabolic formworks have caused some problems because of their wooden-clad surface, especially when it has been in the open for a long period of time, because of the slow process of placing the main metallic frame. This "tablex" wood is very flexible but it is not resistant to humidity. Gradually, this problem has been avoided by using very flexible and resistant laminated wood that is normally used in shipbuilding, increasing its weather-resistance.

3.4.2.2. Smaller pieces The smaller paraboloids, measuring from 15–50 cm, are previously prefabricated (Figure 16). They are usually constructed with smooth,

Figure 16. Photographs showing smaller paraboloids that are previously prefabricated (figure is provided in color online).

Figure 17. Photographs showing the preparation of smaller paraboloids (figure is provided in color online).

3 or 4 mm thick steel bars, which when placed contiguously on top of two axis bars create a paraboloid (Figure 17). The inside surface of the formwork is smoothened with epoxid mortar (using very dry sand to avoid incompatibility problems with the resin), which shapes the paraboloid's surface better. Painting the contacting zones with red lead and correctly vibrating the concrete, a smooth surface can be obtained after removing the formwork.

3.4.3. Hyperbola-shaped formwork pieces The hyperbola-shaped formwork pieces, although based on the previous ones, are solved in a different way, according to these hyperboloids' geometric position. When placed on the inferior part of the capital, the wooden ribs, cut in a hyperbolic shape (like that of the open part of a bell) are placed on the outside of the mold (Figure 18). A board is adapted to these ribs by means of nails and screws. This sort of board, 5 mm thick, can be twisted and adapted as convenient (it is commonly used in wooden ship construction, from where it was imitated).

When the formwork is placed on the superior part of the capital, the wooden ribs are placed on the inside of the mold. The hyperboloid's neck, being smaller and having a bigger curvature, is solved by superimposing circular wooden sections with their corresponding inclination also cut on the sides (Figure 19). There is a cutting machine

Figure 18. Photographs showing the formwork of the hyperboloids when they are placed on the bottom part of the capital (figure is provided in color online).

Figure 19. Photographs showing the formwork of the hyperboloids when they are placed on the superior part of the capital (figure is provided in color online).

at the Temple that is used to make the solid wooden collars and the other components. The outside of the mold, which will be in contact with concrete, is painted with red lead so as to cover the porosity and improve the quality of the finish.

These solutions are generally reached after years of working on these ruled surfaces, thanks to the comprehensive knowledge of their geometric development that is attained. Some of the problems that will arise during construction can be foreseen by means of scale model studies, which are carried out in the Temple's large model workshop.

4. CONCLUSIONS

Initially, it seems logical that Gaudi proposed ruled structures as a response to the criticism that Modernism received in the beginning of its downfall, in the first years of the twentieth century, referred to its high building costs.

However, the strength of the geometric architecture (which is precise and powerful) that Gaudi proposed opened up a new era, during which his work can be continued following his own criteria. Examples of this architecture in the present can be found in the works of architects such as Calatrava, Isozaki, and others. The solutions Gaudi gave make it possible to industrialize the building process, thus keeping the original approach within reasonable costs and adapting the materials used to every situation.

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