Ceramic Additive Manufacturing in Architecture

Computational Methodology for Defining a Column System

João Moreira[1], Bruno Figueiredo[2], Paulo Cruz[3]
[1] Universidade do Minho [2,3] Universidade do Minho, Lab2PT
[1] joao_pedro_moreira3@outlook.com [2,3] {bfigueiredo|pcruz}@arquitetura.uminho.pt

The present paper describes a research that explores the design and production of customised architectural ceramic components defined through parametric relations of biomorphic inspiration and to be built through additive manufacturing. In this sense, is presented a case study that develops a system of both architectural and structural components - a column system. The definition process of the system is mediated by computational design, implementing not only structural analysis and optimization strategies, but also mimetic formal characteristics of nature to an initial grid, creating a model that adapts its formal attributes, depending on its assumptions and the material constraints. This process resulted in the definition of a set of solutions that better answer to a specific design problem.

Keywords: *Additive Manufacturing, Ceramic 3D, Computational Design, Structural Optimization, Biomorphism*

1 INTRODUCTION

The present research aims to contribute to the development of knowledge in the use of additive ceramic manufacturing in architecture. This research works mainly on the topics of ceramic additive manufacture and fabrication of structural components, however to develop them it interconnects with other equally important themes. Namely, the integration of computational design, structural optimization and biomorphism for the definition of structural components. The aim is to develop a column system, which acts as an auxiliary design tool, integrating the design of the respective structural components, according to certain initial conditions, and then producing it with the use of additive ceramic manufacture.

With this objective in mind it is proposed the use of computational models for the integration and control of a set of parameters - biomorphic and structural - that are intended to be the origin of the definition of the column system. Later, with the final design achieved, we aim an exploration of the structural optimization of the prototype, as well as the manipulation of the g-code and the machine.

2 DEFINITION OF COMPUTATIONAL MODEL

The development of the whole process of the column system was performed through Rhinoceros 3D, a three-dimensional modelling software, and

Grasshopper, a graphic algorithm editor native to Rhinoceros, which allowed the system to be developed parametrically.

As it was intended to explore the association of biomorphism with architecture, it was tried to explore the application of reticulated grids to the column. And so, the first question arises "How to develop this kind of grids parametrically in Grasshopper?". For this we began with an elementary geometric form to simplify the development of the parametric model.

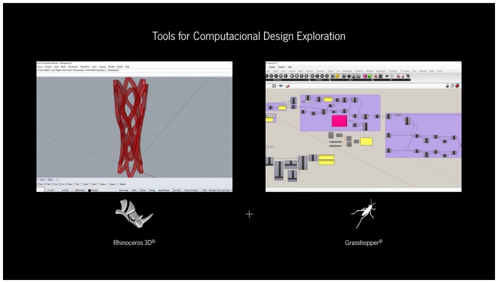

Figure 1
Tools for Computacional Design Exploration

21 CONSTRUCTIVE STRATEGY

The first strategy was the application of models that generate structural meshes, initially in a random way, from a population of points, however there was no control over the geometries generated. In order to understand the problem of this approach it is necessary to understand that the ceramic additive manufacturing process, through Liquid Deposition Manufacturing (LDM), has a condition to be taken into account. This process demonstrates a weak ability to produce objects with amplitudes greater than 30º in relation to the Z axis, running the risk of the object falling and the printing failing (Figueiredo et al., 2017). Therefore, because there was no control over the final geometries, the manufacturing through ceramic material became complicated.

In an attempt to control the generated geometries, regular grids were applied to the population of points. Thus, the final geometries that made up the reticulated grid were known at the outset. However, because they were regular, the amplitudes remained higher than 30º, and because the computer generated these forms they could not be manipulated after. Therefore, a restructuring was sought in the process of defining the cross-linked structural grid, changing the process operator, that is, instead of allowing the computer to automate the design of the cells, it was attempted to be the user to define it, ensuring greater control over the grids design.

However, the nodes between the ribs did not give a satisfactory structural continuity to the design of the prototype, due to the fact that the grid was generated horizontally around the column. Therefore, a restructure of the computational code was developed that tried to solve this question and that at the same time simplified the parametric model, because the current approach made the generation process too slow.

Thus, by maintaining the elementary basis of the prototype, we explored the definition of the reticulated grid by dividing the base geometry into subsurfaces rather than a population of points. From this, the desired pattern was drawn, and the computer applied it recursively to all subsurface surfaces, thus constructing the grid. In this way, the nodes ceased to be a problem, since the smoothing process of the grid was done vertically, guaranteeing a satisfactory structural continuity. With this, we were faced with a work base that we considered to be consistent and could continue to explore the biomorphism associated with the column.

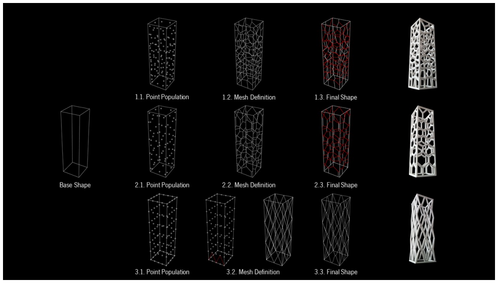

Figure 2
Constructive Strategies

22 COMPLEXITY AND BIOMORPHISM

Based on the observation of the structure of the trunks of plants, a formal mimetic relation with the Ficus plant was proposed for two reasons. First, it has been found that the design of its trunks seems to refer to a cross-linked structural grid, and secondly, because it is a plant structure, it has a great fluidity and formal organicity, so that its ridges appear to move freely. With the introduction of these features in the column system it was possible not only to consider the generation of new formal possibilities, but also to interconnect the idea of biomorphism with architecture.

To the base design of the system was applied a variation of its section along its height, as well as rotations were applied in these same sections, resulting in a design closer to the characteristics of the Ficus plant. From this moment on we had an operational parametric model, able to generate various solutions from a group of parameters that defined the column, doing it in a parametric, fast and simple way.

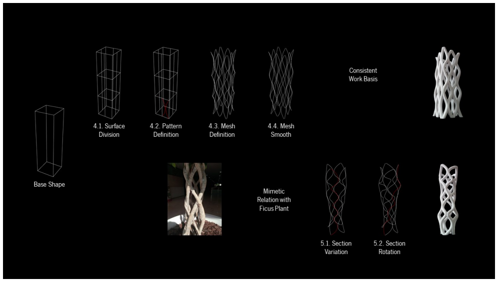

Figure 3
Strategies for Complexity and Biomorphism

23 STRUCTURAL ANALYSIS AND OPTIMIZATION

One of the themes also explored in the present paper was the structural optimization, possible through a previous structural analysis. This was possible by integrating two plugins specialized in these tasks, specifically Karamba3D, which analyses the structural behaviour of three-dimensional geometries when certain loads are applied to them. For this analysis the software works with a base of simple elements, so the first task that this one executes is the translation of the three-dimensional object to vector elements. From this we obtained the values of the weight and deformations of the column, two crucial aspects for structural optimization, because we aim to minimize these characteristics.

The optimization process was done through Octopus, which privileges the control over the development of the design of the reticulated structural grid, applying evolutionary principles to the computational design. This software allows an analysis of a set of parameters, or genes, seeking to fulfil multiple objectives, in an attempt to generate a series of optimized solutions between the maximum of each of the objectives introduced. In this case, it seeks not only to minimize weight and deformation but also the amplitudes, due to the poor capacity of the ceramic material to produce elements with high amplitude values. The results of this optimization are presented through a cloud of points, and from this it was possible to identify 3 type solutions, a hexagonal base solution (A), a triangular base solution (B) and quadrangular base solution (C) for later comparison.

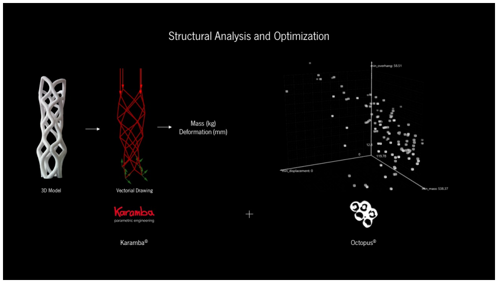

Figure 4
Structural Analysis and Optimization using Karamba3D and Octopus

24 FINAL PROTOTYPE DEFINITION

For the selection of the prototype to be produced, two parameters were considered. The first one, more objective, based on the results of the structural behaviour of each of the columns and a second, more subjective, concerning the design of the prototype. The process of defining architectural objects always implies the control and definition of the morphology and proportions of these objects, so this analysis also weighed in the selection of the prototype.

The selection began with a comparison of the structural results of the three columns, which immediately led to the removal of solution B from the options. With the choice to be divided between the other two solutions, the option ended up with solution A. Among the three hypotheses, this one presents not only a better deformation and axial strain value, but also a design that formally interested us to experiment because it is the one that presents more similarities to the trunk of the Ficus plant.

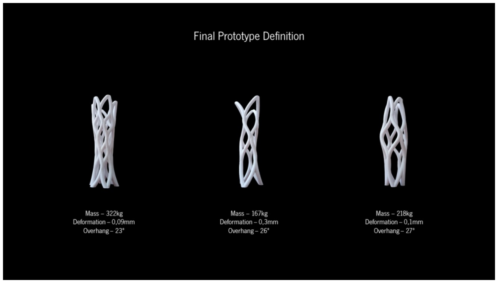

Figure 5
Final Prototype Definition

3 PREPARATION AND PRODUCTION OF THE PROTOTYPE

When dealing with additive manufacturing processes it is important to realize the process behind the method and in this sense, it is important to realize that the language of the digital design and the language that the printer reads are different. Therefore, it is necessary to translate the object language into the printer language, called g-code. There are several software capable of this translation, however it was chosen to execute it through Grasshopper®, allowing not only a customization of the code, but also developing it on the same platform as the project, approximating the stages of design and construction, which are generally autonomous and distinct (Carpo, 2013).

31 FIRST TESTS AND PROBLEMS

The objective of the first tests of manufacture was to define the initial parameters of manufacture, with respect to the height and the thickness of the layer, so different combinations were explored, being established in the end that would be used 3mm of thickness and 1,5mm of height , to a scale of 1:5, which could then be adapted based on the scale wanted to manufacture. These manufacture tests also allowed to check already some problems in the manufacturing process, namely the fact that the extruder tip dragged ceramic material during its course, creating several imperfections in the prototype.

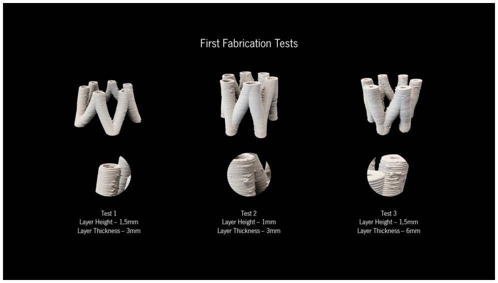

Figure 6
First Tests and Problems

32 OPTIMIZATION OF THE FABRICATION PROCESS

To try to prevent the extruder tip from dragging material along the path defining the prototype's design, a simple 5 mm rise in the Z axis was generated in the print code whenever a certain part of the print path was completed. Thus, at such times, the extruder tip stopped extruding material, moved up in the Z axis, moved to the next design location, dropped and continued the extrusion and so on until the manufacturing process was completed. With these changes implemented, results that showed good levels of quality began to emerge.

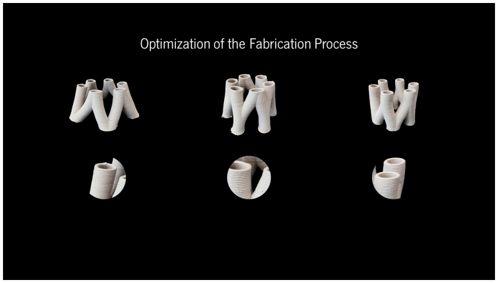

Figure 7
Optimization of the Fabrication Process

33 FINAL PROTOTYPE FABRICATION

There is, with this research, the ambition to manufacture a full-scale prototype, and in this context, we can have two approaches with regard to its production method. A first approach that deals with printers with small volumes, for the production of structural components. These components are divided into parts, through section plans that cut the geometry, and a second approach, where these limitations are non-existent, thus making possible a continuous manufacturing of the prototype.

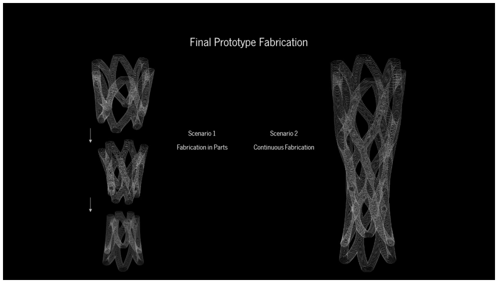

Figure 8
Final Prototype Fabrication

331 FABRICATION IN PARTS

Starting with the first scenario, the complications in assembling the parts were already evident, due to another characteristic of the ceramic material, the question of the retraction, which begins at the drying stage and stabilizes after the firing process, affecting the final dimensions of the prototype. In this case, this meant that the connections between the parts would not work. Therefore, the solution was to implement strategic compensations on the tops of each part, so that with the established retraction the pieces could fit together. Therefore, it was necessary to know the retraction indexes of each part.

Through a comparison of the dimensions of the digital drawing, which we see in red, and the printed pieces, which we see in white, it was found that the tops of the pieces retracted 15% and the bases retracted 8%. These differences are due to the fact that the bases are resting on a refractory plate, which due to its texture causes friction and limits the retraction of the prototype, as well as due to the self-weight of the parts.

Knowing the percentage of shrinkage of each part it was possible to calculate that the top of part 1 would have to be increased by 6.5mm and the top of part 2 would have to be increased by 11.6mm so that with the retraction the dimensions of the connections allowed the fit between them.

With this, it became possible to interconnect the parts, so that mechanical fittings were later developed to fix them. These fittings are simple tubular profiles, also produced in 3D printing, in this case in polymer material, and are placed inside the ribs, as it was intended to minimize their presence in the design of the column. Its lateral flap tries to avoid contact between two ceramic surfaces, avoiding the risk of parts cracking or even breaking in the moments of connection.

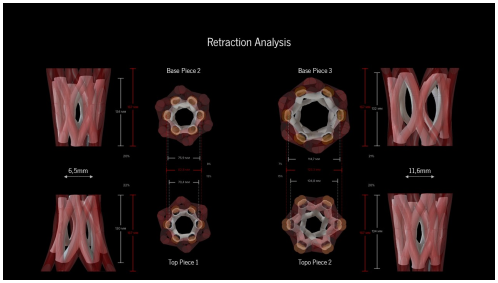

Figure 9
Retraction Analysis

332 CONTINUOUS FABRICATION

In the second scenario, the issue of shrinkage does not have the same degree of importance as in the first, because the prototype is developed continuously, however if we are faced with a situation where the printed prototype needs to have dimensions such as those of digital drawing, we must take into consideration the retraction values.

As it was intended to compare the results between the two methods, we analysed the retraction values of this scenario also. In this case, the retraction at the top was 15%, just like the other scenario, and the difference was at the base, which fell to 11%. However, the most unexpected results were the rates of retraction in height, which presented even higher values.

In this case, the prototype printed in parts retracted 21% and the continuous printing prototype retracted 17%. At the start it was thought that the continuous printing prototype would exhibit higher retraction values because it was a larger and heavier piece, so it was thought that these factors would accentuate the retraction, but the opposite was true. What is thought to be the origin of this result is the area that is exposed to the air, the first scenario, printed in smaller pieces has the inner volume more easily exposed to the air, however in the second scenario, due to the its height, this contact is smaller, affecting the way the retraction process acts on the prototype.

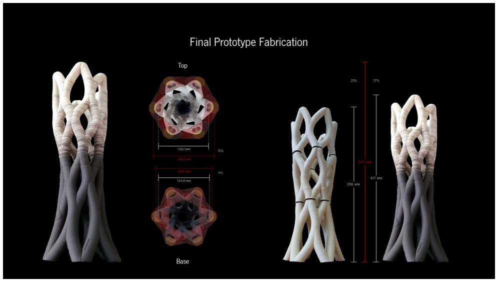

Figure 10
Fabrication Scenarios Comparison

4 FINAL CONSIDERATIONS

The association of additive manufacturing with ceramic material allows to explore new ideas and objectives in the built environment, however it is necessary to take into account certain considerations. Namely, its difficulty in producing amplitudes higher than 30º and especially, we need to consider the retraction values, since they have serious repercussions on the final result of the prototype. Finally, the integration of computational and parametric design in architecture is an added value for the work process, because it is a tool that not only helps the design process, but also streamlines the whole construction process of a given project.

REFERENCES

Agkathidis, A 2017, *Biomorphic Structures: Architecture Inspired by Nature*, Laurence King

Cruz et al, J 2017 'Ceramic 3D Printing – The Future of Brick Architecture', *IASS 2017*

Carpo, M 2013, *The Digital Turn in Architecture*, John Wiley & Sons Ltd

Kolarevic, B 2005, *Performative Architecture: Beyond Instrumentality*, Taylor & Francis Group

Reddy, J 2006, *An Introduction to the Finite Element Method*, McGraw-Hill Education

Witte, D 2016 'Ceramics in an AM Process for the Building Industry', *Imagine 10*