Additive Manufacturing of Ceramic Components for Façade Construction

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Abstract

Additive Manufacturing (AM) opens new fields of research and development in the architectural design and construction industry, enabling a geometric freedom that can result in the design of components with specific requirements and multifunctional behaviours.

This work explores the integration of digital design tools and AM extrusion processes on the production of ceramic architectural components for façade construction, reshaping and expanding the boundaries of what is possible to achieve with masonry construction in a wide range of applications (opaque walls, ventilated sunscreens, and shading systems).

Several stoneware prototypes were developed, encompassing different challenges such as the morphology customisation, the versatility of use, the exploitation of the maximum degree of curvature, and the optimisation of structural patterns.

Keywords
Additive manufacturing, 3D-printing, digital fabrication, ceramic components, façade construction

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1 INTRODUCTION

One of the first references to the potential of Additive Manufacturing (AM) in Architecture arose in the mid-1990s under the term 'Incremental Forming' (Mitchell & McCullough, 1997). Often referred to as 3D printing, AM consists of the production of objects through the successive addition of layered material, resulting in a sustainable and a very cost effective method, due to the fact that material is deposited only where required. This is in contrast to subtractive processes or traditional casting and moulding techniques, which, in addition to producing a high degree of waste of raw material, do not benefit customisation.

The advent of AM opened new areas of research in architectural design, construction materials, and in the building industry. Moreover, when combined with computational design and simulation tools, their potential is exponential, namely by enabling a broad geometrical freedom that can result from specific design requirements, design optimisation, and challenging functions (Sarakinioti et al., 2020).

Regardless, the debate between the direct application of AM on site and the production of discretised architectural components for subsequent assembly on site, the commercialisation of houses built through AM is already a reality (Castañeda, Lauret, Lirola, & Ovando, 2015). Just as AM was highlighted as a key technology that accelerated the transformation of the manufacturing industry towards Industry 4.0, it is expected that within the next decade an increase in successful integrations of AM in the building industry will constitute a revolution in development strategies in the built environment.

A first set of experiments in AM for the building industry was mainly focused in cementitious materials (Khoshnevis, 2004). The ability of transposing AM techniques to the scale of the building represents a major issue for its application to the construction industry. In this sense, the main constraints are the dimensions and mechanisms of the extrusion apparatus and the reaction of the material. The principle of depositing the layered material assumes that the manufactured object fits within the working area of the 3D printer. For this reason there are two approaches that can be taken: (i) Continuous deposition manufacturing – Scaling the printing apparatus; (ii) Manufacture of discrete elements – Scaling the components to the available print area.

In a report entitled 'Shaping the Future of Construction', the World Economic Forum discussed the 'future impact' and the 'likelihood of new technologies', based on the results of the 'Future of Construction Survey' (World Economic Forum, 2016). According to this study, the 'contour crafting of buildings' is not likely to occur and its impact is considered low. The likelihood and impact of '3D printing of components' and 'advanced building materials' is considered to be moderate and that of 'prefabricated building components' is extremely high. This fact justifies why many research groups and corporations interested in testing AM technologies in the construction industry end up following a line of thinking that is based on discrete elements. In this approach, instead of requiring a machine that provides a larger work area than the building to be built, it is proposed to adjust the size of the different parts according to the physical characteristics of the machinery (the 3D printer work area, the size of the kiln if necessary, etc.).

As Mario Carpo (2019) points out, 'instead of printing bigger and bigger monoliths, it may conceivably be easier to start with any number of parts, as many and as small as needed', leaving the correct positioning and assembly of the parts to another machine.

In this way, there is an approximation of traditional building systems based on three factors: (i) the various constituent components of the building are prefabricated with smaller dimensions; (ii) transportation to the work site; (iii) assembly in their positions, creating larger structures.

Ceramic materials are a natural resource with unique properties whose application goes back to the prehistoric age, to the first attempts of man to provide his own shelter. Features such as hardness, density, durability, and the possibility of having a vast number of shapes and finishes, make the application of this material in buildings widespread. The history of architecture and construction is inseparable from the history of ceramics, a key material for the manufacturing of masonry, cladding, and pavement and roof components.

Several protagonists of the architectural vanguards of the twentieth century explored the use of ceramic materials in a multiple range of innovative design languages.

The striking façade of the Fagus-Werk Factory, in Alfeld an der Leine, Germany, an early expression of Modern Architecture, designed in the 1910s by Walter Gropius and Adolf Meyer, masterfully combined brick masonry walls with steel-glass curtain walls, a harbinger of the later so-called 'new objectivity' of Bauhaus architecture (Ramcke, 2001).

With the modernist movement in the early twentieth century, ornament went out of fashion among many architects. However, in the 1920s, primarily in Germany and in the Netherlands, the 'brick expressionism architecture' used bricks and tiles as the main visible building material to create ornamented buildings with a rounded or organic appearance that was simultaneously completely modern (Boëthius, 2019).

In the middle of the twentieth century, Alvar Aalto recurrently used brick masonry: Baker Dormitory in Cambridge, 1947-48; or the Saynatsalo town hall, 1949-52. His predilection for ceramic materials was extended to the design of ceramic glazed tiles to solve specific functional aspects, formation of corners and skirtings, such as the round curved tiles used for pillar cladding in the Helsinki University of Technology (1953-66) or the wedge-shape brick that he devised for the wall of the House of Culture in Helsinki of 1952-58 (Pallasma, 1998).

In the post-war period, a critical examination of the Modern Movement will find an important resource through the observation of local architecture. Kenneth Frampton (1980) celebrated it as critical regionalism due to the dialogue between Modern abstract forms and traditional construction techniques. One of Frampton's references is the work of José Antonio Coderch, namely the 'modern brick vernacular first formulated in his eight-storey ISM apartment block built in Barcelona' in 1951. Yet, in Ugalde House, built in 1952 at Caldas de Estrac, one of the most renowned projects of the Catalan architect, the local cultural identity was introduced through the use of the traditional *baldosín* ceramic tiles in the floors (internal and external) and roofs combined with a more abstract expression of curved white walls.

Frampton also considers the work of Mario Botta an expression of critical regionalism. The Swiss architect, who worked for Louis Kahn for a short period, is known for his draughtsmanship that manipulates geometry at small and large scales. He often uses bricks as a covering material to poetically underline the severity of strong volumes, yet which are based on very simple shapes.

It is worth mentioning the proposals of Eladio Dieste, in the 1960s and 1970s, for thin shell vaulted systems made from brick and ceramic tiles. The use of this 'reinforced masonry' structure in Gaussian vaulted roofs allows for the achievement of spans up to 50 metres (Dieste, 1996). In this period, the Uruguayan engineer and architect designed several buildings in Montevideo (warehouses, a gymnasium, and silos plant) and a Market in Porto Alegre (Brazil) that even today represents some of the most challenging applications of ceramic building components in structural design.

In the 1960s, Marcel Breuer, despite being one of the masters of brutalist expressionism in concrete, designed terra-cotta flue tiles to produce sunscreens for Hunter College's uptown campus façades, today known as Lehman College (Bergdoll & Massey, 2011).

Louis Kahn, often called 'the brick whisperer', believed that materials had a stubborn sense of their own destiny. His design for the Indian Institute of Management in Ahmedabad, built between the 1960s and 1970s, embodies this notion of geometry as a key principle for the consistent and systematic quality of his work and provided an order for the formal expressions that encompass both composition and construction (Park & Baldanchoijil, 2014).

The possibility of additively producing ceramic components brings new opportunities for the architecture and building industry, opening new compromises between the use of a low-cost high performance material and the execution of complex geometries and multifunctional products, impossible to obtain using any other traditional production process (Cruz, Knaack, Figueiredo & Witte, 2017).

One of the merits of AM is the rediscovery of some of the functions that ceramic products had in traditional construction systems. An example of this is the use of binder-jetting ceramic powder for the development of a nonstandard ceramic brick system, similar to cinder blocks, for the assembly of freeform ventilated façades whose connections were inspired in traditional wood joinery techniques requiring no additional adhesives or mortar (Sabin, Miller, Cassab, & Lucia, 2014).

In this context, also deserving of a mention is the porous 3D-printed ceramic masonry system for passive evaporative cooling in buildings. Inspired by the Muscatese evaporative cooling window, it combines a wood screen and a ceramic vessel filled with water (Rael & San Fratello, 2018).

The potential for producing a customised design with a standard desktop 3D printer with a modified extrusion head for earthenware ceramics has been illustrated with a series of ceramic modular block systems for interior and exterior walls, columns, vaults, and sun shading (Peters, 2014).

The work presented in this article aims to enhance the exploration of morphological, technological and functional aspects of ceramic façade components, encompassing the following objectives: delving into different approaches for the discretisation of irregular surfaces in uniform and nonuniform components; assessing the potential of AM techniques; expanding the functionalities of ceramic components beyond their conventional architectural uses; proposing new systems and developing innovative architectural components.

The fulfilment of these objectives provided new insights to be integrated into the project practice and contributed to add value to ceramic products and the ceramic industry.

2 METHODOLOGY

This work follows a methodology centred on three key aspects that are interrelated and fundamental to an effective application in a real context: (1) controlling the ceramic material properties critical to AM processes; (2) optimising the extrusion process of ceramic materials; (3) exploring the restrictions to free-form geometries.

2.1 MATERIALS

Ceramic can be considered the first human-designed material, as opposed to materials directly extracted from nature and shaped for specific uses such as wood and stone. The word derives from the Greek words *keramos* or *keramikos*, meaning the product of the potter's art.

The most common clay bodies for architectural ceramics - mixes of different clays and additives - are earthenware, stoneware, and porcelain.

Earthenware, including terra cotta, is a low-fire clay body with relatively large particle sizes that is frequently used for tiles and bricks. A wide range of raw materials can be added to the clay body in order to improve workability, such as: quartz sand, shells, calcite, mica, crushed rocks, and volcanic ash.

Stoneware is composed of finer particles and exhibits better mechanical properties and a lower porosity (Martín-Márquez, Rincón & Romero, 2008; Gualtieri et al., 2018). It is commonly used for architectural tile applications and for façade elements (Gualtieri et al., 2018; Rambaldi, Pabst, Gregorová, Prete & Bignozzi, 2017; Ribeiro, Ferreira & Labrincha, 2005). Porcelain is a white kaolinite body, fired at the highest temperatures, and usually fully vitrified, resulting in a non-porous homogenous product with extremely low water absorption. Table 1 presents a basic comparison of the most common clay bodies for architectural ceramics.

TABLE 1 Basic comparison of most common clay bodies for architectural ceramics.

CLAY BODY	DESCRIPTION	FIRING TEMPERATURE
Earthenware	Porous, soft paste; contains added raw materials to improve workability and firing	500 - 1200°C
Stoneware	Hard and compact, not porous. Rough texture and usually grey in colour	1200-1350°C
Porcelain	Very hard and compact. Glass like, white to bluish white in colour	1300-1450°C

Earthenware is less dense than stoneware, which in turn is less dense than porcelain. The density is related to the amount of water that can be absorbed and consequently determines the absorption range of the unglazed fired ceramic. The less dense the ceramic the higher the absorption rate and the greater the porosity. Usually, low-density clays do not vitrify when fired. Clays of high densities can become vitreous and resistant to water infiltration, increasing the resistance to freeze-thaw cycles.

The transformation from clay - predominantly composed of alumina, silica, and water - to ceramic occurs during the firing process. Firing changes the material composition at a micro level as particles are sintered and permanently bonded. Material properties are altered substantially in the process, producing a harder, durable, and water-resistant matter. The process of firing is a complex balance of heating and cooling that must be precisely controlled to achieve the desired quality (da Silva, Feltrin, Dal Bó, Bernardin, & Hotza, 2014; Gültekina, Topateşb, & Kuramac, 2017).

A kiln schedule consists of a ramping-up period in which the temperatures are slowly increased. Following the ramp phase, the ceramic pieces remain at a constant firing temperature for a prescribed duration, then enter a controlled cooling cycle in which the ceramic element returns to room temperature. Rapid temperature fluctuations may result in cracking of the ceramic pieces.

Once the clay body has been formed it dries to the 'green state', either naturally or through more controlled, machine-based drying processes such as with universal ovens. During drying and subsequent firing, shrinkage occurs as moisture is removed (Ribeiro, Ferreira & Labrincha, 2005; Oummadi et al., 2019; da Silva, Feltrin, Dal Bó, Bernardin & Hotza, 2014). Raw material properties such as particle size and moisture content impact shrinkage rates. The smaller the particle size and greater the moisture content the higher the shrinkage rate.

Industrial clay extrusion is a medium to high volume manufacturing process that, compared to dry-pressing, offers better potential for shape customisation. It is a 'wet' process used to form clays with a moisture content ranging between 16% and 23% (Ribeiro, Ferreira, & Labrincha, 2005). During extrusion, a large lead screw system forces clay through a vacuum chamber and through a shaping die, resulting in linear parts that have a constant cross-section (Ribeiro, Blackburn & Labrincha, 2009; Guilherme, Ribeiro & Labrincha, 2009).

Shrinkage rates vary between clay bodies, from approximately 8% to 12% (to the referenced moisture percentage). Approximately half of the overall shrinkage occurs during drying, when moisture evaporates from the surface (Martín-Márquez, Rincón, & Romero, 2008; Gültekina, Topateşb, & Kuramac, 2017). Water moves from the centre out through capillary action. Additional shrinkage, typically 50% of the overall rate, occurs during firing when particles are sintered or bonded together, and all remaining chemical moisture is released from the clay body. Shrinkage during firing impacts all clay bodies. This causes 'differential shrinkage', which can result in warping and even cracking as outer surfaces dry faster than the core material.

In a flat or linear product the dimensional changes due to shrinkage can be easily compensated by oversizing it. In a product with a complex geometry, this compensation is not straightforward.

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, 1924).

Brittleness and vulnerability to crack propagation should be properly considered when conceiving a ceramic product. Designers should avoid creating areas of high stress concentration, which include drastic changes in wall thickness, sharp edges, openings, localized fasteners, acute corners, and non-filleted intersections.

The mechanical performance can be tailored by combining the appropriate clay body with additives. The addition of cellulose or nylon fibres increases the 'green strength' of the dried clay before firing, reducing or even avoiding shrinkage induced cracks. These fibres have little impact on the properties of the finished part because they burn away during firing.

Usually, clay bodies fired at higher temperatures, up to 1300°C, exhibit higher strengths than those fired at temperatures as low as 1000°C. The strength and porosity of stoneware clay bodies are modified by varying the kiln schedule.

Fig. 1 shows a wide range of specimens recently produced at the Advanced Ceramics R&D Lab (ACLab) of the Design Institute of Guimarães (IDEGUI) using a wide range of ceramic pastes (stoneware, porcelain, and refractory clays), fired at different maximum temperatures of 700ºC, 900ºC, and 1050ºC (Ribeiro, 2020). It is perceptible how the firing temperature affects the final colour.

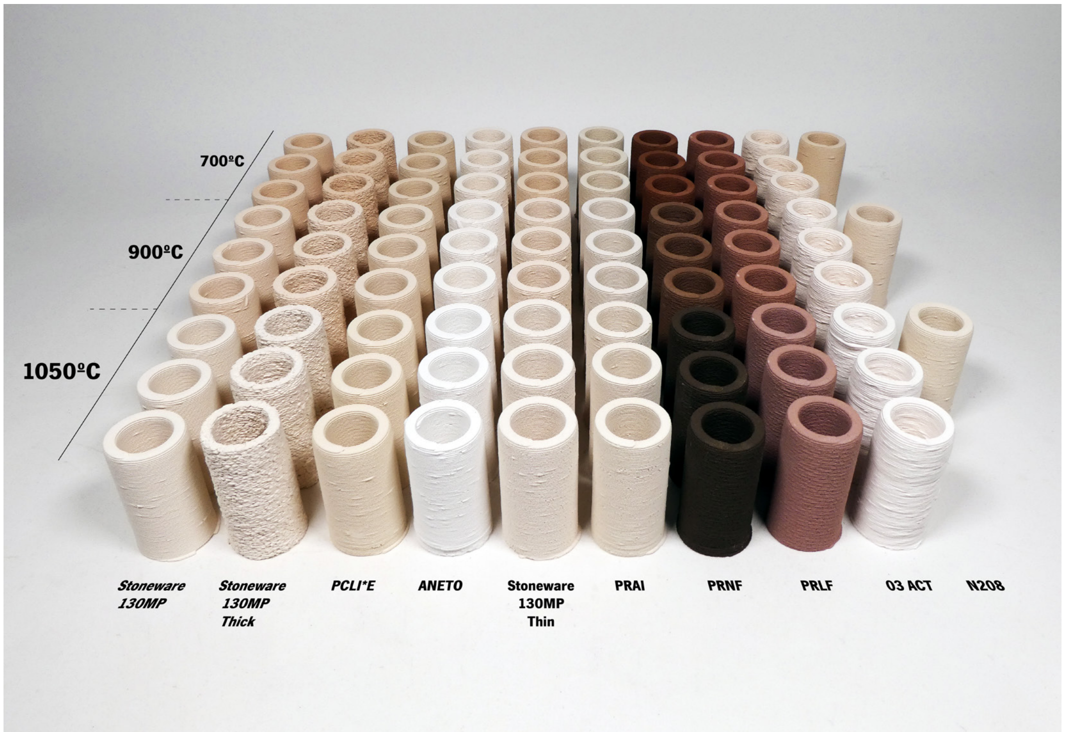

FIG. 1 Specimens produced with stoneware, porcelain and refractory clays after firing at different maximum temperatures of 700ºC, 900ºC, and 1050ºC.

Stoneware usually exhibits a high compressive strength and behaves poorly under tension.
A previous experimental research was performed by testing a set of specimens until compression failure, at the Materials Laboratory of the Civil Engineering Department of the University of Minho, using a hydraulic test machine with 5000 kN capacity (Cruz, Camões, Figueiredo, Ribeiro, & Renault, 2019). The tested specimens comprise manually extruded cylindrical pieces (solid) and cylindrical models produced by AM with the same dimensions (from a single thin wall to a solid model).
The mean value of the compressive strength of the first set oscillated between approximately 200 MPa, for smaller specimens (60mm height by 30mm diameter), and 100 MPa for the bigger ones (120mm height by 60mm diameter). The second set presented an average compressive strength

that ranged between ≈ 77 MPa (for tubular specimens with one thin wall, 60mm height by 30mm diameter) and ≈ 136 MPa (for tubular specimens with three concentric walls, 120mm height by 60mm diameter). The lower values obtained for the one-wall specimens makes evident the excessive slenderness of the thin wall.

The research also carried tests on the compressive strength evaluation of a set of bricks produced by AM (Fig. 2) with dimensions of 100 x 200 x 50 mm. Each brick was composed of 34 horizontal layers, 1.5 mm high and approximately 5.0 mm wide. The external and internal brick walls were composed of two parallel extrusion paths; since the extrusion nozzle has a diameter of 3 mm, the walls thickness is approximately 6 mm. The goal of these tests was to infer the influence of the internal structural design for similar void ratios. Nevertheless, this study concluded that the obtained compressive strength ranges (between ≈ 87 to 111 MPa) denote proper mechanical behaviour for the architectural ceramic bricks wall construction.

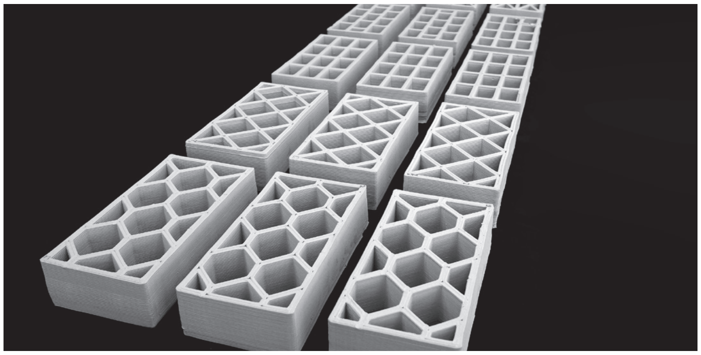

FIG. 2 Different internal structural patterns.

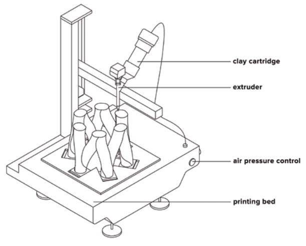

FIG. 3 Lutum® ceramic printers available at the Advanced Ceramics R&D Lab (ACLab).

2.2 PASTE EXTRUSION

The stages of industrial production processes related to architectural ceramics include the creation of the clay body, followed by shaping, drying, firing, post-processing, and packaging. High-tech industrial automation may boost/improve productivity by combining those stages.

Clay is usually extruded through a die in a final cross-sectional shape. A medium production volume, in the thousands of units, is typically needed to offset the costs of designing and making the dies (Bechthold, Kane, & King, 2015). Once shaped, the material is cut to length using an automated wire or blades that move perpendicular to the axis of extrusion.

Although extruded products usually show only one finished surface, some producers prefer to create high-quality surfaces on all sides of the product. To ensure that complex units retain their shape without warping, additional features may be added to unsupported areas. Manual or automated processes after final firing stage may break away additional geometries.

The extruded parts of many architectural applications are usually moulded with engravings, such as slots and grooves, which may help the element to be hooked into metal substructures during installation.

Another manual process is the craft-based extrusion, although it is not commonly used due to the fact that the resulting elements are much less accurate than industrial processed ones. Custom extrusion dies are low cost in terms of tools as they use metal or wood among other materials.

Some factories combine industrial manufacturing with craft-based production methods. Such hybrid production settings have a high potential for customisation of project-specific ceramic systems and often modify their standard clay bodies to meet the performance requirements of a certain project.

The possibility of additively producing ceramic components brings new opportunities for the building industry to explore the possibilities of incorporating components with specific design requirements. 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 it's possible to achieve with masonry construction and opened new domains, with multiple angles of study and experimentation, and with great industrial potential.

Since 2016, clay extruding printers are being intensively used in the ACLab (Fig.3). The extrusion path, material flow, and printing speed of the printing process are digitally defined by a computational model. 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. Print speeds are tuned, taking into consideration the viscosity of clay, specific object design, and layer/nozzle size, with speeds ranging from 20 mm/s to 100 mm/s.

2.3 DESIGN

The integration of AM in the production of architectural ceramic components requires a prior definition of strategies to be adopted in the design process. In the context of ACLab activity, computational design tools perform a key role in the different stages of that methodology.

A first step is the enhancement of the process of morphogenesis, comprising the use and combination of appropriate tools for: the parametric design; the form-finding process; and performance optimisation (Fig. 4 & Fig. 5).

A second feature is the implementation of design rules that automatise the discretisation of building envelopes, from the most conventional rational geometries to the most complex free-form surfaces. This rationalisation of the design processes allows for the definition of customised cladding systems in accordance with functional performance, while also considering material and manufacturing constraints - the Hive Wall (Fig.14) and the Hexashade Vault (Fig.18) exemplify this approach.

Other discretisation design strategies are characterised by the minimisation of the type of architectural components that define a construction system, relying on the combinatorial possibility of connections to configure different architectural objects - S-Brick (Fig.9) and V-Brick (Fig.11) follow those design principles. Their design is focused on the interconnection possibilities that aim for a capability to disassemble and re-assemble the same masonry system in multiple formal configurations.

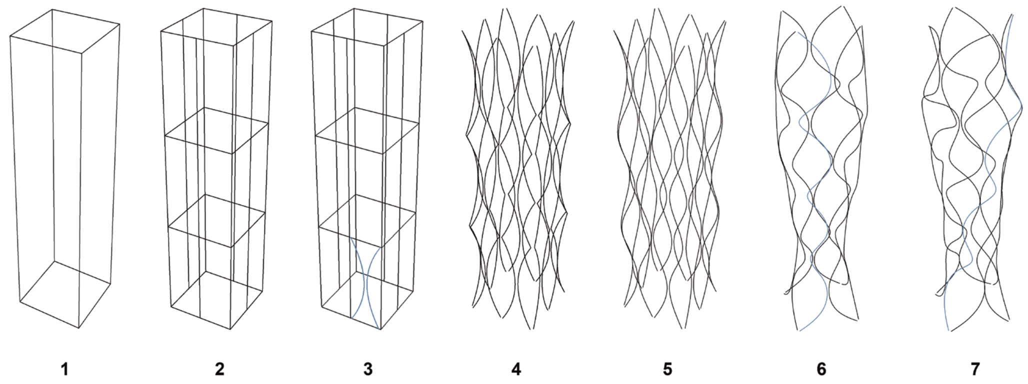

FIG. 4 Ficus Column, different stages from the design process testing different design solutions through the use of parametric design and form-finding techniques. Stages: [1] Base shape. [2] Shape division. [3] Pattern definition. [4] Recursive application. [5] Pattern smoothing. [6] Section variation. [7] Section rotation.

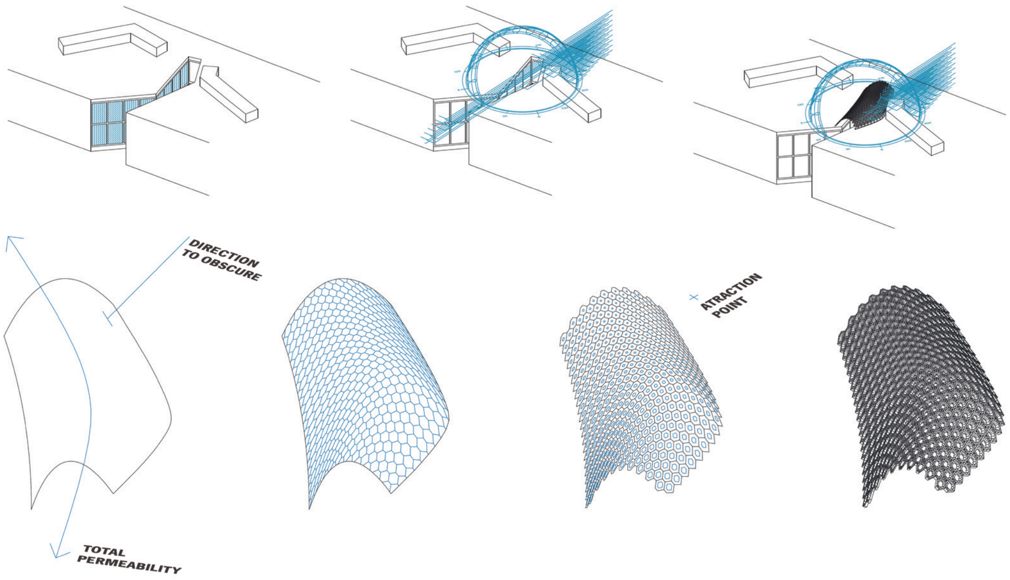

FIG. 5 Hexashade project. Schema of the vault design process considering solar analysis of a glazed surface to optimise a shading hexagonal grid (top illustrations). It also presents the discretisation process of the vault in non-regular hexagonal blocks (bottom illustrations).

Thirdly, the possibility of assembling customised solutions is made possible by the design of adaptable connection systems. In order to accomplish this goal, two design approaches have been tested. In the first, a direct fit of the components is envisaged through interconnecting surfaces. Here, the design of the fitting system is fully parametrised in correlation to the overall shape of the architectural object - Hexashade Vault (see the brick side surfaces, Fig.17). The second approach considers the design of hybrid systems. AM has the potential to allow for the production of complex geometries that are relatively difficult to assemble via conventional methods or interconnections. The integration of external connectors enables the production of complex parts as fully functional assemblies. To create a fully functional prototype, it is possible to manufacture an object up to a certain level, place all the other elements (e.g., polymeric, metallic or other components) and resume the manufacturing process - V-brick wall (Fig.12).

Finally, a seamless framework between the initial design stage and the building stage can be achieved because the design process is developed in a continuous computational environment. Computational models generate the formal definition as well the instructions for the production machinery (G-Code), providing a direct translation of design intentions and avoiding the traditional design interpretation by third parties. This methodology allows for the extension of the morphogenetic design principles to the digital manufacturing technology and respective material constraints. One of the main benefits related to computational design and AM is the enabling of a shift from conventional design methodologies to processes such as Design for Manufacture (DFM) or Design for Assembly (DFA).

3 PROTOTYPES

A set of prototypes of free-form stoneware components was developed to illustrate the wide range of possibilities they open for façade construction. They give an insight into the potential conferred by the chance of customising and optimising their shape and function. In fact, the production of most of those free-form components would be impossible with any traditional manufacturing technique, namely by conventional industrial extrusion process, using a die with a regular cross-sectional shape.

The design principles always focus on a clear response to very specific problems that we think are relevant to future works and to the effective implementation of this production method and material. Each developed prototype has a specific purpose of exploring and combining different attributes and challenges related to AM: (1) The noteworthy inclination of some extruded contours, evident in the Wave wall bricks and in the Hexashade blocks; (2) The interlocking possibilities conferred by V-Bricks, Hive wall bricks, and Hexashade blocks; (3) The versatility of some components, allowing their combination in different orientations, highlighted by S-Bricks, V-Bricks, and Kusudama blocks; (4) The customisation of their morphology and functionality, e.g. the optimisation of their permeability and degree of shading (Hive wall bricks, Hexashade blocks, and Kusudama blocks). Table 2 summarises the main characteristics of the six prototypes.

TABLE 2 Prototypes characteristics.

	WAVE	S-BRICK	V-BRICK	HIVE	KUSUDAMA	HEXASHADE
Façade cladding	•	•	•	•	•	
Ventilated sunscreen		•		•	•	•
Opaque wall	•	•				
Vault shading system						•
Maximum degree of vertical curvature	•					•
Customisation of morphology and functionality				•	•	•
Optimisation of internal structural pattern	•				•	•
Layering in different orientations		•	•		•	
Interlocking			•	•		•

3.1 WAVE WALL

Wave wall project consists of a computational model and AM prototype that proposes a system of ceramic components for façade masonry. Wave wall has the specificity of formally exploiting the maximum degree of vertical curvature of the external face that stoneware extrusion is able to perform without collapsing.

The research project comprises the design and production of a full-scale prototype of a façade masonry system (100cm x 50cm) with 50 components, all of them different. A block with standard measurements (210x100x50mm) was used as a reference in which a free irregular shape was defined that configures its external surface.

The internal structural pattern was studied and found to be the most efficient pattern possible, allowing the correlation of the heat conduction between the two exposed faces and their mechanical performances. For this end, several patterns were considered and for each some variables were defined that can be parametrically controlled, such as the number of cells in U and V directions, the thickness of the cells walls, and the pattern's ability to adapt or not to the external shape of the brick.

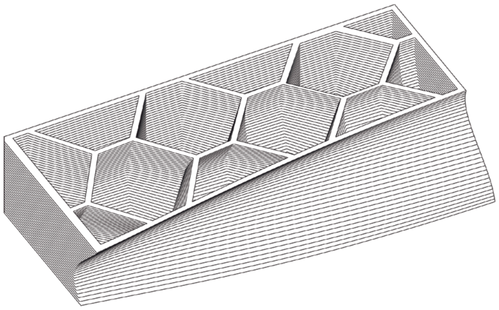

FIG. 6 Wave wall brick extrusion path model.

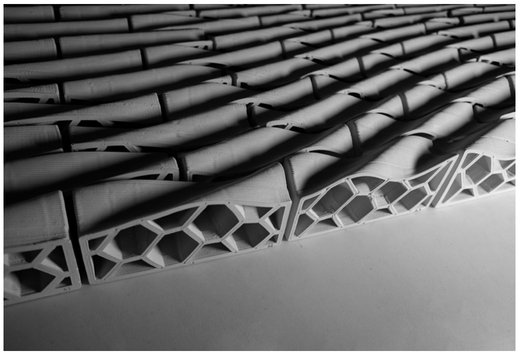

FIG. 7 Wave wall prototype.

3.2 S-BRICK WALL

S-Brick prototype explores the design of bricks whose two larger faces are composed of double curved sinusoidal surfaces. It also takes advantage of AM for the customisation of the brick's inner structure by testing s-shaped curved configurations. These features allow its layering to be done in two directions resulting in walls with different design and functions.

If the bricks are assembled in the extrusion direction it might result in an opaque wall with a corrugated pattern. If layered lying down, a ventilated sunscreen wall is obtained. In this solution, the sinusoidal profile also facilitates the connection between the different layers of bricks, blocking each component in its correct position.

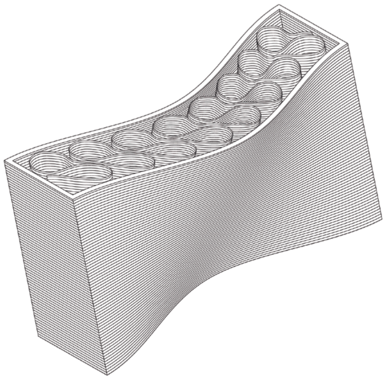

FIG. 8 S-Brick extrusion path model.

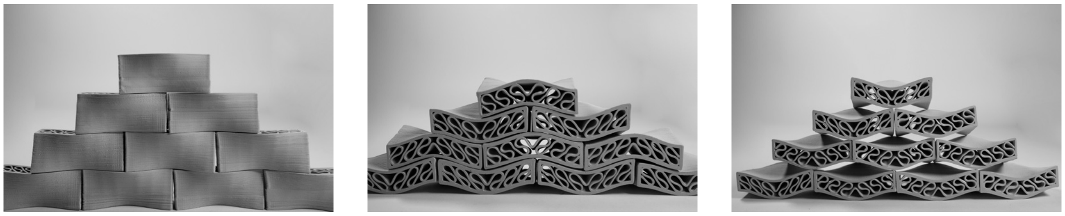

FIG. 9 S-Brick wall prototype variants.

3.3 V-BRICK WALL

V-Brick wall project aimed to explore the discretisation of architectural structures, such as walls, in ceramic blocks through the use of parametric design tools and AM processes. The focus was mainly on the development of innovative design solutions for the joints and interlocking strategy for a freeform design approach.

To augment the degree of morphological freedom, two block types of 50 mm high were developed: block A, which allows the construction of linear walls, and block B which enables a 60° rotation of the walls. The block's design provides a self-interlocked joint which eliminates the need for third-party assembly elements. In fact, there are two grooves on the bottom of the outer wall, seeking a male-female connection, which enabled the structure's construction by simply stacking the blocks.

The external walls of the blocks are composed of two contour surfaces. It was proposed to use a truss-like internal structure to increase the bricks' structural strength, while also optimising the process of continuous material deposition that is performed in AM, and avoiding any undesired superficial deformation.

Finally, as illustrated in Fig. 12, V-Brick blocks have also been used to test the possibility of incorporating AM polymeric reversible fittings, with or without magnets embedded, facilitating quick assembly (Sampaio et al., 2019).

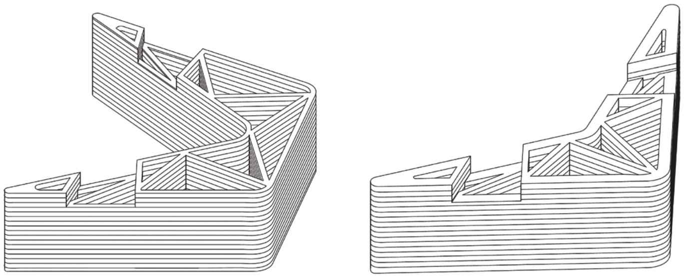

FIG. 10 V-bricks extrusion path models.

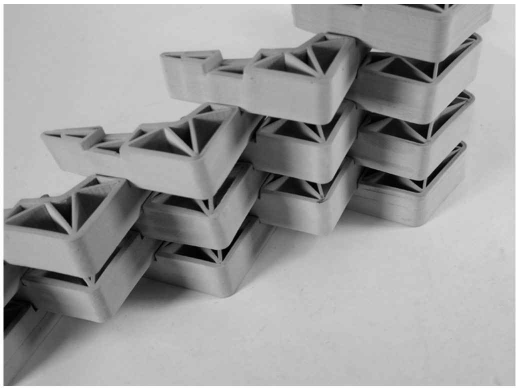

FIG. 11 V-brick wall prototype.

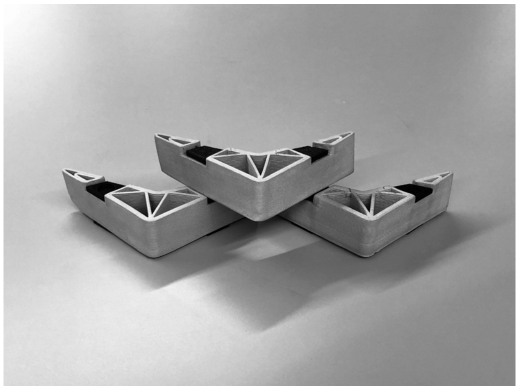

FIG. 12 V-Brick Wall with polymeric connectors and magnets.

3.4 HIVE WALL

Hive wall experiments with the capabilities of AM processes to demonstrate the potential of the architectural application of non-standard ceramic components for façade cladding. The challenge was to define a system for ventilated walls in which the size of the openings is customised, allowing wider or narrower openings in accordance with the need for ventilation, shadowing, or desired visual constraints. The blocks' apertures and geometry are composed of three non-uniform truncated pyramids produced with stoneware.

The assembly comprises horizontal layering that is facilitated by the trimmed formal configuration of the bricks that result in a stable interconnecting and docking system. The prototype corresponds to a section of approximately one square metre, composed of 57 bricks of 10 cm depth, in which the central point corresponds to the maximum opening of the wall, which progressively decreases towards its limits.

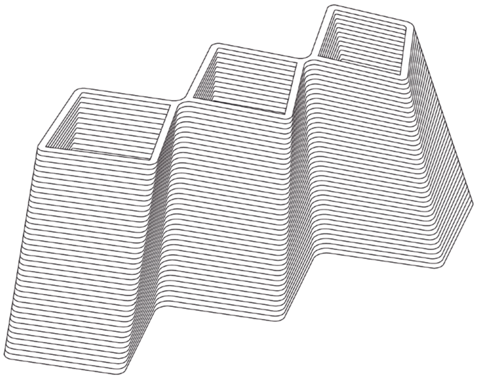

FIG. 13 Hive-brick extrusion path model.

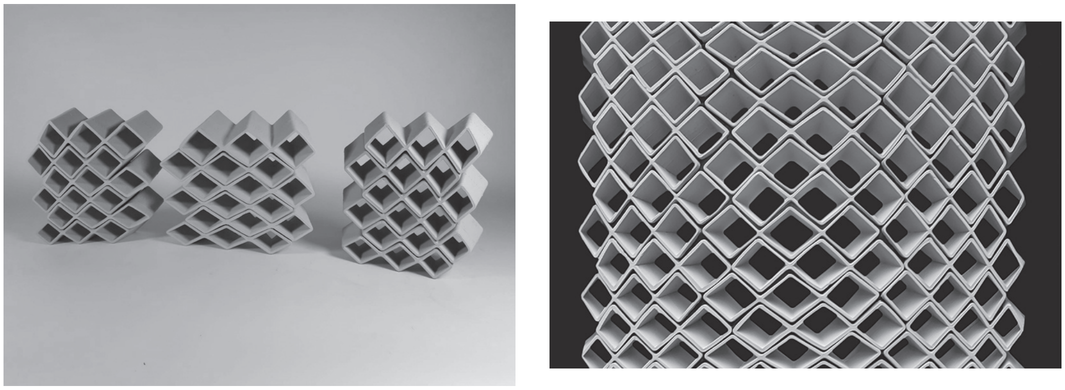

FIG. 14 Hive wall prototype..

3.5 KUSUDAMA WALL

Kusudama wall prototype resulted from research that aimed to explore the use of cellulose to produce architectural components by AM. After an initial evaluation of 3D printed specimens produced with cellulose and composite materials, mixing different percentages of cellulose with different percentages of water, starch, sawdust, and ceramic paste, a set of mixtures was selected in order to produce a reliable prototype wall that expressed the different behaviour and tectonics of those materials - the Kusudama wall.

The design solution was achieved through the use of a parametric design model, envisaging a customised set of hexagonal blocks. Two types of blocks were made from a regular hexagonal grid; the first consisted of a triangular interior opening and the second one consisted of a pentagonal interior opening. The heights of the hexagonal external wall and pentagonal internal wall are 50 mm and 100 mm, respectively. The hexagon is circumscribed in a circle with a diameter of 170 mm.

From the material perspective, the use of a small percentage of cellulose, and other additives of stoneware mixtures, shows a substantial improvement in mechanical performance during the drying and firing stages.

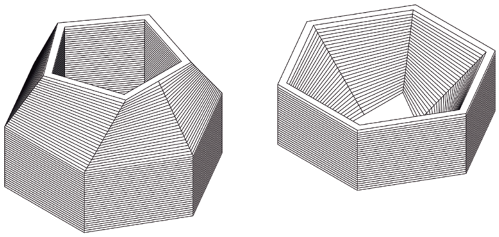

FIG. 15 Kusudama-brick extrusion path models.

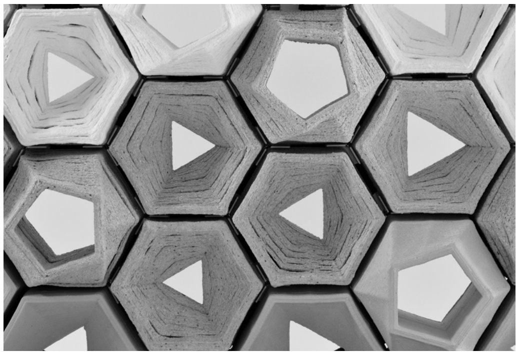

FIG. 16 Kusudama wall prototype.

3.6 HEXASHADE

Hexashade prototype explores the use of hexagonal ceramic blocks for the construction of a vault shading system whose geometry and internal structure are defined according to solar incidence. Based on hexagonal blocks, the optimisation takes place through the geometric variation of the internal structure of the blocks.

The design process is mediated by a computational model, taking into account the sun incidence data, resulting in a system that adapts the internal geometry of each one of the blocks through their relative position in the set, making them more or less permeable depending on the space/time ratio to be shaded.

The prototype is composed of irregular hexagonal blocks with variable internal openings and external configurations. Their dimensions range from 200 mm x 74 mm x 23 mm (the smallest block) and 210 mm x 167 mm x 23 mm (the biggest block).

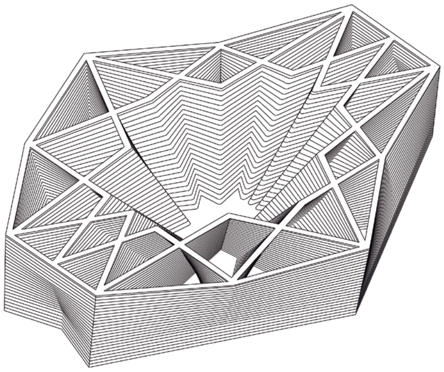

FIG. 17 Hexashade-block extrusion path model.

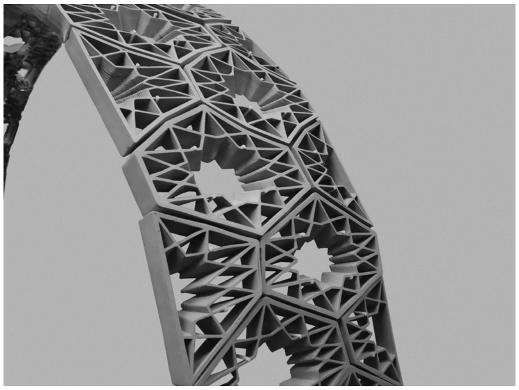

FIG. 18 Hexashade vault prototype.

4 CONCLUSIONS

The history of architecture, characterised by its technical and material, as well as aesthetic evolution, is enhanced by the evolution of ceramics. The authors of this paper believe that there is room for achieving significant improvements in the implementation of AM in ceramics, beyond the state-of-the-art in the building industry and in industrial applications.

The production of reduced-scale prototypes helps to dispel doubts about their functionality and the efficacy of the AM process. The manufacturing constraints, recognised by experimentation, must be integrated in the computational models from the design phase, in order to avoid the need for subsequent changes.

The prototypes presented in this work reveal viable architectural and constructional solutions and clearly validate the fulfilment of the objectives proposed. In fact, they wholly demonstrate the potential of AM techniques and the efficient use of resources; they made use of different approaches for the discretization of irregular surfaces; they integrate innovative architectural components with enhanced functionalities.

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