Free-form Ceramic Vault System

Taking ceramic additive manufacturing to real scale

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The use of Additive Manufacturing (AM) for the production of architectural components has more and more examples attesting the possibilities and the advantages of its application. At the same time we seen a fast grow of the usage of ceramic materials to produce fully customised architectural components using Layer Deposition Modelling (LDM) [1] techniques. However, the use of this material, as paste, leads to a series of constraints relative to its behaviour when in the viscous state, but also in the drying and firing stages. Thus, when ceramic dries, the retraction effects may be a barrier to the regular use of this material to build future architectural systems. In this sense, it is important to study the material behaviour and know how to control and use it as a primary construction material. To do that we present the challenges and outcomes of project Hexashade, a ceramic vault shading system prototype whose geometry and internal structure is defined according to the solar incidence. This paper explain how we expect to build a real scale self-supporting prototype.

Keywords: *Ceramic 3D printing, Additive Manufacturing, Vaulting Systems, Parametric Design, Performative Design*

1. INTRODUCTION

Digital manufacturing processes allows a faster and more precise production of complex architectural components, expanding considerably the architect role and the possibilities of how and what is possible to build. The merge of digital design tools and additive manufacturing technologies enable the execution of entirely customised systems, developed to specific contexts, answering with balance and adapted solutions.

The research described in this paper follows a previous work named 3D Printed Ceramic Vault Shading Systems (Carvalho et al.) that was also developed in the context of the Advanced Ceramics R&D Lab (ACLab) projects. Based in the Design Institute of Guimarães, the laboratory intend to explorar the applicability of AM techniques such as LDM of ceramics, on architectural design and production processes.

The study focused on the development of a self-supporting domed roofing system, formed by customised hexagonal blocks in which the size of their openings and internal structure configuration allow to control the solar incidence. During this study a 1/2 scale prototype (Figure 1) of a part of the origi-

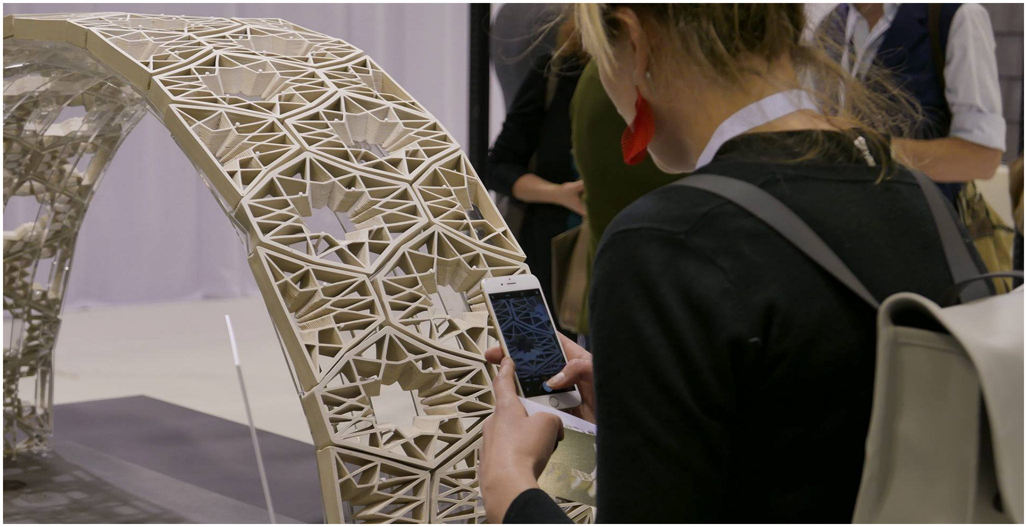


Figure 1
Ceramic Vault
Shading System
Prototype in
exhibition.

nal structure was produced. In this sense, the present paper aims to synthesize the problems encountered during the various phases of this study and to point out methods and solutions for their mitigation.

2. CONTEXT

The previously described research resulted in the enunciation of problems that prevented the manufacture and assembly of a full-scale prototype as originally planned (Figure 2 - right). Instead of this formalization, the study resulted in a reduced-scale prototype with no self-supporting capability, requiring an acrylic substructure to support it, and listing a series of formal and material issues that made it impossible to produce a full-scale model. Of these problems, four are of particular importance: (a) the aforementioned absence of self-supporting capacity; (b) the connections between components that did not worked properly due to non-correspondence between juxtaposed faces; (c) the retraction of the parts during the drying and firing phases caused a mismatch between the physical models and the digital models; (d) the punctual surface cracking due to non-uniform shrinkage which drastically reduced the load capacity of the structural elements.

2.1. Lack of self-supporting capacity

The lack of self-supporting capacity of the shading system assembly is perhaps the main obstacle to the production and construction of a full-scale model. Of the small scale models carried out so far none of them have the capacity to support their own weight without the aid of another element, contrary to the initial objective of the project.

Contributing to this fact will certainly be the dimension of the height of the pieces wall (arch thickness) which does not allow a stable support, either for the part or for the set. In addition to being reduced, there is still the problem that this thickness is constant throughout the arch, so that the elements that are on high stress have exactly the same structural capacity and weight as those that have to respond to lower requests, with no correspondence between structural request of the set and the response capacity of the elements.

2.2. Deficient connection between components

The deficient connections between components result from the natural deformations of the ceramic paste during the later stages of manufacture, dewatering and firing. This characteristic is natural in viscous materials that incorporate water in its composition and tends to cause deformations in the constructed elements by the reduction of volume, be it general or punctual, in the latter case determined by the existence of complex geometries.

Also, the friction between the printing bed (refractory plate) and the produced part (first layer), which is beneficial during printing, is bad in the later stage by not allowing the free movement of the component at the base, causing the loss of moisture to result in more deformations, in this case unpredictable. During the execution of the test models, various types of connection between the ceramic elements were realized, from fittings formed in the part itself, to the execution of external connecting pieces made from other materials, namely in PLA by FFF. None of the elements tested revealed the strength needed to ensure the integrity of the system.

2.3. Retraction of ceramic material

From the retraction of the ceramic material in addition to the aforementioned deformations on the surface of the parts, there is also a general mismatch between the scales of the digital and physical models. One of the characteristics evidenced during the execution of the reduced scale tests was that the retraction of the ceramic paste is not regular, varying throughout the piece. It was noted that the retraction value of ceramic pieces has large oscillations in the various directions, these variations being directly related to the geometry and quantity of material (mass) in each direction.

There is a large discrepancy between the retraction values in the two main directions of the executed pieces (X and Y), and the only difference between them is the extension of the segments that form them. It is observed that the smaller the dimension of the piece in a certain direction (smaller quantity of material) the greater the value of its retraction, since to resist the efforts of contraction of the ceramic will be less volume of material.

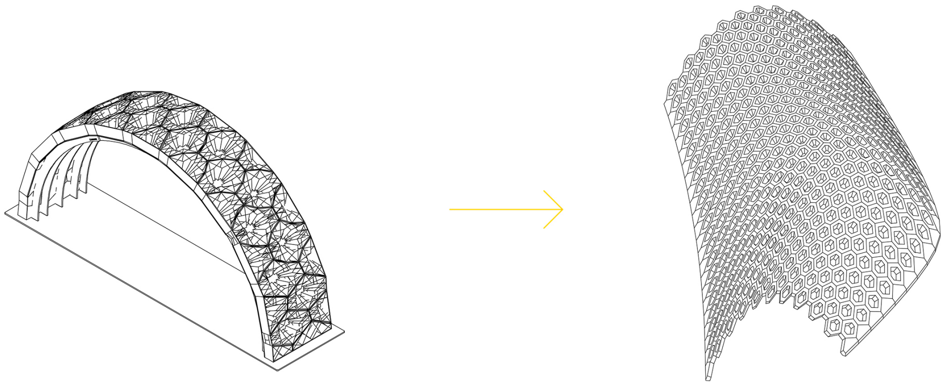


Figure 2
Hexashade 1/2 scale prototype (left) and the complete shading system (right).

Scheme of 3D Printed Ceramic Vault Shading System
Scale 1/2

3D Printed Ceramic Vault Shading System
Full model

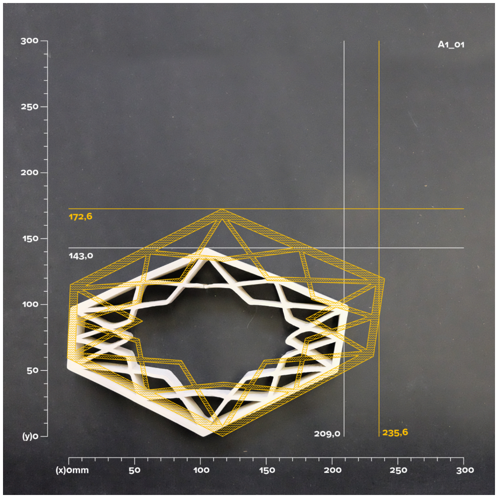


Figure 3
Retraction analysis.
Comparison
between the digital
and physical model.

2.4. Surface cracks

During the execution of the first printing tests it was recurrent the appearance of breaks and cracks in the walls of the printed elements. Its origin is related to several factors that later began to be considered for the execution of the parts, resulting in modifications of the configurations of the entire production process.

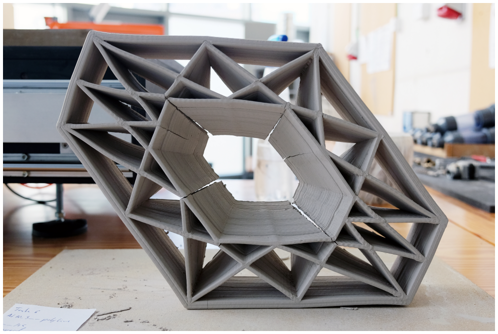


Figure 4
Surface cracks.
Real-scale model.

From these we highlight (a) the friction that exists between the printing base and the base of the part, which can result in breaks when the resistance exerted to the movement is higher than the resistance limit of the material, (b) the loss of water under uncontrolled environmental conditions, and (c) complex geometries, which may be incompatible with the mechanical configurations of the equipment or with the material, and which may lead to non-uniform distribution of material by the element, causing various retraction values.

In Figure 4 it is noticed that the breaks follow a pattern and, in this case, concentrate on the encounters between different extrusion paths, namely in the connections between the internal structure and the internal walls that conform the opening of the piece, pointing out ways to its possible elimination.

3. METHODOLOGY

In order to mitigate all these problems, a careful analysis of the variables under study was made, as well as the cross-referencing of data inferred from other projects developed at the Advanced Ceramics R&D Lab, such as the Wave Wall [2], and external examples of design solutions that presented good results, such as the 3D Printed Shelter from ELStudio [3].

For the execution of these changes the object of analysis is divided into two moments. Firstly, as a whole (set of all the pieces), for the resolution of the lack of self-supporting capacity and connection between elements, and in a second, in which each piece is individually treated, for the deformation that compensates the retraction effects.

3.1. Lack of self-supporting capacity

In order to solve the first problem, the lack of self-supporting capacity, it was thought a formal revision of the whole set, resulting in a redistribution of mass by the pieces based on the relative position of each component in the set. That is, a generalized increase in the dimension perpendicular to the arch in each of the pieces, decreasing in value from the base to the top.

In the previous proposal all the blocks had the same height and the same number of layers not considering each position in the set. In the context of this proposal the height will be variable, with more height in the lower position parts, meaning heavier and stronger areas at the base, making this is a more optimised solution for the structural needs of each part of the arch (dome).

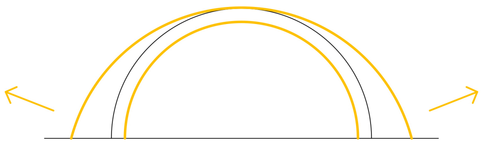


Figure 5
Mass redistribution scheme.

In order to be able to print a block with variable height it was decided to distribute the number of printing layers evenly on each block. As shown in Figure 6, in the areas of smaller height the spacing between the extrusion paths is smaller than in the higher parts. In order to maintain control of the extruded material quantity, trying to keep a proportional relation between less layer spacing with less material deposition (preventing excessive shedding), it is proposed to reduce the speed of the spindle (extruder) in these sectors, maintaining the travel speed constant.

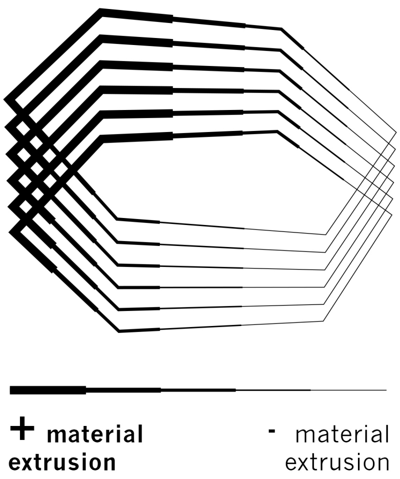


Figure 6
Material extrusion scheme.

The implementation of this process implied the update of the previous code, developed in the ACLab [6], including the possibility of customization of the speed parameters (displacement of the extrusion nozzle in X, Y, Z and the number of revolutions of the extruder spindle) and its translation into G-Code speed parameters.

In addition to the customisation of G-code it is also necessary to reconfigure the printer controller, in order to modify the pre-established relationship between travel and extrusion speeds. At the same time, thinner blocks near the keystone, with less structural request, will be conformed by fewer print layers.

3.2. Connections between components

The connections between the various components of the assembly that made it impossible to assemble correctly due to the non-correspondence between faces, which also meant that the assembly did not have the capacity to withstand load requests, requires a new formal change, characterized by the abandonment of connections made by complex geometries and the application of light surface deformations, only in order to counteract the direction perpendicular to the loads, preventing the displacement of the blocks from the original position, locking the assembly.

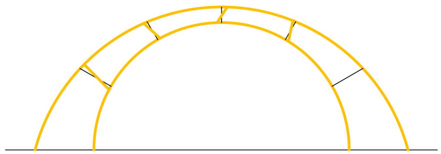


Figure 7
Interlocking system scheme. Smooth deformations that block the movement of the parts.

This change, represented in Figure 7, similar to the one used in the investigation of Matthias Rippmann and Philippe Block (Rippmann et al.) is characterized by the implementation of slight deformations on the side faces of the blocks in opposite directions, leading to that when the assembly is complete it is impossible to detach any of the parts, making it a reciprocal and solid structure that does not require additional support elements.

3.3. Retraction issues

In order to solve problems related to retraction, has been implemented a computational model that analyses each of the elements and makes the necessary formal modifications, so that in the end, taking into account the characteristics of the ceramic paste (retraction values), the final model is an exact physical representation of the digital one in which it is based.

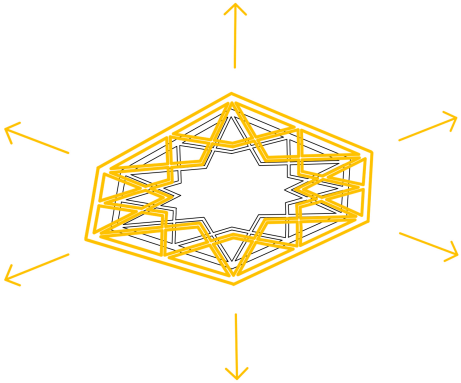


Figure 8
Computational model scheme. Deformation of the initial digital model taking into account the retraction values.

This reverse engineering exercise simulates the LDM process that considers the formal configuration of the objects after occurrence of the retraction effects, that is, scaling up the digital model to when it retracts, became equal to the original digital one. The shape changes introduced by the computational model encompass three moments, the base shape control polygon (modification of the X and Y axes), the top shape control polygon (modification of the X and Y axes), and distance between the two previous polygons (shape change in the Z axis).

3.4. Superficial cracks

The issue of surface breaks is not only explained by the normal behavior of the material over time (retraction), but is more difficult to prevent or avoid. The surface breaks happen at particular moments, where the tensional stress in the material exceeds the maximum resistance of the same, leading to the collapse of the connections.

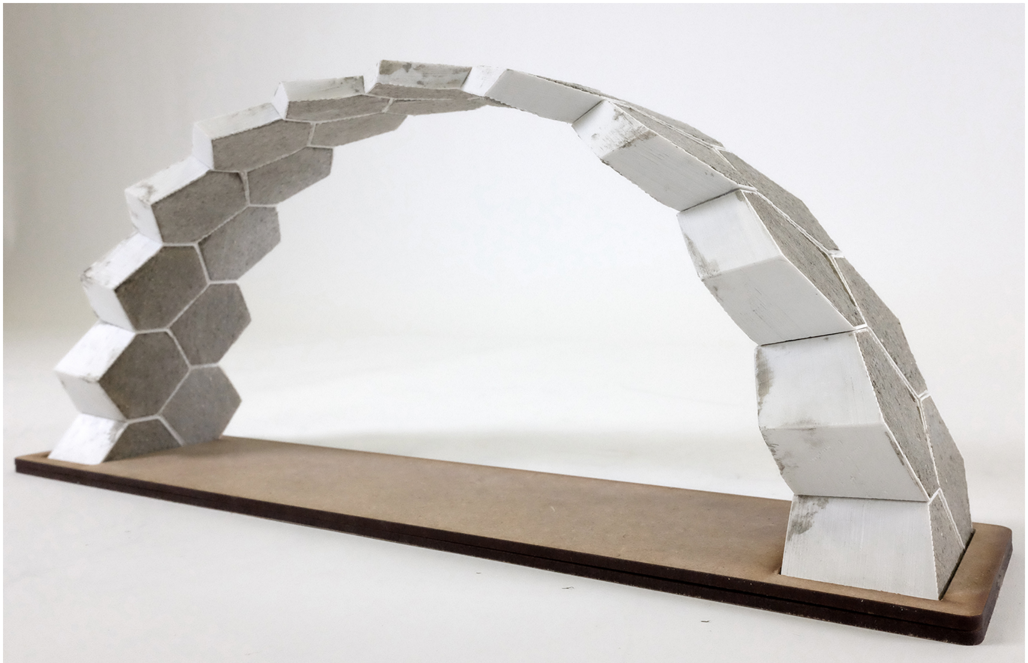
To avoid breakage, the inclusion of additives in the composition of the ceramic paste, namely glass fiber and sawdust was tested, giving the pulp greater resistance to tensile stresses during the dehydration phase. The inclusion of additives in the ceramic paste, while providing the blend with more tensile strength at the moment it is retracting, lowering the water levels, also has implications for the final performance of the element, insofar as it changes its composition compared to an element solely formed by ceramic. In addition to changing the chemical properties of the material and consequently its response to stresses, the addition of some types of material to the ceramic paste, namely fibreglass (Figure 9) considerably changes the finish of the piece, giving it an appearance rough finish with many irregularities.

To prevent the occurrence of breaks along the surface of the elements produced, in addition to having control over the temperature and humidity of the space where the parts will remain to dehydrate, there should be control over the geometry of the segments, introducing variables such as thickness and height of the layer, and on the print paths, defining the most suitable deposition sequence so that the successive passages do not weaken the part.

Figure 9
Mixture of ceramic with fibreglass.

In addition to the breaks that occur during the dehydration phase, sometimes there are breaks during the cooking phase (in a controlled environment). To avoid such breakages, changes to the cooking programs will be made by modifying the heating curves and consequently the reaction of the material to the heat. We will be particularly concerned with the ce-

Figure 10
Small scale model with the implemented changes.



ramic expansion phase (approximately 600ºC) and with the vitrification phase (approximately 1250ºC), trying to smooth the effects of the chemical alterations.

4. RESULTS

The modifications described above mainly result in formal changes in the components, assuming the stabilization of the configurations of the material, maintaining the composition and the amount of water present in the ceramic paste.

Since our goal was to reach a self-supporting structure, the first iteration to the previously explored methodology would have to be in relation to the capacity of the structure to support itself without external elements, something that is achieved by the redistribution of the mass inside the assembly that conforms the structure, although there is place to a considerable formal change. Here, a logic of agreement between loading requests and the volume of material in each component was applied.

In addition to the need to reformulate the mass distribution in the set, it was necessary to revert the effects of ceramic retraction. Here the results obtained are not characterized by the abolition of such material characteristic but, as mentioned above, by the analysis of the retraction values and subsequent compensation, causing the produced geometry to be a controlled deformation of the initial geometry that, in the end of the entire production process, gets much closer to its digital version.

In the connections between pieces, once only soft surface deformations have been used, there is a good correspondence between juxtaposed faces of different blocks, allowing good fittings. Although these deformations are relatively small, in some cases they cause the increase of vertical inclination, and consequently increase the deformations on the surface. These deformations can be corrected during the phase in which the block is dry, by the regularization of the surface by abrasion tools.

Related to the use of additives to help stabilise the ceramic material while it is still not resistant, the results show that despite helping to compensate the lack of response of the ceramic to tensile and flex stresses during the drying process, this addition causes that, by the method how the production is made, the fibbers sometimes cause defects in the surface finish.

5. DISCUSSION

The problems pointed out at the beginning of this paper may prevent the execution of some projects in which, as in the case of Hexashade, its structural integrity is dependent on the formal correspondence between the juxtaposed faces of the elements that compose the set, or the co-correspondence between the model produced and the digital model.

In this sense, the presented methods constitute a set of actions that we consider as possibilities so that there is correspondence between the digital model, totally developed in computer environment and its material formalisation produced in ceramics through the LDM technology. These methods aim to control the behaviour of the ceramic paste during the moments after the production, predicting and counteracting the deformations that it may suffer, according to the characteristics of the material to be used in the production.

AM in viscous materials such as ceramic or concrete are quite challenging in that they allow a very close connection between tradition and innovation, incorporating formal and material parameters not yet explored.

Assuming this as a continuous work, with further studies and new tests to be done, we point as the next step the use of superplasticiser additives that help to control the plasticity of the ceramic material while the amount of water present in the pulp is reduced, a situation that, pervisibly, will result in less significant deformations and easier to control.

ACKNOWLEDGMENTS

This work has the financial support of the Project Lab2PT - Landscapes, Heritage and Territory laboratory - AUR/04509 and FCT through national founds and when applicable of the FEDER cofinancing, in the aim of the new partnership agreement PT2020 and COMPETE2020 - POCI 01 0145FEDER 007528.

We are also grateful to the Institute of Design of Guimarães for hosting and supporting the activities of the Advanced Ceramics R&D Lab on the use of their facilities and equipment, and all the assistance from the technician Samuel Ribeiro.

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