Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 180 (2017) 1150 – 1159
Procedia Engineering
www.elsevier.com/locate/procedia

International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

Mass customization with additive manufacturing: new perspectives for multi performative building components in architecture

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Abstract

Innovative production methods and advanced manufacturing techniques slowly but certainly seem to find a way to be introduced in Architecture thanks to the progressive tools for computational design which enhance digital fabrication processes and programming. In this context Mass Customization refers to the possibility to evolve from already existing systems to the novel ones that can be personalized, without increasing their cost and causing the new technologies to emerge.
Among various manufacturing techniques, Additive Manufacturing (AM) is considered a revolutionary technology that offers a new freedom in Architecture and expands the range of possibilities for design, production and performances of novel architectural forms, construction systems and materials employed. The main advantage of Additive Manufacturing is the quasi total freedom in organizing material deposition, where the matter can be placed only where structurally needed and in that way provide interesting scenarios in the optimization of construction components and new forms of printed tectonics.
This paper will analyse an experimental case study of a 3d printed clay brick designed and manufactured with innovative technologies in order to respond to the new requirements of market and introduce new perspectives of Mass Customization with Additive Manufacturing for the design of Multi Performative Building Components.

Peer-review under responsibility of the organizing committee iHBE 2016

Keywords: Mass customization; computational design; multi performative building components; additive manufacturing.

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1877-7058
Peer-review under responsibility of the organizing committee iHBE 2016
doi:10.1016/j.proeng.2017.04.275

1. Introduction

Architecture quite often seems to be resilient to changes. Therefore, advanced manufacturing techniques and innovative production methods appear to be neglected or postponed within this field. This is due to traditional construction methods and consolidated processes of production which are driven by economic issues more than the effective need for innovation and improvements. However, emerging construction processes are more and more influenced by novel design methodologies that enable new ways of manufacturing. Among them, computational design, early stage engineering, topology optimization and material distributions are the most significant ones [1]. In this context *Mass Customization* refers to the possibility to evolve from already existing systems to the novel ones that can be personalized, without increasing their cost and causing the new technologies to emerge. Among various manufacturing techniques, *Additive Manufacturing (AM)* is considered a revolutionary technology that offers a new freedom in Architecture and expands the range of possibilities for design, production and performances of novel architectural forms, construction systems and materials employed. The main advantage of Additive Manufacturing is the quasi total freedom in organizing material deposition, where the matter can be placed only where structurally needed and in that way provide interesting scenarios in the optimization of construction components and new forms of printed tectonics. In this sense, Additive Manufacturing can arguably match the economic viability of fordist and lean production, together with a very high level of customization and precision related to a mutual dependence between computation and advanced manufacturing techniques, giving a new competitiveness to Architecture Engineering Construction (AEC) sector. Particularly, in order to meet requirements of nowadays performative and competing design-to-fabrication techniques, it is important to produce elements, components or overall integrated systems with highly specific characterisation, while keeping its cost lower.

2. Innovative technologies for mass customization

Mass Customization can theoretically be considered as an oxymoron, since it is putting together the two seemingly contradictory notions like 'mass' and 'customization' [2]. It focuses on the idea that personalizing industrial production is gaining a higher relevance either in the design concept, either in the production and construction phase, raising the possibility to develop Innovative Technologies.

Innovative Technologies for Mass Customization in Architecture are at least two: **computational design** and **advanced manufacturing techniques.**

2.1. Computational design

Computational Design is a contemporary technique that enhances overall design-to-fabrication processes by incorporating various material, structural and geometrical data to compose, describe and inform architectural design and performances. This means that the process is no longer linear, assessing properties and performances when the design phase is over, but reiterative, where information are exchanged and connected to design from the very beginning.

Computational Design can give at least three possibilities:

- to engineer a specific form from the early concept of the Design Process;
- to customize machines and tools for the materialization of a specific design;
- to activate certain embedded properties of a material more than others as a main driver of performative design.

Designers are therefore able to combine and develop multiple tools and create geometrically complex structures, optimizing various parameters to control whether the inputs or the analysis results. The knowledge of a proper coding language, such as Python, C# or Visual Basic, opens up wide range of possibilities for scripting desired geometries and creating custom made tools or plugins with highly specified properties and performances. The advancement in this possibility to ‘compute’ and therefore add information while developing a specific structure, expands the opportunities to create new designs that can be optimized in shape, materials, production methods and most of all, in their performances. An interesting example of such process is design of a performative tessellation developed by ACTLAB with the use of Additive Manufacturing with thermo polymers (Fig. 1). In particular, the system was defined based on the complex geometry and interlocking principles of the tassels, without using any adhesives or additional connectors, while taking in consideration fabrication constraints, material properties and shape optimization. In this way it is proposed a potential façade system that emphasizes on the performative tessellation and advanced geometry rules [3].

Fig 1. Interlocking system of thermo polymer components, specifying rules for assembly and production (ACTLAB, 2015).

2.2. Advanced manufacturing techniques

Advanced Manufacturing Techniques represent a new way of production and construction within industrial context, where precision and direct fabrication are requested, that is at the same time flexible and adaptable for advanced personalization, based on design requirements. New computational opportunities, enabling the direct production of CAM files for CNC machines, allow the production of customized products directly from design drawings, encouraging a stronger control of production constraints and possibilities. The mutual relation between software advancements and the use of computer numerically controlled machines (CNC) or robotic arms in building construction have opened new frontiers of investigation that is pushing towards high performance systems and components with a reasonable time and cost. The main advantage comes from the possibility to produce unique components, which would not be economically sustainable to produce with traditional manufacturing techniques [4]. Advanced Manufacturing Techniques are mainly divided in cutting, subtractive or additive techniques. All of them refer to data processing through machines, which work with different tools in order to shape a material. This paper will focus in particular on Additive Manufacturing (AM), that is a specific technique of incremental formation executed by the addition of subsequent layers of materials without using supplementary instruments or moulds, in a process that is fundamentally opposite to the milling subtractive procedure [5]. This process offers a wide degree of flexibility and economic potential because the components are made directly from programmed materials and can be therefore optimized in structure and type of matter that is used. Important factors are determined by: geometry limitations, dimensional constraints and time management. All these factors determine a set of possible geometries, which are producible through AM. In order to increase the trade, manufacturing enterprises of AEC need to expand beyond their boundaries and seek for a solid innovation strategy towards the sustainable use of ever-decreasing resources [6]. To do so, constant development of advanced manufacturing and design techniques is fundamental.

3. The contribution of additive manufacturing

Additive Manufacturing is acknowledged as a revolutionary manufacturing technique, able to change the paradigm of what we can conceptualize and produce. Additive manufacturing has been used for years to make prototypes, visual models or mould masters, but it is only in the last decades that it started to be increasingly adopted as a direct manufacturing process, producing an end, ready for use, product [7]. Research into the field is evolving towards incorporating sophisticated materials and material organization methods within the fabrication process. Advances in structural material deposition empower the use of an increasing number of high-end materials with exceptional properties and make AM a promising manufacturing technology that goes well beyond prototyping.

AM can be executed with the use of different machines, which means that it is not a matter only of diffused '3d printers' but also of robotic arms or other machining tools that have different capabilities in relation to the material and technology used. AM machines can be of two main typologies: gantry or delta. The first group of printers is characterized by a gantry system, where the material extruder is usually moving in X and Y direction, while the printing plate where material is deposited moves in Z direction, whereas Delta provides a system that can move in all the three directions contemporary.

In the process of Additive Manufacturing there are different typologies: Selective Laser Sintering (SLS), StereoLithography (SLA), Digital Light Processing (DLP), Fused Deposition Material (FDM). Currently, most of the AM processes are based on plastic materials such as ABS, PLA, acrylate, photopolymer, polyamide (nylon), epoxy, polycarbonate and PMMA (acryl glass) or metal powder. Material mixtures might be modified for specific applications - like aeronautical engineering - in order to perform specific properties of the materials. Some of these have been introduced to the general AM market making high performance plastics available.

Some of the studies that underline material optimization and high structural performance obtained by 3D printing are the structural steel joints developed by Arup, in 2014. The collaboration with the engineering design software and consulting company Within Lab, but also with CRDM/3D Systems and EOS as additive manufacturing experts, brought to a proposal for steel nodes for lightweight structures characterized by a complex shape and customized design. Made from steel, each of the 14-centimetre-tall prototypes is produced at just under half the size of a real node and has been put through preliminary material tests. The topological optimization allowed to reduce material where not needed and reinforce where loads are stronger (Fig. 2). AM process is particularly relevant within the perspective of mass customization and explains the increasing development of new competences in the production techniques and applications in this field.

Fig 2. Arup studies on topological optimization of metal 3D printed joints.

4. Experimentation for customized building components in clay with AM

The experiment described in this paper is developed under the activities of ACTLAB, Research Unit that is a part of ABC department at Politecnico di Milano University, with the contribution of professors, phd and graduating students, that are focusing on the development of Innovative Building Components and structural systems. Among various works, this paper will concentrate on analysis of a 3D printed clay brick designed to incorporate multiple performances such as insulation, electric properties and lighting integration.

4.1. The design

This experiment starts from the idea to develop a customized design of a very traditional building component: a clay brick. The concept relies on the possibility to have a flexible system of tile modules, which could be site specific and ad hoc buildable with AM in relation to the context. The design of the component is developed analytically with respect to a framework of requirements and performance typical of a clay component, with the addition of standard features of a wall system. The concept thus identifies the basic functionality to be integrated in a wall with insulation, electrical junction boxes and pipes, lamps, allowing the creation of specific shapes when required. The dimensional constraints are guided by modular coordination with the existing technical elements and standard formats on the market of a non-load bearing clay brick. The main idea presented herein is to use this type of components not only for new construction, but also for existing buildings systems when having to be refurbished. An algorithm developed with the use of Grasshopper and Python has been applied to determine the wall thicknesses and amount of material distributed, while optimizing structural performances of a design and considering production constraints. It has thus been identified as an ideal format (similar to what exists in trade), and compatible with printing constraints, a dimension of 250 x 250 x 120/125 mm. This dimension could also fit within exiting insulating EPS panels (500 x 1000 x 50 mm), integrated with electrical pipes of 8 mm or junction box of 120 x 100 x 70 mm. Another advantage of this system is the possibility of integration within any kind of form or structure, in relation to its use. Due to the necessity to preserve structural equilibrium within a wall, design of cantilevered parts of the brick has been performed within the mass quantity not superior to 40% (Fig. 3).

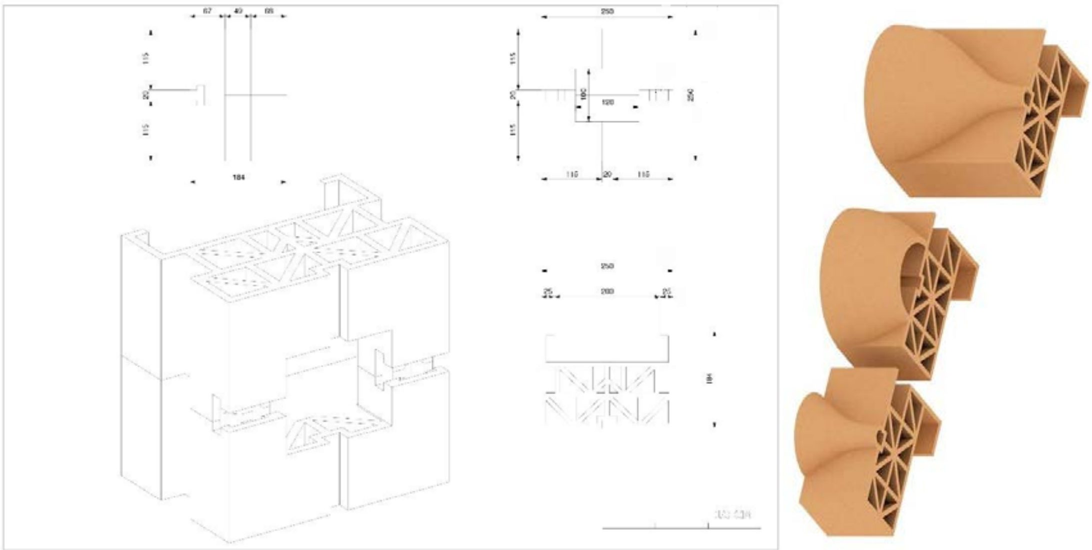

Fig. 3. Design of the clay brick component in relation to modular coordination and exiting standard formats.

4.2. The material chosen

The correct mixture has to be chosen in order to ensure either a good degree of fluidity, either a good extruded filament cohesion. The substances used to make the mixture of clay are: slip from red earthenware casting for 58% of the mixture, chamotte red end (or-0.5 mm) for 20% of the mixture and sodium-carbonate for 1% of the mixture. To this mixture it has been added 21% of water. All the materials chosen are natural and easily accessed on the market. Based on decided mixture, the design has been refined with addition of internal ribs organized under the angles of 90° and 45°. This was fundamental in order to assure an isotropic response of the component. Even though this trial was not laboratory tested, it proved empirically to be working for a higher horizontal load resistance.

4.3. Printing, drying and cooking

The printer used for the fabrication of the brick is a Delta Wasp 40/70, with a cylindrical printing area of 40 cm diameter and maximum height of 70 cm. When extruded, the clay material is not becoming immediately solid and it needs certain time to harden. For this reason, the certain risk of structure collapse when progressively printed exists. To obviate this problem, the brick was designed in such a way to allow printing with numerous points of connection between the inner and outer walls so that the object stereometry determines its progressive support during the printing process. The extruded clay material might also collapse against excessive directional changes; it was therefore a good practice to create sections in the XZ or YZ plane that are not less than 55 ° angle. Considering the printing volume and fabrication constraints, some additional factors had to be taken in account: maximum mass of clay available for extrusion depending on the extruder's reservoir capacity. Specifically, the reservoir of Delta Wasp 40/70 had capacity of 7 kg and extruder diameter of 3mm. Moreover, it should be also considered that during the processes of drying and firing, the dimensional shrinkage of about 10% occurs due to evaporation. The printing process of the two components took less than 8 hours (Fig. 4). Both the bricks had the space provided for insulation and cantilevered parts for lighting. After the production, the component has been naturally dried for 2 weeks. The correct drying process is indeed crucial for the final curing of the prototypes, due to quite uncontrollable temperature changes that can cause material reduction in an irregular manner. This had partially happened to the prototype, due to change of temperature and humidity percentage during day and night. The components have been afterwards than subjected to 9 hours of baking at 1050 ° C and a further 9 hours of controlled cooling. The finished clay product was found to be reduced in volume by 10% with respect to the design values. This withdrawal process happened due to the gradual water evaporation, both in the phase of drying and firing.

Fig 4. Clay 3D printing studies for components with specific design requirements (insulation assembly and light integration).

4.4 Absorption and Structural Testing

The two bricks have undergone two main tests to verify their characteristics and performances: the water absorption test and the structural resistance test (Fig. 5), with the main goal of comparing the characteristics of additively manufactured components with the conventionally produced ones of similar properties, while balancing the possibilities of customization and obtaining improved performances.

Firstly, the absorption test has been run under EN UNI 772-21, which determined the rules for verification of a printed clay prototype. The parameters observed are: Md (g) - Mass after drying, Ms (g) - Mass after immersion, Ws (%) - Water absorption. This test consists in 24 h soaking of the prototype, assessing his weight before and after immersion, considered that the prototype must be completely under water. After soaking it has to be dried in a ventilated oven at 105 ° C + 5 ° C. 5.3. Moreover, the weight scale must have a precision of 0,1%.

After the test was performed, the results were following:

Md= 3321,5 g

Ms= 3951,6 g

Ws = ((Ms-Md)/Md) x 100%

Ws = ((3951.6-3321.5)/3321.5)*100= 18.97%

The outcomes showed that the absorption is not significantly changing compared to the traditional non-load bearing clay brick.

Additionally, the IRIS test that consist of 60 seconds soaking of the prototype has been performed, with the following results:

Dry weight= 3321,5 g Weight after 60 seconds (sup face) = 3411,1 g;

Weight after 60 seconds (sup face) = 3419,7 g

CWi= ((Mso,s-Mdry,s)/Ast)x1000 (kg/(mq x min.)) Mso-Mdry= 89.6 gr. = 0.089 kg

IRIS test regulates the maximum weight absorption, and this test was quite successful for the 3D printed brick which was complying regulations.

Secondly, the structural tests have been made in compliance with UNI-ISO Norma EN UNI 772-1-2011.

The first procedure has been to grind the brick in order to have parallel surface with a very low tolerance in order to be able to run the test. First load was applied and soon after the load speed was reduced in order to reach breaking point in more than one minute (as per regulation). A very accurate dimension measuring has been done in order to calculate gross and net area.

The test resulted in succeeding values:

N/A (MPa): (300 1000)/ 32994.3847 =9.0924 (MPa)*
N/A (MPa): (338 1000)/32994.3847=10.2441 (MPa)*

The values have been further normalized in relation to drying process that could potentially cause some irregularities to the h/d ratio. Thus the final resulting values are:

*N/A (MPa): 9.0924*1*0.6= 5.45544 (MPa)*
*N/A (MPa): 10.2441*1*0.6= 6.14646 (MPa)*

The values of the net area normalized:

N/A (MPa): (300 1000)/15170.7614=19.7748*1*0.6 = 11.86488 (MPa)*
*N/A (MPa): (338*1000)/15170.7614=22.2796*1*0.6=13.36776 (MPa)*

The breaking point occurred under the load of 330 KN as a first cracks and 338 KN as final disruption.

Compared with the traditional non-load bearing clay brick, additively manufactured brick showed to have higher resistance values: 5 N/mm^2 on the horizontal face and 7 N/mm^2 on the shorter face. Therefore, the utilization of 3D printed clay bricks proved to have a superior performance and behaviour and that can be freely employed within the traditional walls and structures, complying the regulations. However, the 3D printed brick in such configuration was compared only with non-load bearing traditional bricks. Certainly, in order to make it comparable also with the load bearing systems and structural bricks whose resistance is 40 N/mm^2 on the main face and 7 N/mm^2 on the short one, additional analysis and material optimization principles are required.

Fig 5. Absorption and structural testing of the 3dprinted clay brick.

4.5. Final consideration on the experimental case study

The case study of the printed clay brick illustrates very well the advantages and potentials of Additive Manufacturing techniques, involving material, machinery and software in an interdependent relation. Furthermore, geometry played a key role in the optimization of form and structural behaviour, mechanical properties and therefore construction requirements of the prototype development. In this case the idea of staying within the standard dimension boundaries in order to fit in an existing and conventional wall structures, has guided to specific size restrictions, but allowed a lot of freedom for design, material and production developments.

Another important factor in the realization of multi performative components is the material selection. Thanks to emerging technologies of nowadays, we are able to engage the materials on their molecular level and 'customize' their properties for the specific functions and roles that they will be taking with a design. Material optimization is able to respond to the sustainability issues through its advanced use and distribution methods. Particularly, in the case of printed brick, a lower void ratio could be considered (in this case it was 54%) in order to increase the structural resistance.

Hence, additive technologies have the potential to go two steps further than traditional methods, and to design specific performative patterns according to a high-variety of purposes. With such a fabrication process it is possible to generate complex shapes without any additional production complication or costs increase. It is also viable to freely organize internal material distribution over the volume, according to desired parameters.

While in the past the predominant optimization technique was to design form as a function of material, graded building components might offer an entirely new approach: the design of material as a function of form [8]. Future assessments and developments of AM systems could take into consideration improved time management, as proposed by the forthcoming 4D printing [9], which is taking into consideration time in the printing optimization of an object. This approach will enable a deeper consideration of all the integrated factors: in the specific case study, for example, a time reduction from 4 to 2 hours might significantly improve fabrication efficiency while slightly compromising precision.

5. New perspective for multi performative building components in architecture

Design of Multi Performative Building Components is an innovative approach to be introduced in AEC constructive systems that can improve the quality of the existing built environment, using advanced technologies that open new possibilities and provide novel opportunities for the sector.

Additive manufacturing and computational design drastically reduce the gap between the project design and production phase, creating a direct design-build system which can be highly customized with the use of personalized tools and techniques, considering the properties of materials that are used, their optimized organization and the final performances aim. A particular system or component is thus 'performing' among various scales and behaviours, perhaps the most common being structural resistance, thermal behaviour, illumination control and light permeability.

This results in a shift of paradigm from traditional architecture: one component is now able to serve multiple functions, instead of having multiple heterogeneous components each responding to a specific role. The evolution of materials, of computational design and advanced manufacturing techniques, enhances the search for high performance at an average cost, going towards the Mass Customization of future building components assembled on site [10]. As a matter of fact, the abilities of freeform adaptation and the development of multi material and multi performative structures represent the milestone in advanced architecture and building construction, opening the whole new and more competitive profession field within the AEC sector, where the main focus is set to the highly performative, fully customized building systems with increased quality on multiscale processes.

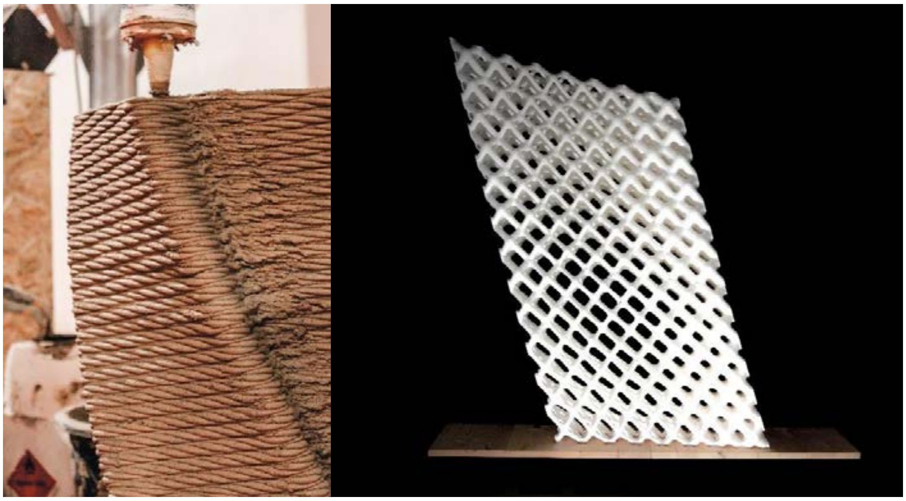

Fig. 6. Further developments on Additive Manufacturing techniques and applications within the research of ACTLAB. (a) 3D printing of a cement and resin based full scale complex form columns (b) cellular lattice based load bearing skin systems in PLA.

Acknowledgements

Thanks to ACTLAB Research Unit at Politecnico di Milano, Luca DeSantis for the work developed in his thesis in collaboration with +Lab of Politecnico di Milano and Wasp Company for technical collaboration.

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