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Design-to-production of a precast post-tensioned concrete shell structure using the CASTonCAST system

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Abstract

The CASTonCAST system is a research project that aims at developing technology to facilitate fabrication and construction of precast concrete shell structures. During the last decade, the project has progressed through a series of prototypes towards the complexity of full-scale shell structures. In this paper, the latest prototype consisting of a precast post-tensioned concrete shell with a footprint of 7.5x4 meters is presented. Given its more intricate form, structural behavior and larger scale compared to previous prototypes, this research expands the CASTonCAST system across all design-to-production phases. This paper describes a complex design process integrating geometric, fabrication and structural constraints based on the CASTonCAST geometric method, Graphic Statics and Discrete Element Modelling as well as the improvements in fabrication and assembly.

Keywords: concrete shells, prefabrication, post-tensioning, prototype

1. Introduction

Shell structures base their resistance on their double-curved form, which allows them to be very efficient in terms of material consumption. However, the realization of their double-curved shapes poses an important challenge. While in-situ concrete construction has historically been predominant in the building of concrete shells, the advantages of prefabrication such as short construction time, reduced labor costs, reduced costs of formwork, and enhanced quality control are increasingly recognized [1]. Early precast concrete shells were limited to regular geometric configurations like spheres and cylinders. Recent advancements in construction technology have broadened the fabrication possibilities. Projects such as Striatus [2][3] and the Phoenix, utilizing 3D-printed concrete components, exemplify this progress. Another approach is the CASTonCAST system, aimed at achieving similar advancements in constructing freeform shells.

The CASTonCAST system constructs shells using stackable panels, offering fabrication simplicity by allowing direct casting atop one another, reducing intricate formwork needs. It enhances storage and transportation efficiency by conveniently stacking panels. Research development followed a series of prototypes: proof of concept plaster models (2010-11), a small-scale post-tensioned concrete shell (2014-15), a 5.5-meter post-tensioned arch-cable structure (2017-18), and finally, a full 7.5-meter span shell inspired by Heinz Isler's tennis hall shells at ETH Zurich (2020-2023). The shell measures 7.5x4 meters, weighs 2500 kg, comprises 64 unreinforced concrete components, and is supported at four corners. Primarily working in compression, it's post-tensioned to act as a monolithic structure and deal with local internal tension forces.

Figure 1: Shell (above) and stacks (below) [©Lluís Enrique]

2. Design process

In the conventional approach to shell design, the shape of the shell is determined through a form-finding process and subsequently evaluated and refined for fabrication considerations. The CASTonCAST method reverses this logic, first integrating fabrication constraints into the form and after approximating a structural form. Since manufacturability is prioritized over structural efficiency, the final shape may deviate slightly from a purely compression-only form as a trade-off for easier fabrication.

For this prototype, the design of the shell draws inspiration from Heinz Isler's tennis hall modular shells. While it doesn't precisely replicate the same shape and proportions, it adheres to its same concept: a shell with a rectangular footprint supported at its four corners featuring the Isler's elegant lifted edge along its main span. To achieve the structural form, the design process intertwined the generation of geometry with the study of the structural behavior.

The design process started by tessellating a single-curved surface ideal for a barrel vault under uniformly distributed loads, continuously supported on two sides. This simple starting point had the goal of defining the main parameters of the shell's form (length, width, height, and thickness range) and tessellation (number of stacks and number of panels per stack). A structural analysis using graphic statics along its main span shows that the shape of a thin barrel vault is adequate to support its self-weight (Figure 3). However, its lack of double curvature does not allow it to withstand additional external loads, such as point loads.

The next step involved adding curvature along its transversal section to achieve the double-curved shape, reminiscent of Isler's tennis hall shell (Figure 4). This resulted in thick panels along the longer outer edges, where the shell had a more pronounced changing curvature. In terms of structural performance, the undulation along the transversal section helps to increase the static rise in the center of the shell just like in two-hinged arches. This elegant trick used by Isler, which can also be observed in the works of Eladio Dieste, allows the shell to be stable against both its self-weight and point loads.

Finally, two large openings were made along the short edges of the shell, defining the four corner supports and activating the shell action. To achieve the floating effect of Isler's shells and reduce unnecessary weight, the panels along the two main outer arches were made thinner by utilizing only a portion of the panel. Additionally, the outer longer edges were designed to gently curve outward, enhancing its expressiveness. To study the structural behavior, force flow was examined vertically and horizontally. Given the predominant structural action along the longitudinal direction, analyzing forces in the vertical section using graphic statics adequately reveals the shell's overall behavior. By selecting a rise of the arch that closely follows the section of material, we can approximate the arch's thrust longitudinally. Examining the floor plan, we concluded that the shell functions as two tilted arches supporting each other.

Furthermore, we identified two additional aspects: Firstly, the chosen tessellation pattern, selected for fabrication and transportation reasons, did not align perpendicularly with the expected flow of internal forces within the shell, resulting in shear forces at the panel interfaces. Secondly, the outward curvature of the shell's longer edges induced tension forces within the structure. To address these challenges, a grid of post-tensioning cables and male-female pin joints were integrated in the design.

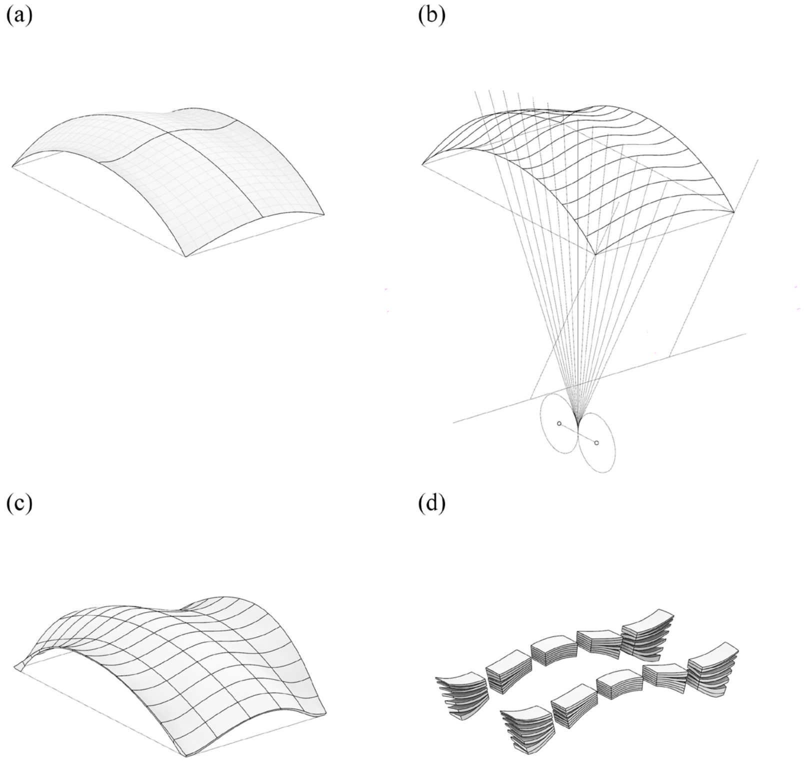

Figure 2: Design process: input surface (a), tessellation (b), shell (c) and stacks (d) [©Lluís Enrique]

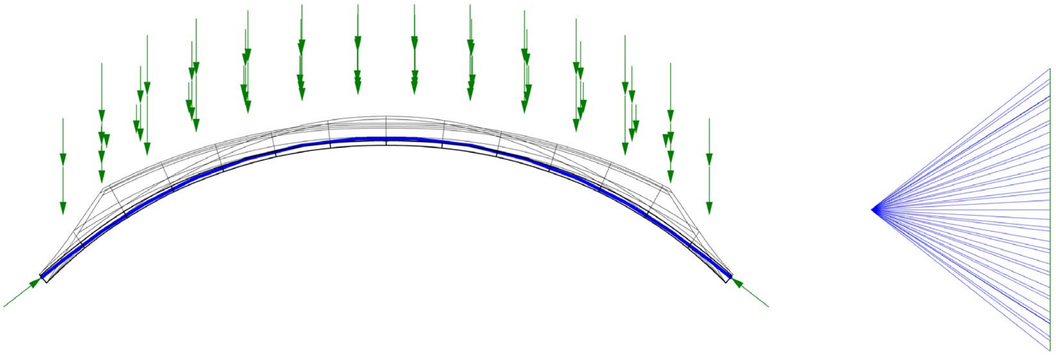

Figure 3: Graphic statics analysis [©Lluís Enrique]

To better quantify the three-dimensional structural behaviour of the shell, a Discrete Element Modelling (DEM) analysis with rigid blocks was carried out through compas_3dec [3], which uses the commercial DEM software 3DEC by Itasca as a solver in the background. The DEM analysis considered the discretised geometry used for the fabrication of the tiles and their material properties, such as the density and the Young's and Shear moduli. Since the post-tensioning and the male-female connections were not modelled in DEM, their effect was conservatively approximated by only increasing the friction angle (90˚) at the contacts between tiles, which were modelled adopting the Mohr-Coulomb failure criterion, setting cohesion and dilatancy angle equal to zero. On the other hand, it is worth mentioning that the modelled interfaces with perfect face-to-face contact conditions were not able to catch the effects on the structural behaviour due to tolerances in the fabrication of the tiles observed on the prototype. These imperfections were measured and will be the object of further investigations following a procedure adopted by one of the authors to simulate and understand their impact on the structural behaviour [6]. Various boundary conditions were simulated in the DEM analysis: global stability under self-weight, differential settlements, and pointed and distributed loads. By showing how the three-dimensional force distributions change according to the boundary conditions, these analyses enabled us to gain valuable insights into the structural behaviour of the shell, as shown in Figure 4.

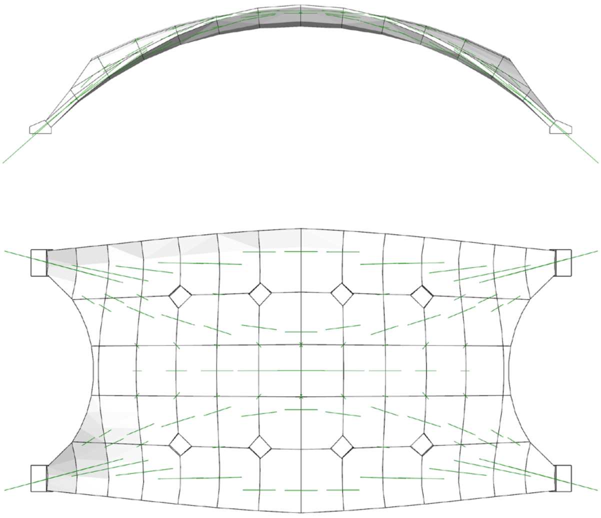

Figure 4: Discrete Element Modelling analysis [©Alessandro Dell'Endice]

3. Fabrication

The fabrication of the panels for the shell closely follows the steps outlined in the previous prototype described in [7]. However, the following adaptations were made:

- Thinning the panels along the outer arches by adding concrete filler during casting.
- Adding vertical separation elements for panels with openings or curved edges.
- Embedding polystyrene foam blocks to create the void for the prestressing heads.

Regarding the concrete mixture used, this closely resembled that of the previous prototype. This time, however, sustainable cement was used (Holcim Susteno) to minimize the environmental impact.

4. Assembly

The panels were assembled using a steel scaffolding with a simple timber formwork to approximate the shell's curvature. The scaffolding provided support for the panels while positioning them accurately. Unlike the previous prototype, assembly started from the center and progressed to the corners to accommodate larger tolerances.

Construction steps were as follows:

1. Erecting the central arch and post-tensioning it.
2. Fixing the corners to secure support positions precisely.
3. Adding longitudinal arches adjacent to the central one.
4. Constructing outer arches, followed by the insertion and activation of transversal post-tensioning cables for stiffness.
5. Tension ties connecting supports were stressed, bringing them closer together and slightly lifting the shell for decentering.

Panels featured male-female connections for easy assembly. These were designed according to the assembly sequence.

Figure 5: fabrication (left) and assembly (right) [©Lluís Enrique]

5. Conclusions

The paper presents a prototype of a shell structure resulting from a design process integrating geometric, fabrication and structural constraints. These are the main conclusions of the work:

- The shell structure stood outdoors for slightly over two months without visible problems.
- While the shell's tessellation is not ideal for the distribution of forces, the impact of shear was successfully mitigated using male-female pin-joint connections and post-tensioning.
- Combining 2D graphic statics analysis with 3DEC proved effective in shell design.
- Edges and corners require better design, as they proved to be weak points during assembly and disassembly.
- Imperfections due to fabrication and assembly resulted in a network of hinges in the shell.
- Precise panel fitting underscores the need for larger tolerances in the design.
- Although a scaffolding with a decentering mechanism was designed, in reality, the decentering process could be successfully achieved by slightly bringing the supports closer together by pre-stressing the tension ties between them.

Finally, this project once again demonstrated the value of the CASTonCAST fabrication method in combination with post-tensioning for the construction of doubly-curved thin concrete shells, allowing for material saving and structural efficiency.

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