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Publication date
2017

Published in
Proceedings of the IASS Annual Symposium 2017

Citation (APA)
Cruz, P. J. S., Knaack, U., Figueiredo, B., & de Witte, D. (2017). Ceramic 3D printing: The future of brick architecture. In A. Bögle, & M. Grohmann (Eds.), *Proceedings of the IASS Annual Symposium 2017: Interfaces: architecture.engineering.science* IASS.

September 25th - 28th, 2017
INTERFACES
architecture . engineering . science IASS 2017 hamburg

Proceedings of the IASS Annual Symposium 2017
"Interfaces: architecture.engineering.science"
25 - 28th September, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

Ceramic 3D printing – The future of brick architecture

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Abstract

The advent of Additive Manufacturing (AM) of ceramic, brought unprecedented possibilities for the building industry while exploring and incorporating components with specific design requirements. It definitively reshaped and expanded the boundaries of what's possible to achieve with masonry construction and opened new domains, with multiple angles of study and experimentation and with a large industrial potential.

This paper presents the main challenges and outcomes of an ongoing research project aiming to explore the integration of digital additive manufacturing techniques in the architectural design and production processes of free-form stoneware bricks for building envelopes. The project uses a clay extruding printer, Lutum®, built by the company Vormvrij available at the Advanced Ceramics R&D Lab, at the Design Institute of Guimarães and at Technische Universität Darmstadt. The path, material flow and printing speed of the printing process are defined digitally. The movement speed, extrusion flow and the air pressure can be controlled manually to adapt the specific printing process to the characteristics of the clay during the printing process itself. The widely accepted Pfefferkorn method has been extensively used to evaluate and control the plasticity of the stoneware used.

Keywords: Additive manufacturing, ceramic 3D printing, robocasting, clay extrusion, brick architecture, building envelopes, parametrical drawing, print resolution, material mixtures.

1. Introduction

The past decades have been by a rediscovery of architectural ceramics - a material system that has long served merely as a practical surface treatment for buildings, but that is now coming into its own as a multi-functional, intensely aesthetic boundary layer for buildings (Bechthold *et al.* [1]).

The possibility to additively produce ceramic components brings new opportunities for the building industry to explore the possibilities of incorporating components with specific design requirements (Knaack *et al.* [2]). This means that, the research path to define these innovative systems and production methodologies is still in an embryonic stage, but it will reshape and expand the boundaries of what is achievable with masonry construction. It will define new domains, with multiple disciplines with a vast industrial potential to be studied and experimented.

There are still challenges to overcome before mass customisation of ceramic components becomes an innovative technology in the building industry to: use of computational design tools regarding methodologies for the production of optimised customised ceramic building components by use of

Several measuring techniques and devices are available to determine the optimal water content in a clay body required to allow this body to be plastically deformed by shaping. The widely accepted Pfefferkorn method has been extensively used in this research to evaluate and control the plasticity of the stoneware used. It determines the amount of water required to achieve a 30% reduction in height in relation to the initial height of the test body under the action of a standard mass (Pfefferkorn [10]).

Measuring plasticity according to Pfefferkorn is based on the principle of impact deformation. A defined sample with a diameter of 33 mm and an initial height of 40 mm, produced either manually or by extrusion, is deformed by a free-falling plate with a mass of 1.192 kg (Figure 2). The initial height is related to the impact deformation height, the result of which is the ratio of deformation. As a rule, this measurement is taken with bodies with varying moisture content.

The results are expressed as graphs showing height reduction as a function of moisture content. The ratios of deformation or the impact deformation heights (H_0, initial height; H_f, final height) are plotted against the moisture content. The steeper the curve, the "shorter" the body, i.e. the more the body its plasticity reacts to variations of the moisture content.

The Pfefferkorn method was adopted to compare the plasticity of three different ceramic materials: Gres-130-MP, a ceramic paste normally applied in manual and mechanical processes, whose plasticity can vary from order to order [11]; Gres-Art13-AT, a powdered stoneware for processing into ceramic paste normally used for bonding ceramic pieces [12]; Creaton No. 208, a powdered stoneware for processing into ceramic paste normally used for manual and mechanical works [13].

To carry out the tests with the powdered stoneware samples, there was initially water added to the stoneware to obtain a water content of 20wt% in the mixture. The water content was slightly increased during the tests and three cylindrical specimens were made after water addition. The final height of each individual specimen was measured directly after each Pfefferkorn test. The weight of the specimens was also recorded before and after desiccating in an electric oven, to be able to calculate the moisture content of each specimen. The tests were carried out until the mean height of the samples decreased to 70% of their initial height (12 mm (30%) decrease of the initial 40 mm).

After performing the Pfefferkorn test (Figure 3), the pastes were used to print cylindrical specimens with the Lutum® equipment for quality perception at the printing level. Different results were observed for the three pastes used. The initial specimens manufactured with the Gres-130-MP paste presented cracks along the path of extrusion, which led to the addition of water to obtain a workable paste. An incremental addition of water resulted in the production of a series of specimens with different moisture levels, which demonstrated that a moisture content of 35% is best suited to obtain a printed surface of good quality. The Pfefferkorn tests performed on this mixture resulted in deformations between 5 and 7 mm, i.e. deformations between 12.5% and 17.5%.

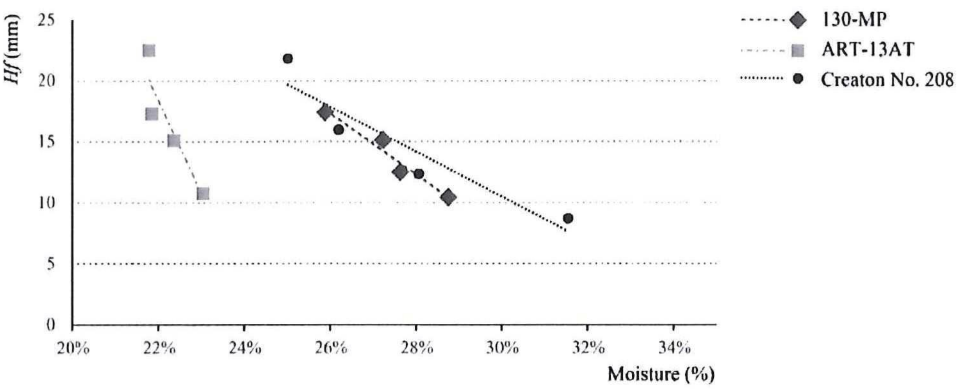

Figure 3: Pfefferkorn chart results

In the tests performed with paste Gres-130-MP the pressure varied between 3.5 and 4.0 Bar. The increment of pressure shows a tendency to augment the height of the printed models. Extrusions performed with higher pressure also result in specimens with larger overall width and thicker walls. This indicates that the auger has not enough internal resistance.

Table 1: Measurements of the printed models with paste Gres-130-MP, after the drying and firing process

Model ref.	Vel. (mm/s)	Press. (bar)	Layer (mm)	Height dried (mm)	Width dried (mm)	Thickness dried (mm)	Height fired (mm)	Width fired (mm)	Thickness fired (mm)
m1	20	3.5	1	18.76	38.57	4.68	16.47	36.04	4.13
m2	40	3.5	1	18.63	37.58	3.86	16.38	35.21	3.53
m3	80	3.5	1	18.44	36.94	3.72	16.35	34.80	3.30
m7	20	4.0	1	18.67	39.33	4.93	16.52	36.78	4.51
m8	40	4.0	1	18.54	39.29	4.86	16.45	36.72	4.47
m9	80	4.0	1	18.62	39.46	5.23	16.42	36.62	4.63
m4	20	3.5	2	18.71	36.61	3.59	16.52	34.18	3.12
m5	40	3.5	2	18.63	36.47	3.50	16.55	34.13	3.08
m6	80	3.5	2	18.62	36.31	3.47	16.52	33.92	3.31
m10	20	4.0	2	18.77	39.33	4.96	16.68	36.37	4.35
m11	40	4.0	2	18.80	38.87	4.81	16.77	36.08	4.32
m12	80	4.0	2	18.78	38.72	4.72	16.70	35.82	4.06

After testing printing processes with layers of 1 and 2 mm height, it was observed that specimens consisting of more layers (higher print resolution in Z direction) resulted in slightly lower objects. Therefore, specimens printed with fewer layers (lower print resolution of 2mm thickness in Z direction), have shrunk less, being closer to the height of the digital model.

The tests that were carried out suggest that for specimens composed with higher layers, the width and wall thickness decrease in dimension, despite being larger than the digital model.

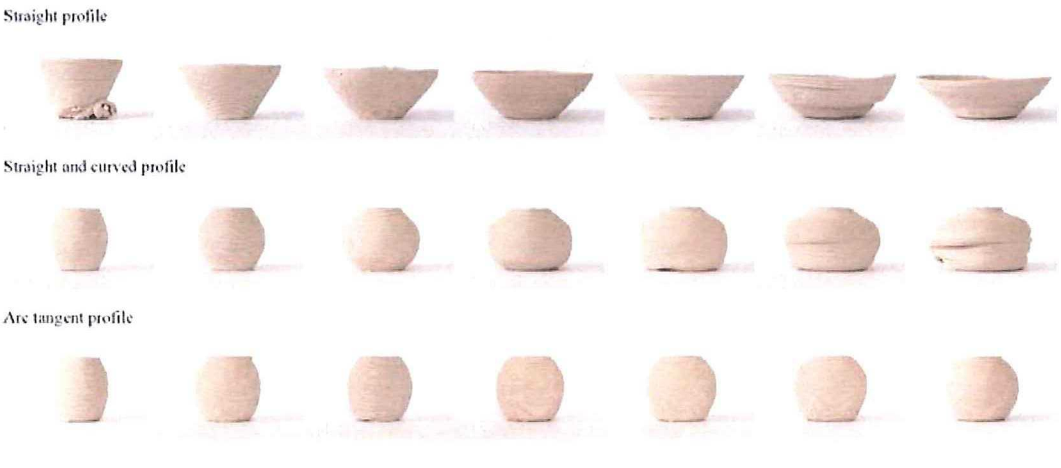

Figure 5: Three series of specimens produced to infer formal discrepancies between digital and printed model

To understand how the samples shrink during firing a volumetric measurement would be more accurate. Also the height is directly influenced by the amount of material extruded and the volume of the test sample. The material must have been flowing through the auger when the pressure is increased, making it hard to draw conclusions on the influence of speed alone.

In the specimens defined by straight profiles, convex deformations are also noticeable in the upper layers. In wider profiles, this effect also results in a form that can be best described as a sinusoidal curve. Such deformation is clearly perceptible in the specimens with 52.5° and 55.0°.

3.3 Deformation mechanism

As mentioned before multiple parameters play a role and not all of them were controlled during the tests carried out. The mechanism causing the deformation cannot be directly related to shrinkage caused by the evaporation of moisture if the parameter regarding the material displacement is unknown. The material displacement can influence the behaviour of the fresh extruded clay significantly. The force applied on the layers underneath is an influencing factor, for example, but also the dead load of the material itself. Nevertheless, the research on the deformation is very informative and indicates how to continue.

4. Digital models and AM of ceramic elements

As showed by authors such as Kolarevic [15], Oxman and Oxman [16], after the first thoughts and explorations on the role of digital tools in architecture during the last two decades, there is a significant evolution and number of researches on computation and digital fabrication tools in architecture. This evolution has been affecting the formal language of designs, their performative behaviour but also the materialisation of building components. Different terms have been used to describe the integration of computational models in architecture, which are linked to specific functionalities of these models. If the term "algorithmic design" refers to a broad notion on the use of mathematical methods, "generative design" and "parametric design" adds the notion of the possibility of computation to generate new design solutions, or a family of design solutions, by combining different parametric relations between design elements (Klinger and Kolarevic [17]).

4.1. Design customisation through computation

The implementation of computational models in the architectural design process made the customisation of design solutions composed of non-standard elements possible. For the materialisation of these solutions, in contrast to standard building systems, digital fabrication techniques allow and embrace the production of non-standard objects and components (structural, facade, etc.) – process known as mass customisation –, resulting in the possibilities of optimising variance in relation to pre-defined designed criteria (Kolarevic *et al.* [18]). More recently, the term form-finding is being applied to design processes that implement computational models to simulate and generate optimised design solutions regarding single or multi criteria goals. If in the past, design methods were supported by trial and error approaches, deductive reasoning and accumulated knowledge, form-finding processes are being used to improve the performance of buildings and their components (Oxman and Oxman [16], Kolarevic *et al.* [18]). In recent years, numerous developments in building materials properties are influencing the way architects, engineers and construction professionals foresee improvements in buildings performance (Aksamija [19]).

4.2. Free-form stoneware bricks

What differentiates the most digital controlled AM from mass production systems is the high level of customisation and formal freedom. If we imagine the process of designing and manufacturing a brick, AM is able of breaking with the assumption that the external shape of the brick mainly answers to geometrical requirements, while the inner structure assures the desired performance.

The research presented in this paper proposes an alternative methodology for the conception of this ceramic component. The experiments started with explorations that used a brick with standard dimensions as a reference in which an irregular free-form shape was defined. A set of computational

By following the same procedure, data such as the velocity along the extrusion path, speed of additional traveling paths (non-extruding movements) and the extrusion flow is added to the initial G-Code script. The visual control of these data strings allows to assign different printing speeds and flows to different parts of the geometry efficiently, i.e. to assign variations on the finishes and to control the material placement in the overhangs.

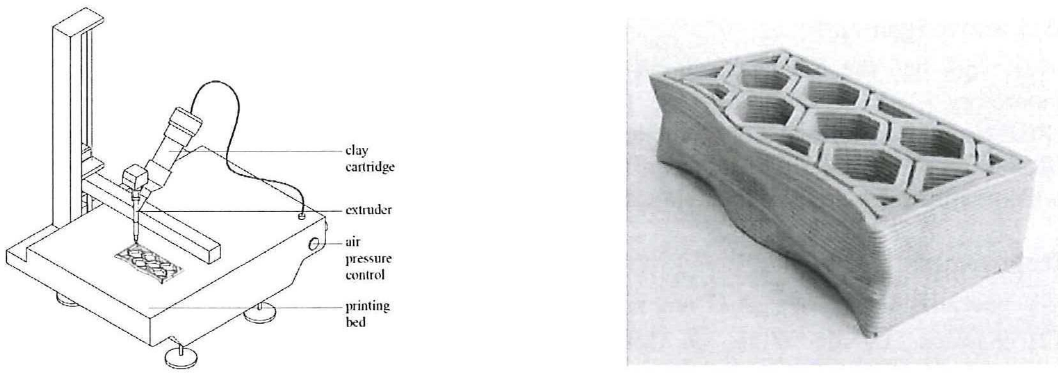

Figure 9: Lutum® 3D clay printer schema and a printed free-form stoneware brick with hexagonal inner structure

5. Conclusions

As referred to, the aim of this paper is to present the three main contributions of the ongoing research on the integration of AM techniques in the design and production of free-form stoneware bricks for the built environment.

The Pfefferkorn test showed to be an adequate process for the systematisation of the knowledge of ceramic material properties concerning the inference of the proper plasticity for optimal results in AM processes, for the Lutum® 3D clay printer used at both institutes. Tests with three different ceramic materials were presented. Printing tests with the Gres-130-MP ceramic paste suggested that a moisture content of approximately 35wt% — representing a deformation between 12,5% and 17,5% in the Pfefferkorn test — is appropriate for reaching an homogenous and smooth printed surface with the hardware used.

By printing a series of specimens from the same cylindrical digital model and by varying the parameters that control the 3D printer within these series, it was possible to clarify the settings of these parameters that result in more significant deviations between the digital and printed models. In summary, it has been suggested that: an increase in extrusion velocity decreases the height, width and wall thickness of the models; in contrast, incremental change in pressure results in higher, wider and thicker specimens; the height, width and wall thickness of specimens printed with less (but thicker) layers are more similar to the digital model, moreover the finishing surface being less smooth than specimens printed at a higher resolution in Z direction which results in thinner layers.

A series of specimens was produced with the aim of inferring geometrical constrains and formal deviations of the printed models. As synthesis, the results suggested that geometries with constant curvatures are more accurate and profiles with more than 40° of inclination result in major deformations of the shape.

Although influences of differentiating pressure and print speed were noticeable, material displacement needs to be controlled and measured in the next experiments, to obtain accurate information on the mechanism that causes the shrinkage.

Finally, a computational workflow has been described to control the design and fabrication of customised free-form stoneware bricks in an AM production process. The workflow considered both,