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Challenges of 3d printed architectural ceramic components structures: controlling the shrinkage and preventing the cracking

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Abstract

The use of ceramic materials in the additive manufacturing (AM) of architectural components has more and more examples and undeniably shows the potential of its application. However, one of the main characteristics inherent to this material, which happens in drying and firing phases, is the shrinkage of the material, which causes deformations and cracks in the surface of the produced elements. Thus, the shrinkage of the ceramic material may constitute an obstacle to the regular use of this material in the AM of architectural components. In this sense, it is important to study and point out ways and strategies to mitigate this drawback, making possible the correspondence between the final produced models and the digital ones in which they are based. This paper presents the main challenges and outcomes of several projects that use Liquid Deposition Modelling (LDM) of clay-paste as construction methodology.

Keywords: Ceramic 3D printing, additive manufacturing, ceramic retraction, parametric design, computational models, shrinkage, ceramic paste, Liquid Deposition Modelling.

1. Introduction

Digital manufacturing processes allows for a faster and more precise production of complex architectural components, expanding the role of possibilities of how and what is possible to build. The merge of digital design tools and AM technologies enable the execution of entirely customized systems, developed with a specific target, responding to the problem issues with balance and adapted solutions.

Features such as hardness, density, durability and the possibility of having a vast number of shapes and finishes provide the application of this material in buildings all over the world for centuries [1].

The combination of the use of additive manufacturing technologies and ceramic materials can result in a compromise between a high performance material and the execution of complex geometries, impossible to obtain by any other production process, or by traditional methods.

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.

One of the negative aspects of using ceramic pastes for the execution of architectural elements is the difficulty to control the natural retraction of the material when it loses the water present in the mixture, namely the behaviour that this effect will have on complex or irregular geometries. Simultaneously and as a consequence of this characteristic, and others, there may be room for breaks or cracks that result in the reduction of the response to the load requests on the produced element.

According to K. Khalili [2] the dehydration process is the major source of defects in most ceramic products, ranging from aesthetical to mechanical properties, such as strength or elastic modulus. Susang

Costa [3] refers that the evaporation of water from the surface gives rise to restrained shrinkage generating tensile stress leading to shrinkage cracks when stress forces reach the material strength. Ana Anton and Ahmed Abdelmahgoub [4] affirm that by the shapeless contraction of the material, caused by the loss of water, there may be breaks along and between the extruded layers, resulting in loss of structural capacity due to the failure of the material around these breaks. Therefore it is important to understand the behaviour of these forces and how they cause delamination of the extruded layers.

There are several projects that use this technology to develop architectural components such as the work developed by the groups Emerging Objects [6] and Building Bytes [7], both specialized in three-dimensional printing, however there seems to be always acceptance of this feature, never solving the effects of retraction.

In this sense, and based on a set of researches developed in the last 3 years, we consider that it is important to point out ways to control the behavior of the ceramic material during the production of architectural components that use the LDM methodology, and finally, to model considering the retraction of material.

2. Context

The above subject, in particular the problems related to the shrinkage of the ceramic material during the drying and firing phases, is evident in a series of investigations carried out by Advanced Ceramics R&D Lab in recent years, having the aim of mitigate or at least understand them, allowing greater control and knowledge of the material behaviour during the various stages of the production process.

As the most representative projects that testify this problem that affects formal agreement and structural integrity, we have the example of (a) Wave Wall, a wall system for building envelopes based on the traditional format of a ceramic block, (b) Hexashade, a domed shading system which is constructed from hexagonal blocks in which its internal structure varies in function of its position and the space-time ratio we want to shade, (c) Ficus, a system of structurally optimized biomorphic columns constituted by several stacked elements, and (d) Hive Wall, a honeycomb wall constructed from the stacking of blocks in predefined spaces.

After careful analysis of successive formal and structural failures, we formalized a set of methods and practices that can help control the behavior of the ceramic paste during the various production phases, taking better advantage of this material. To this end, a set of measures has been put in practice to overcome these issues, making the final physical object approximate the geometry of the initial digital model on which it is based.

3. Deformation by friction

The LDM deformation by friction occurs as soon as the material is extruded, at which point the water present in the ceramic paste begins to evaporate, leading to a decrease in the size of the printed part. Friction occurs between the printing bed, where the production of the part is made, and the base layer of the object. The high roughness of the printing bed which at an early stage assists in adhesion of the base layer to the printer surface, later becomes a destabilizing element and causes severe constraints on the material and on the final product in that it prevents that the material has a natural and balanced behavior. When the ceramic material loses its incorporated water its volume decreases by a percentage relative to the initial amount of water present in the paste. However, due to the constraint caused by the base, the volume reduction is not uniform in the object and results in non-correspondence between the top and bottom retraction values. The effects described above are evident in Figure 1. The left image shows the first printing tests of the Ficus column in segments, where it is noticeable that the base of each of the elements of the set has a scale significantly superior to the top of the previous piece and with which it should be coincident, resulting from the high friction that exists between the plate and the base layers of the part and that does not exist at the top of the element.

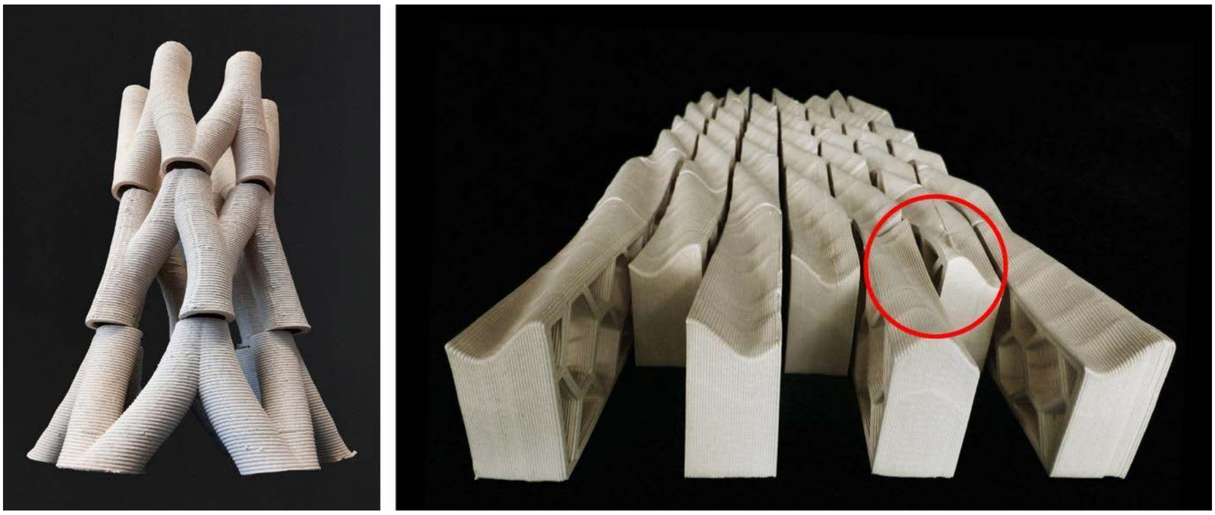

Figure 1. Segmented Ficus column – Initial test. Wave Wall – Effects of friction in retraction.

In the image on the right (red circle) it is observed that the wavy form of the top of the blocks surfers a large deformation in the base of the block, again caused by the resistance offered by the printing bed. In this case as a result we obtain a clear offset in the curvature of the corrugated surface that forms the front face of the wall.

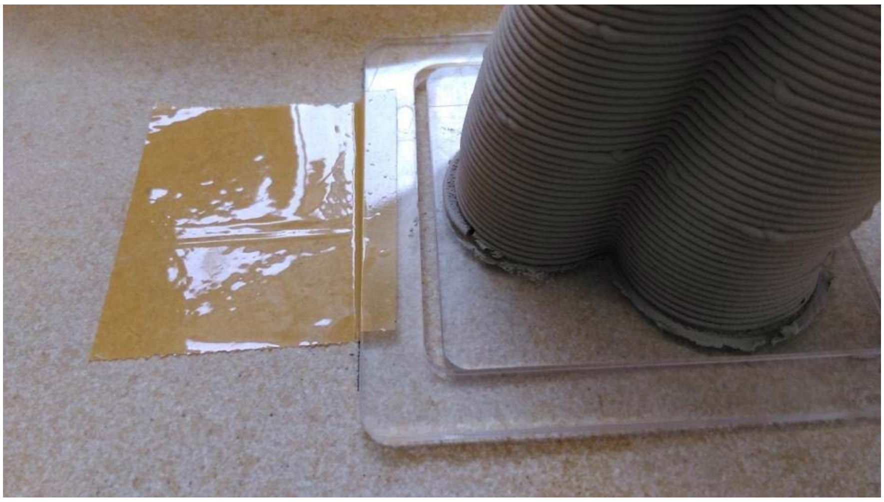

Figure 2.Example of free base with restricted movement.

To solve the problem manifested by the friction between the printing bed and the element produced, two solutions that can work in different contexts were thought. In a first phase, in order to solve situations similar to those evidenced in the Ficus column, where the base of the piece is constituted by several separate elements, we propose the introduction of a base that allows the freedom of movement of each one of the parts that touches the base after finishing of the production process. First, freely, leaving all directions freely, and second, restrictively, limiting freedom in the desired directions. Figure 2 shows an example of how to introduce a restrictive base that limits movement in a single direction and relieves structural stress on the object, allowing it to move naturally. In the image is also observable the effects of retraction by the distance that exists between the guide and the base plate.

Complementarily, in situations where it is not possible or feasible to use the previous method, we propose the implementation of a computational model that analyzes the geometry of the element to be produced and makes the necessary formal modifications, so that, in the end, taking into account the characteristics of the material, previously designated, the final model is an exact physical representation of the digital model that gives rise to it. 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 the distance between the two previous polygons (shape change with respect to the Z axis).

Figure 3. Result of the application of the computational model.

4. Deformation by non-uniform mass distribution

Besides the differentiated retraction being caused by the difference in the freedom of movement of the ceramic material during the post-production phase, there is still another factor that conditions the retraction and that causes the appearance of deformations on the surface that make the correspondence between the digital models and the parts produced. This factor is characterized by the non-uniform distribution of mass in the extension of the object, which later will cause instability in the retraction in the different moments that punctuate it. In areas where there is more material concentration, more mass, retraction values tends to be smaller than in areas where there is less material. Consequently, the part will suffer abnormal deformations during the drying phase.

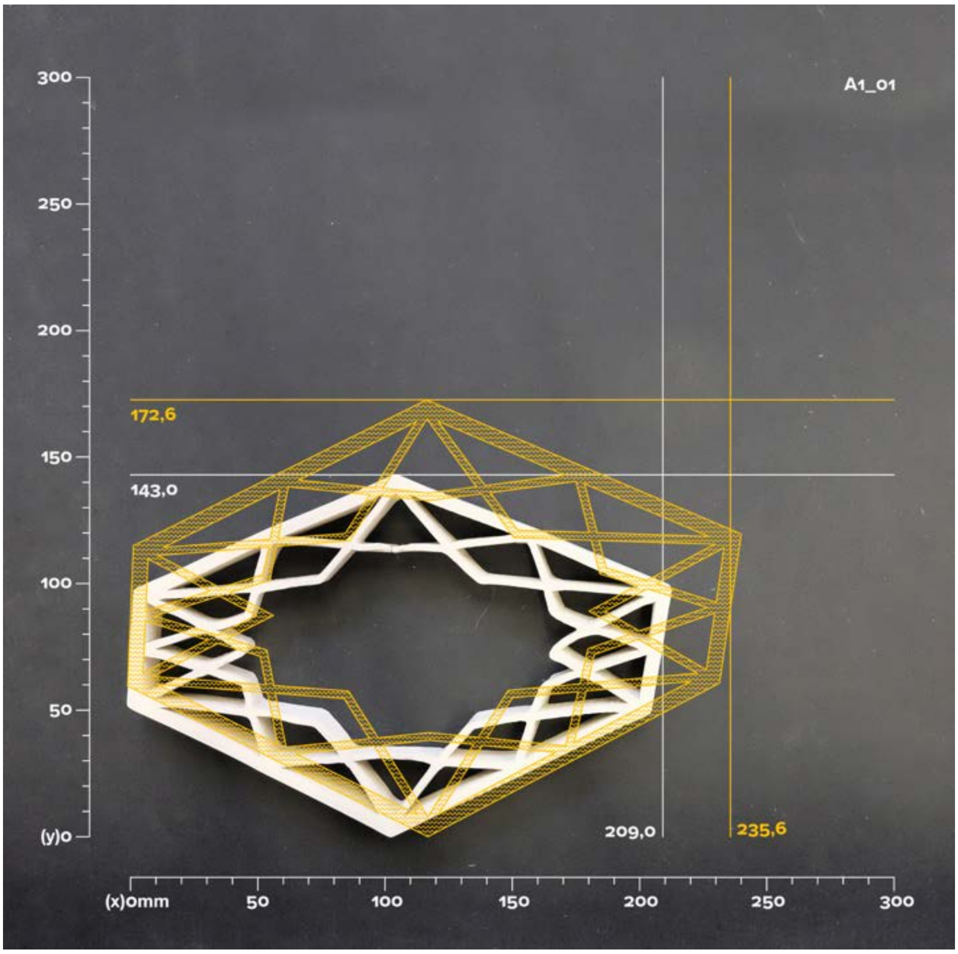

Figure 4. Hexashade, test arch 1 – piece 1 – retraction analysis.

Figure 4 expresses the discrepancy that exists between the retraction values of the two opposite directions (X and Y) only distinguished by the amount of material in each one of them. It is possible to observe that the smaller the extension of the piece in a certain direction, causing that the quantity of material is also smaller, there will be place to sharper values of retraction, since the resistance of the material to the efforts provoked by the dehydration will be smaller, leading to the retraction value being higher.

5. Wall breaks and cracks

The wall breaks of the produced elements also appear as a consequence of the previously exposed deformation. They are manifested mainly when there are large variations in the mass distribution in the three-dimensional object, resulting in axial tensions of varying intensity, which when they exceed the resistance limit of the ceramic material cause breaks in the wall of the element, reducing the resistance to mechanical requests.

We consider that there are two types of breaks. These are a direct consequence of the geometry of the piece, as is the case of the mass distorted distribution that causes differentiated tensions in the part, leading initially to deformations and, in more extreme cases, to partial or total rupture of the wall of the element. The second type of break is manifested when the friction between the printing base and the object exceeds the force the material can handle. This type of break occurs mainly when the amount of material in a particular direction is reduced in comparison with its extension, that is, when a linear element of short extension has few layers (little material in height) or is very thin (little transverse material) is expected to occur during dehydration of the material.

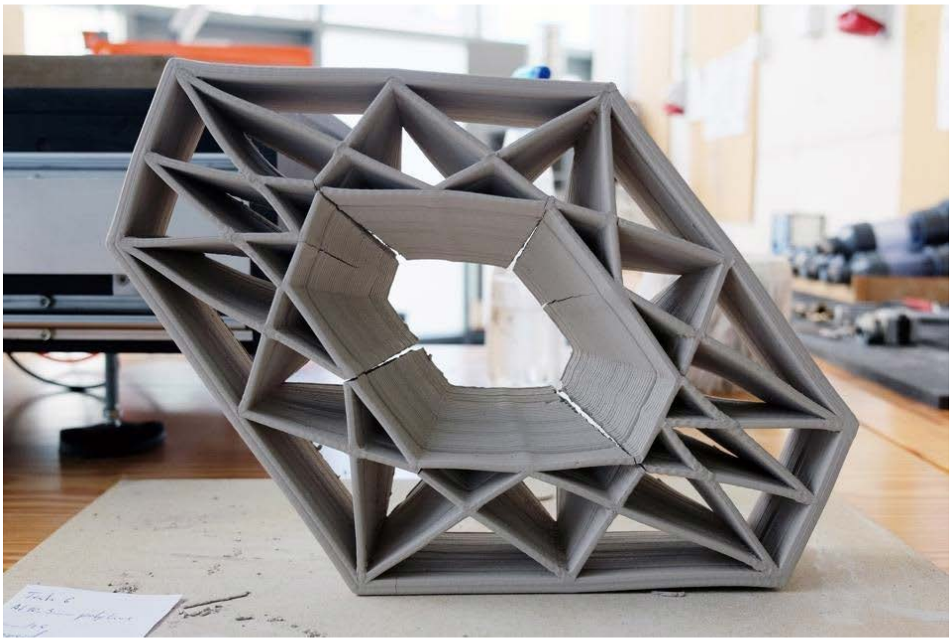

Figure 5. Hexashade, test arch 1 – real scale – interior wall break.

The issue of surface breaks is not limited to the material's normal behavior and behavior over time and is more difficult to prevent or avoid. The superficial breaks occur, as already mentioned, at particular moments, where the tensional stress in the material surpasses the maximum resistance of the same, leading to the collapse of the connections. In order to avoid cracking, the inclusion of additives in the composition of the ceramic paste, namely glass fiber, sawdust and cellulose was tested, giving the pulp greater resistance to tensile stresses during dehydration.

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 consequent its response to stress forces, the addition of some types of material to the ceramic paste, such as glass fiber (Figure 6), considerably changes the workpiece finish, giving it a rough final appearance and with many irregularities.

Figure 6: Tests of ceramic paste with fiberglass (5%).

6. Deficient joints

As a consequence of all previous defects, the deficient association of ceramic elements is a problem that can prevent the execution of some projects in which, as is the case of Hexashade, its structural integrity is dependent on the formal correspondence between the juxtaposed faces of the elements that make up the whole set. Here the effect of non-uniform retraction causes slight deformations of the side walls of the pieces which, when assembled, make impossible the correct positioning of each element, making the assembly of the aggregation unstable and without self-supporting capacity.

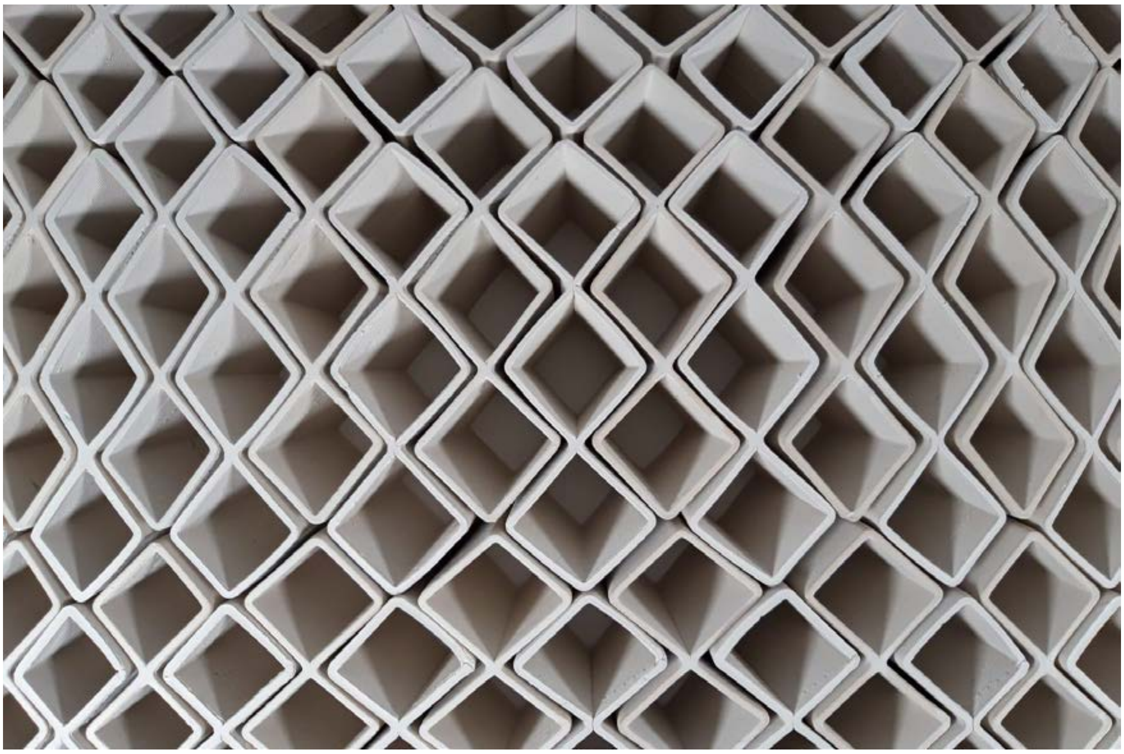

Figure 7. Hive wall - Deficient joins between pieces.

Figure 7, where the example of the Hive Wall is shown, illustrates the problem set out above by clearly showing the differences that exist between the joints connecting the pieces. The differentiated deformations result in joints with different dimensions that make impossible the correct assembly of the parts, compromising the structural and formal integrity of the wall, leading to the need of external support systems.

In this example, where the objective was to construct the wall only from the stacking of the pieces, it was necessary to include another material in order to fill the joints between parts and to reverse the effects of the deformation, giving the support and union needed between the various parts of the assembly.

7. Discussion

The methods presented above represent a set of actions that we consider as possibilities to help the correspondence between the digital model developed in a digital environment and its material formalization produced in ceramic through the LDM technology.

As a result of the methods implemented in order to control the behavior of the ceramic paste during the moments after the production, predicting and counteracting the deformations that it could suffer, we consider that, in the end, although there is no total correspondence between the final product and the model in which it is based, the methodologies presented constitute a positive starting point for mitigating the problems identified at the beginning of this article.

Assuming this as a continuous work that requires further in-depth studies we point to the future the introduction of additives (superplasticizers) that help control the plasticity of the ceramic paste while the amount of water present in the mixture is reduced.

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