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3D Printed Ceramic Vault Shading Systems

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Abstract

The emergence and dissemination of additive manufacturing technologies, namely three-dimensional printing, contributes to a paradigm shift in the process of project design and construction by allowing these two traditionally autonomous phases to approach. The use of digital manufacturing technologies has considerably expanded the formal, performative, and functional limits that ceramic elements can bring to the context of construction and architecture.

This paper presents the main challenges and outcomes achieved during the process of design and production of a vault cover system. Based on the discretization of a vault in hexagonal blocks, this system intends to control solar incidence by its adaptive inner structure. It focuses on objective questions like material composition, ceramic material retraction and the influence that geometry variations have on those themes. These questions try to evaluate the real applicability of digital additive manufacturing techniques, specifically ceramic 3D printing on architecture and design production processes.

Keywords: Ceramic 3D printing, Additive manufacturing, Vaulting systems, Shading systems, Parametric design, Performative design.

1. Introduction

As Kolarevic [1] refers, the information age, like the industrial age have done in the past, is changing not only the way we design buildings but also how we fabricate and how we construct them. Until the beginning of the new millennium, digital design tools didn't reflect their real capabilities as instrument to assist the definition of the project. According to Mario Carpo [2] CAD tools were gradually integrated in architectural practice, not as a diachronic practice tool, but as another medium to represent same architectures. They were regular and continually used to design perfectly vulgar buildings, where the use of these technologies has no apparent trace. In the opposite way, on automotive, aeronautic and shipbuilding industries, digital design and fabrication tools are already widely used, creating optimized products. Today most part of changes in architecture related to this field result from the adoption of CAD/CAM processes used in those industries. The integration of computational models and digital fabrication techniques in architecture results in the possibility of serial production of entirely customized systems. Thanks to those technologies, namely parametric design and additive manufacturing (AM), during the design process, are created systems that formulate various solutions, helping to select the one that best meets the needs of the problem and, after that, to produce unique and adapted components in the same amount of time that traditional production methods spent to make standard components.

The project that we will present next benefits from those two factors in order to respond to specific contexts and multidisciplinary targets. The project is very simple and objective, a direct response to a specific problem, the lack of shading elements in the Advanced Ceramics R&D Laboratory glazed windows (Figure 1– left drawing). The intent was to block certain areas that represent the most problematic solar incidence direction (Figure 1 – middle drawing).

Having the background of previous researches developed at Advanced Ceramics R&D Laboratory, such as the design and production of Wave Wall [3], a free-form ceramic wall system or projects like the Armadillo Vault from the Block Research Group of ETH Zurich [4], Solar Bytes Pavilion [5] and the façade of Al Bahar Towers [6], we proposed a vaulted roof to cover the patio that maintains total permeability at both ends and varying the aperture degree of the surface, depending on the needs (Figure 1 – right drawing). Based on hexagonal blocks, the optimization takes place through the geometric variation of the internal structure of the blocks. The design process is mediated by a parametric model, taking into account the sun incidence data, resulting in a system that adapts the internal geometry of each one of the blocks by their relative position in the set, making them more or less permeable depending of the space/time ratio that we want to shade.

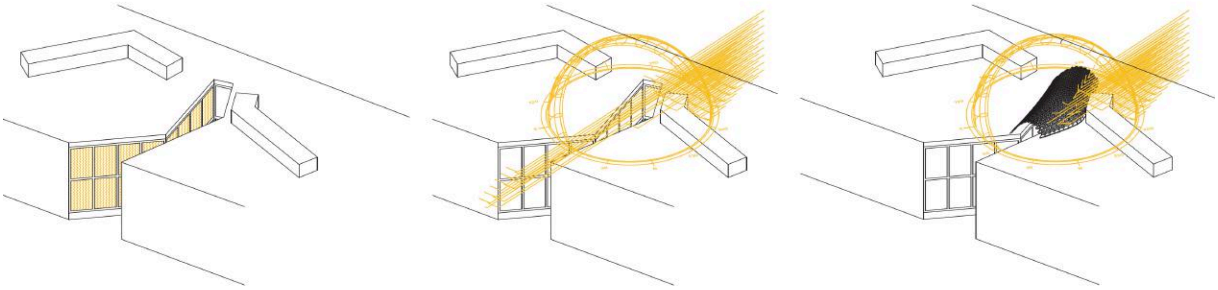


Figure 1. Design Institute of Guimarães. Glazed surface without protection on the left, solar analysis on the middle and solar analysis with the shading system on the right.

This paper focusses mainly on material questions that we been through during the development and production of two test arches. As it was referred previously material composition, material retraction and geometry are the main issues that we face and those that have been shown as the most important in the development of 3D printed ceramic components.

To the production of the ceramic components it was used the Lutum® 3D clay printer, a CNC machine with three movement axes and a paste extruder with a pressurized clay dispenser [7].

2. Design Process

Figure 2. Design sequence of the base surface.

Using Rhinoceros® (three-dimensional modelling program) and Grasshopper® (graphic algorithmic editor) a vaulted surface is created (Figure 2 – left drawing), with the strict function of shading the glazed surface previously mentioned. The geometry of the curved surface that serves as the base of the whole structure has its origin in the analysis of the problem, placing perpendicularly to the direction that is sought to shade, allowing the permeability of the whole set in the other directions.

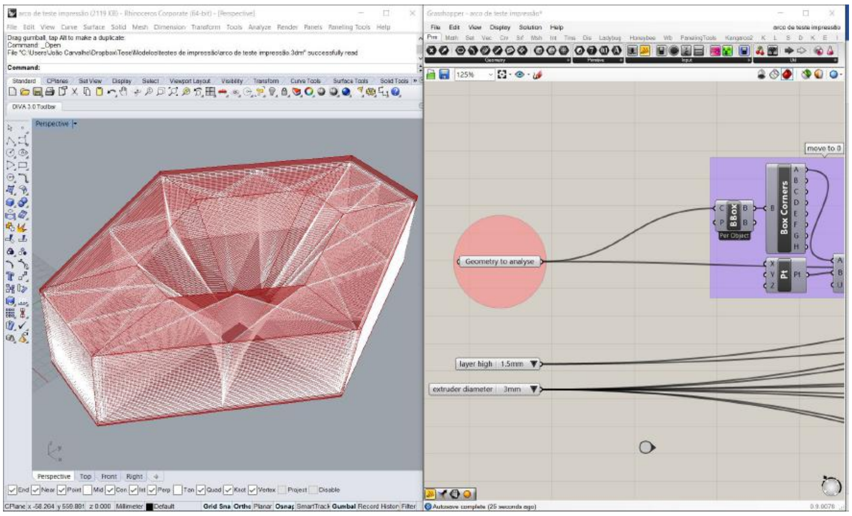
Based on an irregular hexagonal mesh (Figure 2 – middle drawing), the pattern that covers the original surface and divides the structure into blocks, born from the analogy created between the support (patio geometry) and the part (block geometry). This hexagonal mesh is then scaled to the inside, forming apertures, element by element, varying its value according to the position of the part in the set. Starting from the analysis of the solar incidence data (city of Guimarães), is defined a point in space that marks the most problematic direction, the direction to shade. This point makes vary the degree of aperture (permeability) of each of component relative to their actual position in the set (Figure 2 – right drawing).

The design of the internal structure of each block is originated in the two hexagonal shapes described above, in the outline of the block and in the variable aperture extracted from it. The three-dimensional model represented at Figure 3 (left side), illustrates the internal structure design process. By crossing the initial, middle and final points, an internal cross-structure is designed which, in addition to shaping the variable opening of the component, also gives it structural integrity and, subsequently, integrity to the entire structure.

3. Informing the machine

In order to fabricate ceramic blocks by AM it is necessary to create a numerical control code (G-Code) for each one of the elements to be produced. This code contains all the instructions the machine needs to know to produce a particular object. The code provides accurate instructions defining the movement and velocity of the print head and the spindle rotation frequency in order to extrude the exact amount of material for specific nozzle diameter (wall thickness) and layer high.

Due to the lack of a specific software for this printer, and the limited control offered by the generic CAD/CAM software for AM, the solution was to develop our own software. Since some of the information needed for printing was already present on the digital models (Rhinoceros® and Grasshopper®), the aim was to develop a code in Grasshopper® with the ability to transform the block's initial volume into printable geometries (printing paths) that could be translated into G-code (Figure 3). Using a code developed by Ryan Hoover (Xilynus), a new code was created. This new code converts the generated paths into X, Y and Z coordinates, transforming them into textual information, according to the definition of the characteristics of the manufacturing technology to be used [8].



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Drag gumball, tap Alt to make a duplicate
Command: _Open
File "C:\Users\João Carvalho\Dropbox\Tese\Modelos\testes de impressão\arco de teste impressão.3dm" successfully read
Command:
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layer high 1.5mm

extruder diameter 3mm

Autosave complete (25 seconds ago)

Figure 3. Grasshopper® interface. In red the reference volume to determine the printing paths.

The G-Code generator system works from the three-dimensional digital model of each one of the components. Each component is inserted as an object to be analysed and from there the Grasshopper® code divides the surface into layers of predefined intervals, resulting in the definition of straight segments, which are then translated into coordinates that inform the path to be travelled in each one of the segments. The code also provides accurate information about the amount of material that needs to be extruded at various times of the printing process.

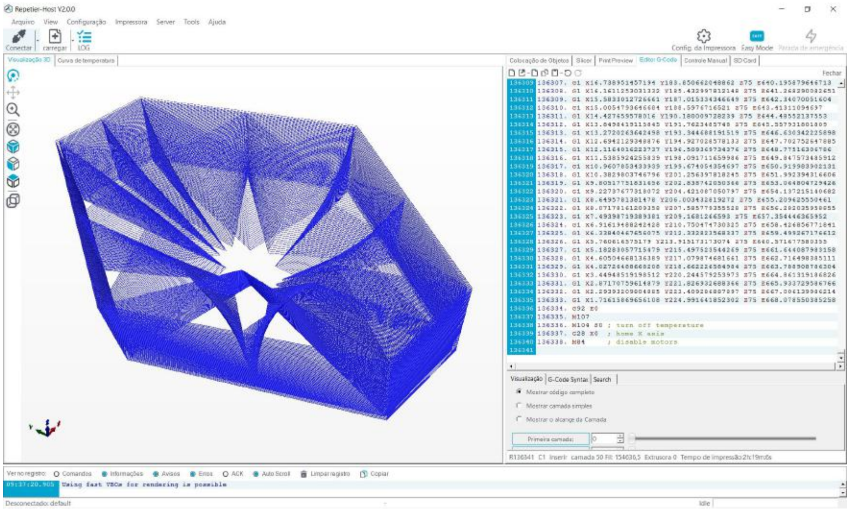

Figure 4. Repetier Host interface. Analyse of G-Code created in Grasshopper®.

4. Ceramic material and production process

Hardness, density, durability, ability to have a wide range of appearances and finish, among other properties have facilitated the application of ceramic in buildings all over the world for centuries [8]. The material used by the printer for the production of prototypes is a ceramic paste, a mixture of sandstone and water. Depending on the amount of water present in the mixture we obtain different types of paste that serve different purposes. For the tests that served as a basis for the development of prototypes, the results of previous works were considered, namely in the selection of the type of ceramic paste of the quantity of water to be used in the mixture [7].

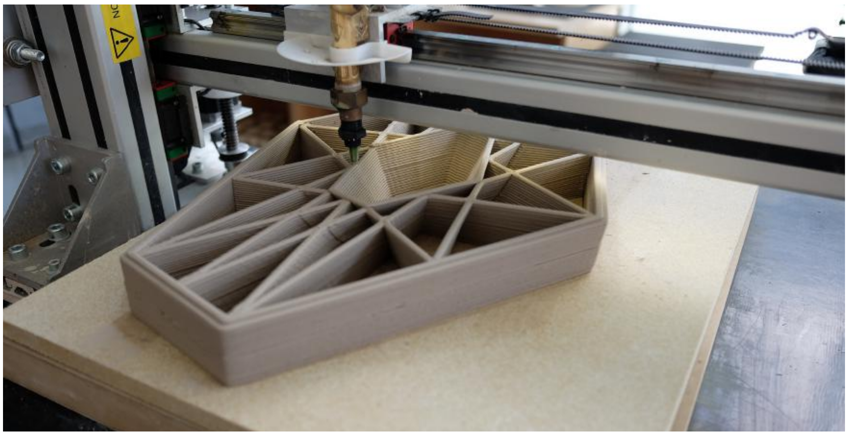

Figure 5. Ceramic 3D printing process (Lutum® Mini).

For the extrusion to be done satisfactorily it is necessary to coordinate three parameters: the air pressure applied to the cartridge, the speed of rotation of the spindle and the viscosity of the paste. In addition to this coordination between material input and output, the composition of the paste must be taken into account, which varies its viscosity and the way the different layers behave each other. Therefore, the more viscous and wet the blend the better the bonding and the lower the risk of breakage between layers, however, the use of a paste having a high-water content may compromise the integrity of the model during and after printing, since the blend may not guarantee the consistency required to perform certain geometries.

During the printing phase, the first printed layer, the one that is in direct contact with the support and serves as the basis for the entire model, is perhaps the most important layer. It is the one that guides the layers that succeed it and, being one of the contour lines of the object, is of particular importance for the determination of the correspondence between the digital model (print paths) and the physical model.

Once the body of clay formed in an element, it dries to the "green state" either naturally or through machine-controlled drying processes. During drying and subsequent cooking, shrinkage occurs when moisture is removed. From the perspective of the drawing, it is important to understand the relationship between clay paste and shrinkage [9].

5. Prototypes

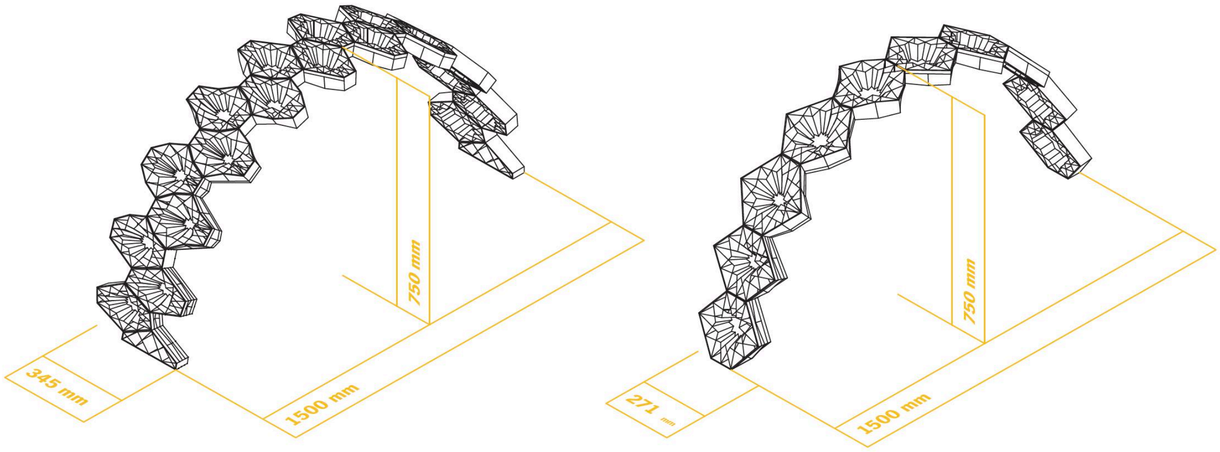

Figure 6. Test arches (Arch 1, with diagonal connections on the left and the Arch 2, with horizontal connections on the right).

Given the complexity, size and number of components of the overall structure of the vault, two test arches with 1/2 scale of the model were developed, which simulate the dynamic behaviour of the structure, besides allowing to study several systems of connection (male-female and mechanical) and aggregation of components (diagonally and horizontally).

Based on a semicircle with 1.5 meters of diameter, the arch is used as a contour for the generating surface of the blocks. While Arch 1 follows the logic applied in the general model, with more elongated parts and diagonal connections, Arch 2 has a regular hexagonal geometry and horizontal connections between them. Both arches test six types of connections where there’s a variation of the surface geometries that make the contact between the pieces, providing in some cases the inclusion of external elements in other materials, like polymers or metals (Figure 7).

Figure 7. Inclusion of connection elements in other materials (PLA).

Before proceeding to the development of test arches, some pieces of the Arch 1 at real scale were printed to test and understand the best printer and material configurations to execute the final components. In these tests, where the variables related to printing (pressure, plasticity, velocity) had particular preponderance, design issues and changes to the numerical control code that inform the equipment (test of different paths for printing) were also studied.

During the initial printing tests (Figure 8), various combinations were performed by varying the extrusion nozzles (3mm, 6mm and 8mm diameter), pressure applied to the cartridge (between 3.0bar and 5.0bar), extruded material flow (between 80% and 150%) and speed (between 60mm/s and 90mm/s). In addition, it was analysed the effect of changing the path of the print head, the printing order of the geometry segments and the number of layers. For the execution of the initial printing tests only one part of the real-scale Arch 1 was printed – comprising parts 9, 10, 18 and 19 – considered to be the most problematic ones, taking into account their degree of openness.

From the analysis of the initial models results, it was verified that if we only take into account the geometric fidelity between physical and digital models, we obtain better results when the 3mm extruder nozzle is used. On the other hand, the nozzles of larger diameter guarantee a greater structural rigidity, both for the part and aggregation set.

Still, and due to the observation of the blocks after curing and due to cooking, the higher concentration of material that exists in the cases where the 6mm and 8mm nozzles are used, results in substantially higher tensions, resulting in the partial and random breaking of the part. In fact, such surface breaks also occur when the 3mm extruder tip is used, however, these manifestations occur in sensitive parts of the components geometry, being predictable and consequently possible to avoid.

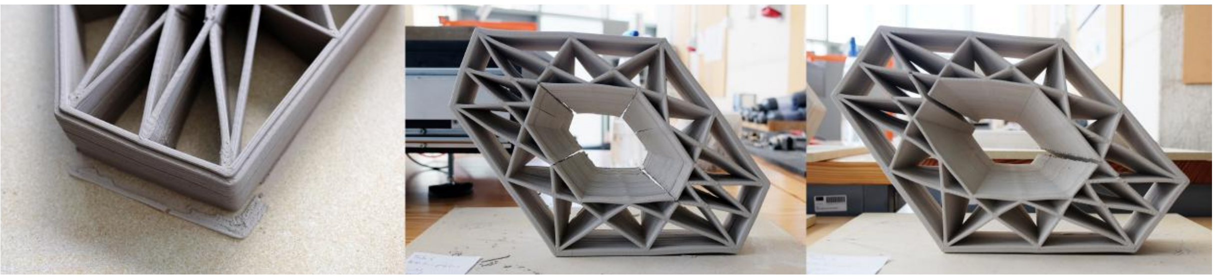

Figure 8. Effects of ceramic material retraction.

The retraction of the material by loss of moisture is perhaps the main problem encountered during the execution of these tests. The image shown above (Figure 8 – left image) is a good example of what happens immediately after the printing of the part, where the difference in size between the initially printed block and the block after losing the water present in the material is clearly seen.

This loss of volume, which also results in loss of agreement between the scales of the digital and physical models, also causes changes in shape, further distancing the final (physical model) part of the original (digital model) part (Figure 9). In addition to the variation of scale, the deformation caused by the retraction in the internal structure of the component is perceptible. In Figure 8 we can clearly see the existence of forces working in opposite directions or with distinct intensities, leading to considerable formal changes (the internal structure presents curvatures not foreseen in the digital models).

After the printing, curing and firing processes of each of the components, there was a place to organize and position all components in the arch set. It was observed that the effects of retraction in conjunction with the methodology applied in the manufacture (deposition of material layer by layer), resulted in non-formal correspondence between the matching faces that serve as connection between blocks. In these connections, the more deformed the initial (digital) surface is, the less the printed model is faithful to it.

In this sense, the smooth connections, which only have a slight deformation on the surface, work better and guarantee a reasonable connection between elements. By contrast, male/female type connections are problematic and they don’t respect the initial geometry and do not guarantee the integrity of the assembly, causing large geometric variations.

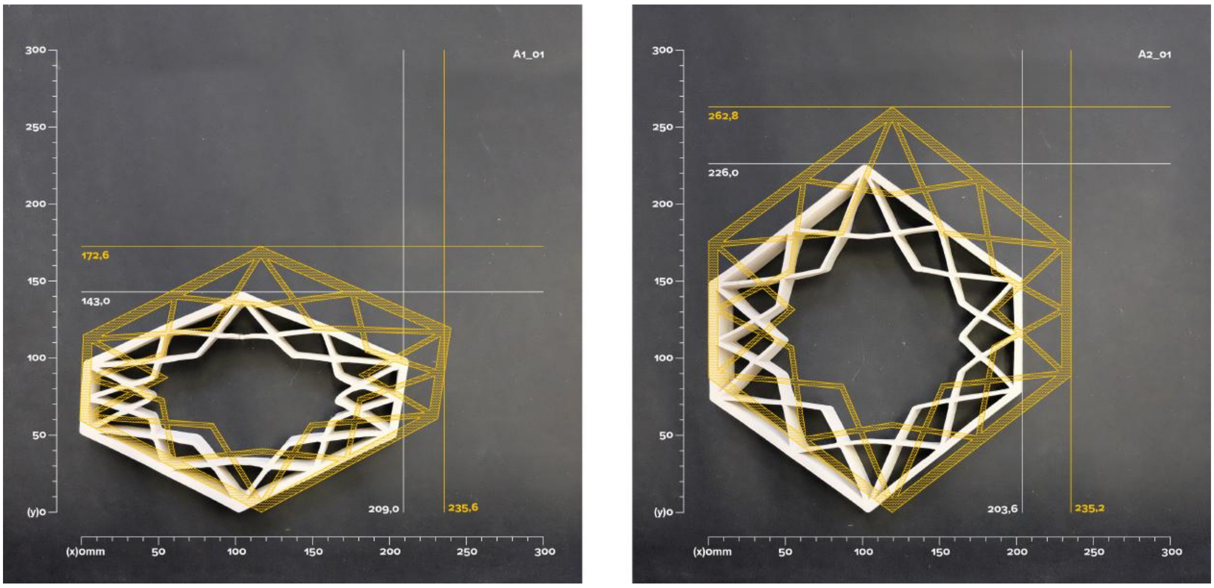

Figure 9. Comparison between digital and physical models (arch 1 on the left and arch 2 on the right). The orange drawing represents the original (digital) size of the top layer of each block.

The aforementioned cracks, as well as being caused by the retraction of the material when it loses moisture, are also related to the way that moisture is extracted from the part. Abrupt changes in temperature result in different losses over time and over the printed model, causing that by the difference of the retraction values that punctuate the model as a function of the mass variation in the same, there is place to total or partial breaking in the surface of the blocks.

6. Conclusion

In the context of additive manufacturing the materialization of complex geometries takes the same time, effort and resources as the production of simpler geometries, contrary to traditional manufacturing processes.

The amount of water present in the paste is one of the most important variables for the agreement or non-formal agreement between the printed model and the digital model on which it is based. From the comparison between digital and physical models it is observed that the retraction occurs in two phases (after curing and after firing) resulting in significant formal variations. The values show that the retraction is directly related to the geometry, dimensions and quantity of material in each direction. In most of the models produced the retraction is between 12% and 17% of the initial size.

The greater the inclination (relative to Z) of the geometries to be printed, the greater the deformation occurring in the curing and firing phases, resulting in higher discrepancies between digital and physical models, and the tests performed show that significant deformations occur with higher surface slopes to 30%. Male/female type connections, due to their formal complexity, result in large formal variations of the surface, making it difficult to operate the printing and assembly processes.

In the sense of what has been exposed, this study reinforces the knowledge on AM of ceramic material, attesting the possibilities and virtues of the application of digital design and manufacturing technologies for the production of ceramic architectural components. In addition to the manifest virtues and advantages that this practice incurs, it is important to note the negative aspects found during the study, in order to mitigate such disadvantages in the future. The effects of material shrinkage during the curing phase, leading to the loss of geometric agreement, allow us to conclude that pulp composition (relation between ceramic-water-viscosity) deserves more attention in future works, in order to consolidate this production system.

Figure 10. Test Arch 1 on exhibition at Material Xperience 2018 in Rotterdam.

Acknowledgments

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