THE CORKCRETE ARCH PROJECT

The digital design and robotic fabrication of a novel building system made out of cork and glass-fibre reinforced concrete

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Abstract. The CorkCrete arch is a 1:1 scale construction aiming at testing the use of robotic fabrication technologies in the production of a novel building system made out of two different materials – cork and concrete (GRC). The combination of these materials is promising since it merges the sustainable and performative properties of first with the structural efficiency of the second one. The result is a material system suited for customized prefabrication and easy on-site installation. The current paper describes the design and fabrication process of the arch, which employed a single parametric design environment to bridge design and fabrication, and an innovative sequence of different robotic processes. The success of this experience invites the team to continue this research into the future construction of larger scale applications.

Keywords. Cork; concrete; computational design; digital fabrication; robotics.

1. Introduction

The research on robotic fabrication technologies has been a recent but vibrant field in architecture. The automation possibilities, flexibility of movements and diversity of fabrication operations of industrial robots have attracted those interested in exploring innovative strategies in building construction. Introduced in architecture by Gramazio and Kohler in 2005 at the ETHZ, the research on robotics has been widely focused in the production of prototypes and installations, usually made out of a single material. However, some architects have started to tackle the scale and complexity of
architectural buildings with such means. The brick parts of the Gantenbein Winery facade designed by Gramazio and Kohler in Flasch (Gramazio and Kohler, 2015), or the Landesgartenschau Exhibition Hall designed by Achim Menges (ICD) and the ITKE at the University of Stuttgart (Schwinn and Menges, 2015) are some examples of such efforts.

In this context, the Digital Fabrication Laboratory (DFL), a research group of the Faculty of Architecture at the University of Porto (FAUP), developed a 2-year funded research project dedicated to investigate how robotic technologies can assist non-standard modes of design and construction in architecture. After the production of several material experiments, this research was concluded with the CorkCrete arch project, to test the use of robotics to embrace the scale and complexity of construction in architecture.

2. The design of the CorkCrete arch

The CorkCrete arch is a 1:1 scale construction aiming at testing the use of robotic fabrication technologies in the production of a novel building system made out of two different, but complementary, construction materials: expanded cork agglomerate (i.e., internationally known as ICB – Insulation Cork Board, but simply referred in this paper as cork), and glass-fiber reinforced concrete (GRC). On the one hand, cork is a 100% natural, recyclable and lightweight material, which can perform many functions at the same time, like thermal, acoustic and vibration insulation (Pereira, 2009; Sousa, 2010). Taking advantage of such performative qualities, an increasing number of architects have used it as an exterior facade material since Álvaro Siza did it on his Portuguese Pavilion in the EXPO 2010. On the other hand, GRC is a composite material where the glass fibers are introduced in the cement matrix to increase the resistance to tensile forces, which is one of the main limitations of concrete (Brookes and Meijs, 2008; Peck, 2006). With this composition it is possible to achieve large-size building components, which are much lighter than traditional concrete ones. For this reason, the application of GRC in architecture is vast and is a growing tendency. Although there are some applications of using cork granules as aggregate in concrete mixtures, the proposed combination of cork and GRC constitute a novel building solution. They define a material system with structural and performative properties, which is suited for customized prefabrication and easy on-site installation in architecture. Envisioning the future construction of larger structures, this work chose to design and materialize an arch to add structural concerns to the formal and material challenges of the design project. To set an original and natural look and a bright interior condition in the
arch, it was decided to employ cork on its outer surface and GRC in the inner one.

2.1. PRODUCTION METHODOLOGY

Robotic fabrication experiments usually explore the use of a single material. By employing wood and concrete, the Utzon/40 research pavilion by Supermaineouvre is one of the still very few examples attempting to robotically fabricate more than one type of material for an architectural construction (Pederson et.al., 2014). The CorkCrete arch project is inscribed in this last tendency. It addresses the critical challenges related with matching the physical tolerances resulting from using different fabrication processes (i.e., robotic and manual) and materials (i.e. cork and concrete). To do so, the geometry of the arch and its material deployment was thought from the beginning in an algorithmic fashion; this rule-based design condition allowed the full development of the project in a parametric design environment. It thus became possible the introduction of adjustments along the process without compromising the digital flow of information between the design and fabrication specifications.

2.2. THE DESIGN DEFINITION

The algorithmic foundation of the CorkCrete arch design prompted the use of Grasshopper to generate all the geometric data. A specific mathematical curve - the catenary - was the generator of the whole form. Inspired by some architects from the past (e.g., C. Wren, A. Gaudi or E. Saarinen), this option helped in assuring a certain degree of structural integrity of the design exploration. To confirm such intuition, a solid version of a normal extruded catenary was evaluated in Finite Element Analysis (FEM) software. The tradeoff between design and analysis helped in refining the curvature of the arch. The catenary curve was described in the programming environment as a polyline (i.e. also called a polygonal chain) and then transformed into a quadratic NURBS approximated curve. This element became the thrust curve (Moseley, 1833) and, together with two offset offspring curves defined the general projection of the inner and outer surface of the vaulted arch. This top-down approach turned Rhinoceros into a simple medium for visualization, therefore, no explicit modeling was employed at any moment of the project.

For both aesthetic and fabrication wise reasons, it was decided to use a polyline instead of a more obvious curve to negotiate the encounter between the cork and the GRC panels. Drawn around the thrust curve, each polyline segment had to correspond to the length of a cork panel, to avoid milling their bottom side too. The split of the GRC panels was also aligned with
some of the polyline’s vertices. Concerning the sides of the arches, they were slightly tilted towards the interior to increase the structural stability of the arch.

The outer (cork) and inner (GRC) surfaces of the arch were conveniently defined to challenge the subsequent use of robotic fabrication processes. Given that cork was going to be milled, a great level of geometric freedom could be explored with this material. A network surface using three curved profiles and the two edges created a double curved surface, which would serve then as the base for engraving an undulating texture effect. The combination of these two features set a major challenge to test robotic milling. The bottom surface of the GRC panels took into consideration the further exploration of hotwire cutting process to produce their moulds. Thus, two straight lines in the bottom of the arch were connected to a “v” curve in the top to define a curved ruled-surface geometry with a very subtle spine-like effect. Despite all this customized and variable features of its geometry, the arch features a double bilateral symmetry to assume a provoking classic presence. The whole material geometry and structure of the arch is described on Figure 1.

Figure 1. The geometric generation of the CorkCrete arch, and the materials’ structure composed by 18 cork panels and 3 GRC panels.

3. The fabrication of the CorkCrete arch

The production of the CorkCrete arch was organized in two parts:

- the GRC panels - through robotically fabricated EPS molds and subsequent manual GRC spraying;
- the cork panels - entirely robotically fabricated.

All robotic processes were conducted at the DFL’s lab using a Kuka KR120 R2700 HA industrial robot. In all situations, the exploration of a continuous parametric design process allowed to automatically generate all the necessary data for the various operations. Figure 2 describes the digital flow
from the programming of the arch geometry and material definitions to the fabrication of its various components. The manual spraying of the GRC took place in the precast concrete factory of the industrial partner Mota Engil.

Figure 2. The single parametric workflow that integrated the design and fabrication process.

3.1. THE GRC PANELS

Taking advantage of the GRC properties, the concrete panels of the Cork-Crete arch were designed as thin elements with 15mm thickness with lateral folds in all with a minimum of 40mm height to assure its structural integrity. The geometry of such elements dictated the need of custom molds, which were fabricated using high-density EPS blocks (Figure 3).

Figure 3. The fabrication of the EPS molds for the GRC panels.

Although it would have been possible to mill the EPS molds, a previous experiment revealed that this process was inefficient regarding fabrication time surface quality and material waste generation. As shown in previous works by Feringa and Søndergaard (2014), robotic hot wire cutting (RHWC) of EPS molds is the ideal fabrication technology to address the situations dealing with ruled geometries, which was the case in the CorkCrete arch. Thus, the robotic production of each EPS mold was organized as a sequence of 3 hotwire cutting and 1 contour milling operations in order to produce the surface curvature and the boundary contour for the GRC panels. Due to the size limitations of the hotwire tool but also the nature of the ruled geometry
(i.e., concave in the top component), the molds had to be split in two symmetrical longitudinal halves. In total, the 3 GRC panels implied the robotic production of 6 EPS (half) mold parts. It should be noticed that the curved geometry of the top part of the arch required the organization of the raw EPS blocks in a “L” shape. Excluding tool changing and setup time, the fabrication sequence for each half took an average of 10 minutes to be completed. The resulting pieces were then glued together to define the final 3 molds, which were then shipped to the precast concrete facility of Mota Engil.

At the factory, the molds were initially treated with a demolding oil, while a set of metal connection rings were inserted into the EPS to become embedded in the final GRC panels. The GRC was then carefully sprayed and manually compacted against the mold, assuring a thickness of 15mm. In the end of this process, a positive EPS piece resulting from the mold carving was placed inside the cavity to provide support for fixing the cork panels (Figure 4). In this way, the building system absorbed the wasted material produced during the robotic fabrication process. After a 24 hour curing time, the panels were demolded and manually sanded to smooth some surface texture resulted from the EPS porosity.

3.2. THE CORK PANELS

As mentioned before, the design of the CorkCrete arch just considered the milling of one side of the cork panels. This greatly simplified the milling process while introduced an interesting design feature in the structure – the polyline joint separating the cork panels from the GRC ones. The stock material used for the cork panels was composed of expanded cork agglomerate blocks with 1000x500mm supplied by industrial partner Amorim Isolamentos. Their thickness ranged from 8cm to 14cm, in order to minimize waste material.

The fabrication routine for each of the 18 cork panels was structured in a sequence of 3 milling operations: (i) milling of the curved surface of the panel; (ii) engraving the texture, and (iii) cutting the contour of the panel (Figure 5). Both the first and third operations used a 150mm long flat end
tool with a 20mm diameter. The second operation used a wide tool with an end shaped as a paraboloid of revolution. By following a few undulating tool paths, this tool carved an impressive texture in the panels. To optimize fabrication time, the panels were produced in batches of 4.

Figure 5. The robotic fabrication of the cork panels.

4. The installation of the CorkCrete arch

To detect possible errors, check the best way to erect it, and survey its structural stability, the CorkCrete arch was pre-installed in the lab. This experience tested the bolt and notch connection system and allowed to detect some minor alignment deviations between three panels, which were easily corrected by hand.

The next day, the CorkCrete arch was assembled in the old garden of the FAUP, in order to record some video scenes to complete a short movie documenting the whole production process of this project. Being the second time, its assembly was faster. It took around 40 minutes with 5 people working without the need for any mechanical means. The compressive behavior of the structure allowed the arch to simply rest over the floor and, after 3 hours, it was disassembled.

Three days later, the arch was assembled for a third time (Figures 6). This time it happened in a garden platform of the school to be officially presented to the public, as part of the final presentation event of the broader research project to which it belonged. Given that the earth was very soft and not leveled, a couple of small rods on each leg were inserted in the ground to provide some extra stability. The arch has stayed in place for 5 consecutive days and was experienced by students, faculty and other visitors (Figure 7).
5. Conclusion

This paper presented an original building system made out of cork and GRC components fabricated through robotic processes. To test this system, the
DFL team designed and materialized the project of an arch, which addressed a wide set of design, material and technological challenges in architecture and building construction.

Regarding the design, the catenary based geometry of the arch proved to be structural efficient in reality. Despite the solid condition of the built form, its assembly could be done manually and for three almost consecutive times, due to the lightness of the combined cork and GRC material system. This is an important feature because is aligned with current trends in the building industry towards lighter and more sustainable modes of construction. At the same time, the combination of both materials defined a singular aesthetic and perceptive effect. The external dark, textured and soft look of the cork covering, contrasted with the bright, smooth and rigid appearance of the interior GRC panels. These qualities triggered the curiosity of the people who felt compelled to visit and touch it. (Figure 8) Nonetheless, the thermal and acoustic insulation properties brought into the system by the use of cork could not yet be observed in this construction. A more enclosed space would be required to begin to understand them.

![Figure 8. Material details and effects of the CorkCrete arch](image)

From the technologically point of view, the use of robotic fabrication was confirmed as a precise and flexible process to fabricate building components. Besides the success achieved in matching different materials obtained by different fabrication processes, the use of robotic technologies opened some real innovative opportunities for the GRC and cork industries. The use of hot-wire cutting assured a fast and reliable way to obtain EPS molds for the production of single curved GRC panels. Regarding the cork panels, their intricate and variable geometry and texture simply could not be done by any other method. The 6-axis movements of the robot were decisive for this application.
After the construction of this arch, the DFL is now pursuing the construction of a larger structure – a pavilion - where other aspects of the CorkCrete building system (e.g., thermal and acoustic insulation and lateral assembly) could be further tested.

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