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Architectural precast concrete shell

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Abstract

This document shows the design and manufacturing process of a modular concrete shell to which digitals and parametric design algorithms were used, combined with digital manufacturing techniques that subsequently were integrated with industrialized prefabrication techniques used in Mexico. A double-curved Shell of reinforced concrete with glass fiber AR was manufactured having plant view rough dimensions of 8.70 m x 7.70 m and a maximum height of 3.25 m in the central point; it was regulated in 9 segments with thickness from 2.5 cm to 6 cm. This element was designed based on parametric algorithms to get the geometric figure and later the digital analysis for its manufacturing and construction was done. To get the construction of the concrete shell the following stages were performed: digital design, modulation proposal, study physical models, molds digital analysis, mold manufacturing, fabrication, maneuvers, exposure of aggregate, segments' setting-up and assembling. This exercise is part of an investigation that assesses the benefits of using digital tools applied to architectural pre-manufacturing processes.

Keywords: double-curved, architectural precast, concrete shell, glass fiber, computational tools, digital manufacturing

1. Introduction

This project arises from the interest of designing and manufacturing double-curved architectural precast elements using a flow of work that combines the use of digital manufacturing techniques with architectural pre-manufacturing techniques and the experience from technicians with knowledge in architectural pre-manufacturing techniques processes (P.C.I. [1]).

Within these principles a proposal is raised to conduct an inverse double-curved concrete shell that were modular and that were manufactured under the principles of both architectural pre-manufacturing and the manufacturing techniques used in Mexico (Arellano et al. [2]).

For the construction of the shell, it was proposed to design a mix of glass fiber reinforced concrete with AR fiber "GFRC" (G.R.C.A. [3]). That allowed the manufacturing of the shell segments without using steel reinforcement, this material allowed us to get an ocher color with average exposition on the upper surface, and minimum thickness in the segments so that the benefits of using the "GFRC" mix were used up (Kosmatka and Wilson [4]). Finally, it was proposed a design into segments that can be assembled during the setting process.

The design, manufacturing and setting stages of the concrete shell will be presented; with this proposal we were able to confirm the benefits of using digital tools combined with pre-manufacturing techniques achieving double-curved surfaces with a certain number of geometrical limitations but it was also proved a flow that would allow to deal with different surfaces and geometries that you can be assembled and manufactured in modular sections.

2. Problem statement and research objectives

The investigation issue was focused on proposing the manufacturing of the shell using pre-manufacturing techniques due to the manufacturing advantages they provide and on integrating the parametric design tools with the digital manufacturing techniques and on being able to conduct designs of concrete mixed applicable to complex geometries. This combination was achieved through the search for solutions that allow the elaboration of double-curvature complex geometries, lessening the execution time, improving its quality and saving on material resources.

The project's objectives for the construction of the concrete shell are: to design and analyze the shell proposal using some digital manufacturing techniques, to propose the modulation of segments to individually manufacture and subsequently assemble them during the setting and installation process of the concrete shell.

In Mexico the concrete shells son structural elements that have an interesting story (del Cueto [5]). Including the double-curvature shell elements (Faber [6]).

3. Digital design and manufacturing analysis

Different digital proposals were carried out to define the shell geometry to be manufactured, having the following options: a 3-support simple shell, a simple shell having more supports and a shell with a central void and inner supports. For this project and experimentation, the shell will be delimited to 3 support design.

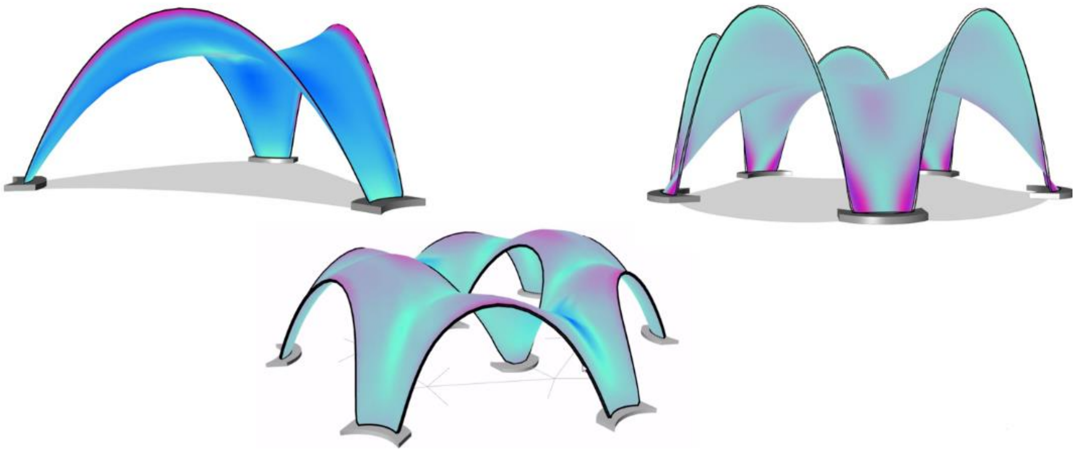

Figure 1: Prototypes concrete shell.

3.1. Digital analysis

At this stage the geometry of the shell prototype was defined, different options were looked over in digital models to obtain different types and forms of shells, picking the option that presents a limited complexity for its construction on a real scale.

The digital analysis of modulation and of possible segments of the shell was conducted as well as some analyses in structural models; afterwards it was proposed the digital proposal for the manufacturing of molds for the casting of the pieces; once these processes were defined, different types of settings among segments were proposal and the site for the prototype setting was selected.

Regarding the digital design, the software Grasshopper was used as well as with interface between Rhinoceros and some plugins.

3.2. Shell generative design

During this stage it was chosen to develop some algorithms that allowed us to obtain different proposals and make us visualize the variants and the possible options. The most representative examples are mentioned as follows:

In this definition the algorithm was programmed to abide by the condition of being able to modify generatively the amount of shell perimeter supports. The applied force values are modified in the free edges. The objective to be able to modify the support from 3 until 2 radial values was accomplished.

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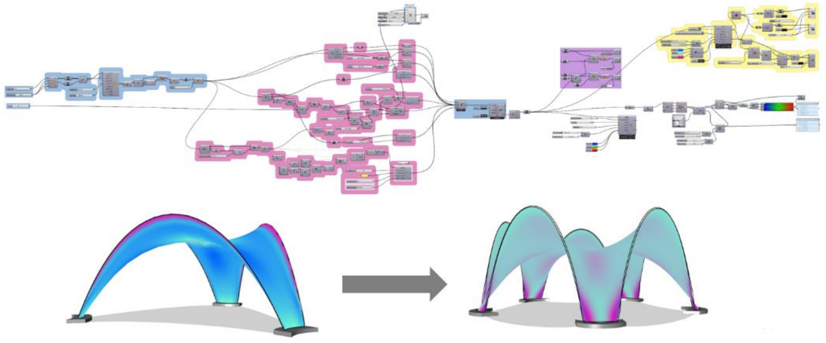


Figure 2: Shell generative algorithm of 3 to 5 supports.

In this definition the algorithm was programmed to test with internal and perimeter supports, with the proposal of including an inner edge in the shell. This algorithm can respond to a non-regular polygon in the plant. This code presented greater difficulty to find the solution to the generative adaptation of the inner supports.

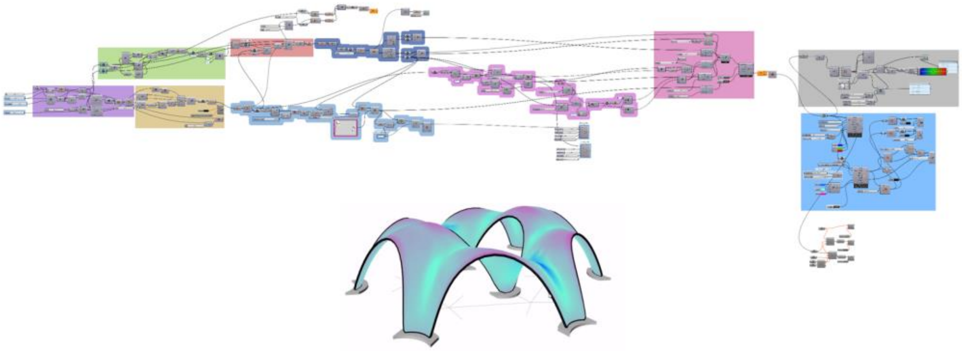


Figure 3: Shell generative algorithm of 5 or more supports.

3.3. Modulation and structural analysis

It was proposed to divide the geometry into 3 sections formed by 3 segments each to have 9 pieces in total and manufacture them in only 3 different molds. Analyses and structural simulations were run to determine options for the thickness of the borders and of the central surface of each segment.

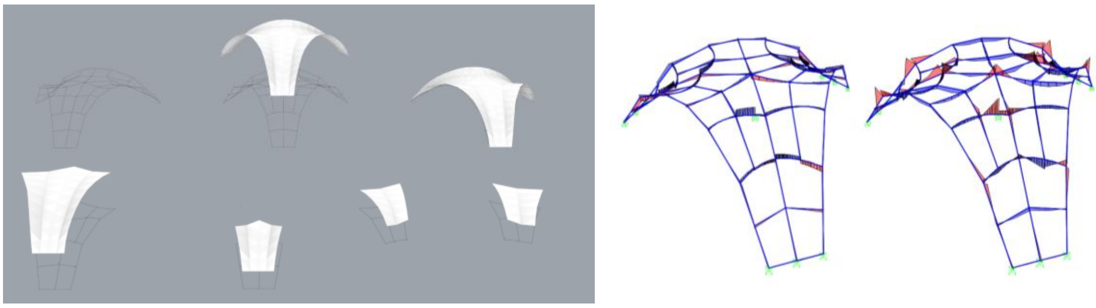


Figure 4: Stage of analysis of modulation of the segments.

3.4. Digital models and physical models for the manufacturing of the molds

To be able to visualize in more detail the geometry of the shell and to propose the manufacturing procedure it was carried out the downscaled 3D impression of the proposal using PLA filament, this physical model also allowed to propose the mold elaboration process for the casting of the shell segments.

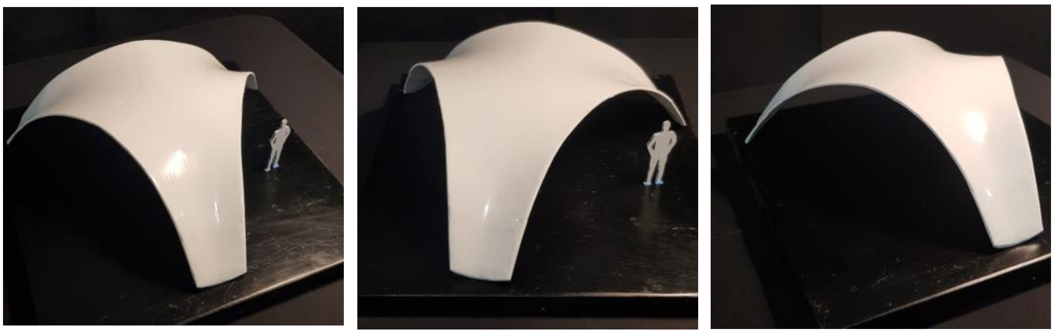


Figure 5: Downscaled physical model of the Shell in 3D printing.

The mold proposal for the casting of the segments was digitally designed and analyzed y it was carried out the laser cut of the sections to assemble downscaled physical models; finally, the mold surfaces to visualize the geometry of each type were detailed.

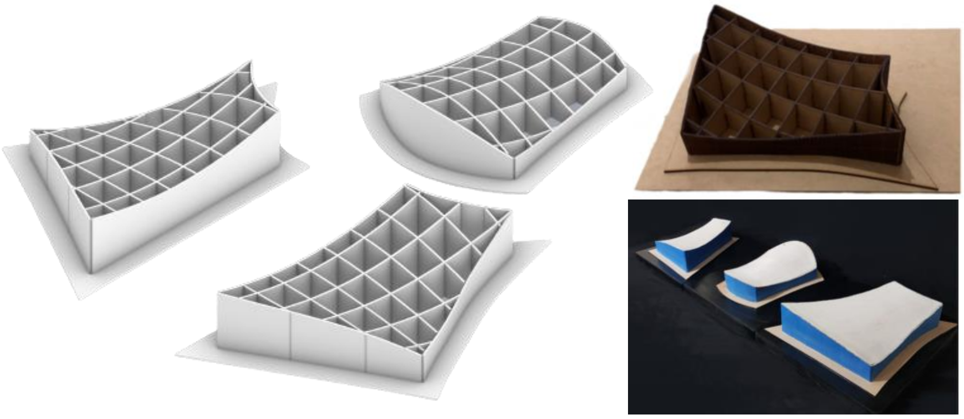


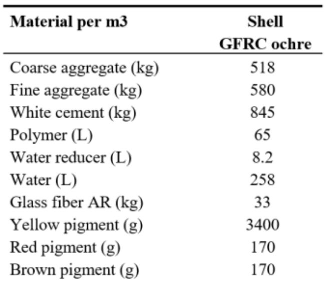
Figure 6: Process of analysis of the molds for casting of the shell segments.

4. Materials and mix design

For the casting of the pavilion segments, it was proposed to use of glass fiber reinforced concrete “GFRC” in color ochre with average aggregate exposure of rough; with approximately 400 kg/cm^2 specified strength was proposed.

But it was also sought that the elements to be manufactured had minimum thicknesses, has high strength, were quite light and had similar characteristics to the architectural premanufactured ones.

The “GFRC” concrete mix design is shown in the next chart:



Material per m3	Shell GFRC ochre
Coarse aggregate (kg)	518
Fine aggregate (kg)	580
White cement (kg)	845
Polymer (L)	65
Water reducer (L)	8.2
Water (L)	258
Glass fiber AR (kg)	33
Yellow pigment (g)	3400
Red pigment (g)	170
Brown pigment (g)	170

Figure 7: Material mix quantities for 1 m^3 of concrete “GFRC”.

5. Manufacturing

At this stage the manufacturing of the real-sized scale shell was conducted starting with the cut and setting up of the shoring of the 3 molds, the preparation of the surfaces, the design of the concrete mix, the casting of the segments, the demolding maneuverings, movements and stowing of the segments to conduct the exposition of the aggregate that allows to get the texture on the surface of the shell..

5.1. Molds

The cut of plywood to obtain the sections of the molds was conducted using CNC equipment, the surfaces and borders and the segments' borders of the shell were prepared and assembled. This shoring was used only to manufacture a shell, but it could be used to manufacture several shells of the same type and geometrical shape. The mold was disassembled and the wood was retrieved to be stored temporarily.

Figure 8: Mold setting up process.

5.2. Casting

The process of the casting of the shell segments was executed, the segments are 6 cm thick on a 20 cm perimeter border and the rest of the surface of each segment counts with a 2.5 cm thickness.

Figure 9: Segment casting process.

5.3. Maneuvers and temporary stowing

At this stage the physical properties of the segments and of the maneuvering accessories were tested; accessories were used to carry out the disassembling, turning and superposing the pieces, transporting them to the work yard to stow them and to subsequently conduct the aggregate exposition process.

On the whole, the pieces stood the maneuvers and the efforts they were subjected to without showing any damage or crack. The laboratory where the shell was manufactured has an old travelling crane with a capacity of 2 thousand kg; hoists with a loading capacity of 1 thousand kg were also used to help the maneuvers and the setting of the pieces in their right position. The weight of the segments goes from 300 kg to 375 kg and the total weight of the assembled shell is approximately 3000 kg.

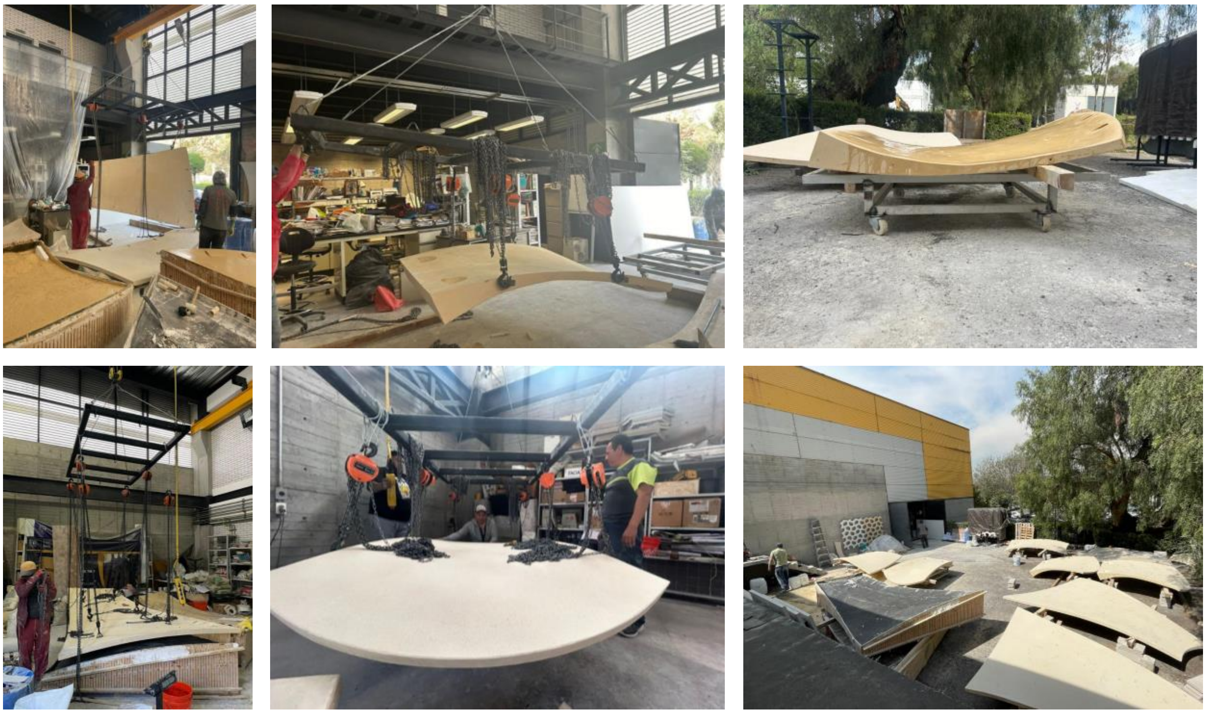


Figure 10: Process of maneuvers of the pre-manufactured segments.

6. Assembly and installation

Finally we reached the challenge to assemble the segments and conduct the setting of the shell; expandable plugs that were secured to the lab foundation floor were used for the connection of the bases; a threaded bolt connection was used for the assembling of the segments, considering that the union of between the pieces' edges, once the segments were placed, would allow to carry the loads among all the segments. Wooden poles were temporarily used to strengthen the segments and also for the personnel security themselves that collaborated in the assembling; subsequently those poles were moved away once all the segments had been places and assembled. For this state the concrete shell was considered as a static element, in another stage the dynamic forces analyses will be carried out.

Figure 11: Connection to the base and assembling among the segments.

Figure 12: Process of assembly and installation.

7. Testing

To obtain data and to validate the glass fiber reinforced concrete “GFRC” used in the manufacturing of the shell, laboratory tests will be carried out and documented and conduct simulations on structural digital models. The tests to be carried out are the following.

- Compression strength test on cylinders of 20 x 10 cm size.
- Flexural strength test on beam of 15 x 15 x 50 cm size.
- Flexural by compression strength test on cylinders of 30 x 15 cm size

The values of the test will be presented at the symposium.

8. Results

It was accomplished to build the proposed shell, besides designing and digitally analyzing the geometry and the mold was proved; subsequently the manufacturing of the elements with the integration of the specialized workforce in pre-manufacturing was carried out; the assembling of the segments and the shell setting were also achieved.

It was possible to prove that the digital design of the molds allows to have accuracy and it also was proven to reduce the setting up times achieving to manufacture complex geometries as the segments of the shell of double curvature.

9. Conclusion

Finally, we must think of how digital tools can help to propose constructive solutions to complex problems, it is also important to analyze how pre-manufacturing can evolve and coexist with the parameters and upsides that the parametric design grants.

Solutions that allow reducing the pre-manufacturing time, improving the quality and saving on material resources must be proposed. Considering sustainability criteria in the processes and in the use of manufacturing materials.

10. Future work

Regarding the concrete shell, simulations and structural models will be carried out to propose their installation in a public space; both the foundation and an installation and assembly in site system must be designed and calculated. Absorption and acoustic transmission simulations will be carried out to analyze the properties that such material provides as the shell geometric form.

It will be sought to develop more spatial structures proposals with precast concrete components, integrating the digital tools and digital manufacturing techniques with the production processes of architectural precast concrete component applied in spatial structures.

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