3D-Printing of Viscous Materials in Construction: New Design Paradigm, from Small Components to Entire Structures

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Abstract The advent of industry 4.0 in the construction sector is profoundly changing paradigms that enhance the building construction sector. During the last decade, the experimentation of 3D-printing exploiting *viscous materials* has undergone unprecedented increases by construction companies. Even if reinforced concrete 3D-printing to construct buildings is growing fast, the use of other materials such as *clay* and *raw earth* is not yet affirmed both for the building *components* prefabrication or monolithic constructions. Currently, few 3D-printing applications with clay and raw earth have been experienced by research institutes and companies (e.g. Fablab-Poliba, Italy; Instituto de Arquitectura Avanzada de Cataluña, Spain; WASP company, Italy) for bricks, walls and entire buildings respectively. Beyond practical applications, the academic investigations focused on specific issues only (e.g. structural performances, new design for prefabrication or complex geometry printability). On the other hand, these examples are isolated, and a systematized design paradigm is still missing in the related literature. This chapter aims to define a new design paradigm for 3D-printing with viscous materials. A five-step procedure is proposed to achieve an effective design for both "*small components*" (to be assembled on site) and "*entire structures*" (to be printed in situ). The five steps will guide the reader towards the exploitation of the potential of the technology by experimenting complex shapes and by also respecting the actual limits of the machines. The

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steps include: (i) Definition of the conceptual design; (ii) Parametric modelling, (iii) Slicing software; (iv) Performance and Printability simulation; and (v) 3D-printing.

Keywords 3D construction printing · Building design · Construction technology · Parametric modelling · Printability simulation · Slicing software

United Nations' Sustainable Development Goals 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

1 Introduction

Additive Manufacturing (AM) is a rapidly increasing technique that allows the production of three-dimensional objects from a Computer-Aided Design (3D CAD) model through the deposition of layers of material. In contrast with subtractive technologies, the additive process does not involve large quantities of waste materials and gives the opportunity to 3D print complex geometries and shapes [1]. Innovative opportunities in the design and architecture field have been recently created by AM development and the peculiar capabilities of this technology. Plenty of research has been carried out on design for AM and particularly on small-scale applications [2]. In this context, the challenge for designers is to create high-quality products meeting functional design requirements by using AM and considering technological limitations, advantages and capabilities for each process. Indeed, by exploiting such novel technology, designers can generate customized solutions with added value compared to industrial ones [3]. On the other hand, currently, well-defined procedures to exploit the advantages of AM are based on the technician's experience and general design guidelines are missing in the related literature.

This chapter is aimed at defining a new paradigm for the design of 3D-printing *components* (to be assembled on site) and *entire structures* (to be printed in situ). In particular, the chapter proposes five iterative steps to achieve an effective component or building design to be achieved with 3D-printing of viscous materials: (i) Definition of the conceptual design; (ii) Parametric modelling; (iii) Slicing software; (iv) Printability simulation; (v) 3D-printing (Fig. 1). The proposed approach is explained from both a theoretical and practical point of view in three subsections. *Firstly*, a specific paragraph explains in detail the five steps to achieve 3D construction printing from the novel conceptual design to the operational use of machinery. *Secondly*, the five steps are explained from a practical point of view by proposing the design and production of *small building components*. In particular, the generation of 3D-printed clay bricks with complex shapes is presented (Fig. 2, left). *Thirdly*, the proposed

method is applied to build a *whole structure* to be printed directly in situ. In this case, the five steps are applied to redefine the conceptual design of the Nubian Vaults to be compatible with a full-scale and support-free 3D-printing production with raw earth (Fig. 2, right).
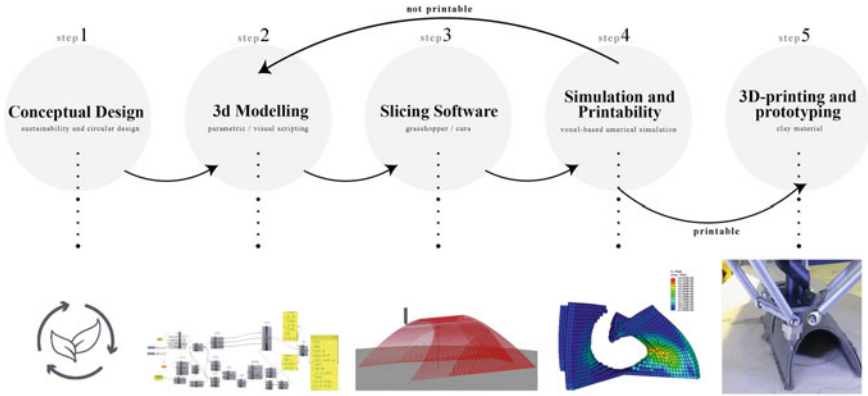

Fig. 1 The five steps to perform an effective design and 3D-printing with viscous materials
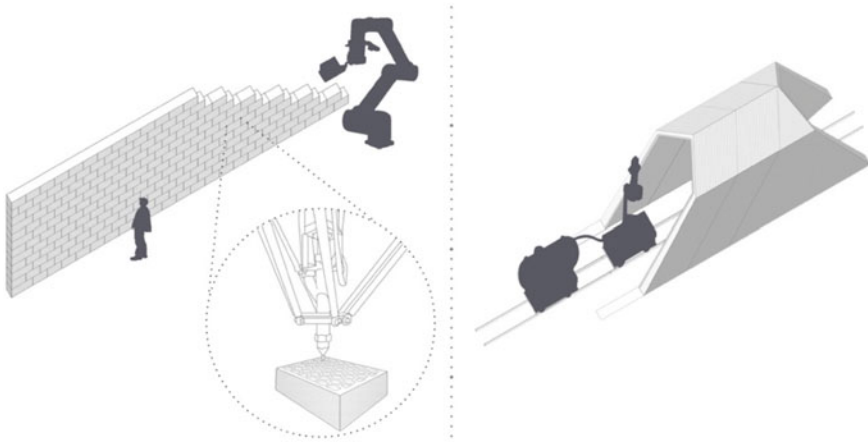

Fig. 2 3D printing of small components (clay bricks, left) and entire structures (Nubian vaults, right)

2 The Five-Step Procedure to Achieve an Effective Design and Prototyping in 3D-Printing

The proposed design paradigm is based on five steps to guide the reader to reach effective design and prototyping in 3D-printing of viscous materials (each step is described in a subsection below). In particular, the *first* step consists of the definition of the conceptual design by identifying the advantages and limitations of a 3D-printing-based production with viscous materials. The *second* step exploits the parametric modelling in order to ensure flexibility of production, customization, parametric analysis and optimization. The *third* step regards the slicing of the 3D model by setting all the 3D printing parameters (including both technology and materials). The *fourth* step is performed in order to analyze the performance of the component and simulate the 3D printing process to verify the effective printability of the designed model. If the printability simulation gives negative results, it is necessary to repeat steps 2, 3 and 4 until the combination of the design, modelling, technology and materials can produce a perfectly printable prototype. The *fifth* and last step consists of the effective 3D printing of the designed object.

2.1 Definition of the Conceptual Design

The definition of conceptual design for additive manufacturing with viscous materials is based on 3 fundamental points: (a) Review of available AM technologies with a focus on capabilities and limitations; (b) Definition of the aim of the project and selection of the most suitable technology for viscous materials for entire structures or components to be assembled; (c) awareness of general limitations of 3D-printable geometries.

(a) In the first stage of conceptual design, an accurate analysis of the current AM processes is required. Seven AM processes are identified in the framework of additive manufacturing standards development by the international standard ISO/ASTM [3]: Directed Energy Deposition, Powder Bed Fusion, Sheet Lamination, Binder Jetting, Material Extrusion, Vat. Photopolymerization and Material Jetting. In the field of architecture and construction, the most relevant and widespread technique is the material jetting processes with viscous materials (e.g. Contour Crafting [4], Xtree [5] and Cybe [6]). Cementitious materials have been the most explored in AM for being cheaper than other materials and characterized by suitable mechanical properties. Nevertheless, there are AM technologies aimed at raw earth and clay deposition [7]. Consequently, the guideline for designers is to select a set of available technologies by considering the following advantages of applying an AM in construction: (i) the possibility to build more complex, functional and customized geometries, composed by parts well integrated and more easily assembled; (ii) use of innovative mixtures as a combination of materials with different properties; (iii) automation of production with reduction of manual work (specifically for entire structures), (iv) possibility to

optimize of the used material by enhancing the life cycle sustainability and reducing resource consumption, waste production and pollution [8].

(b) In the second stage, a specific AM system can be selected and applied, according to design objectives and required performances. Anyhow, the first selection of the specific AM system depends on the size of the element to be produced. Currently, two different functional approaches can be identified: (i) application of large-scale systems for the fabrication of entire structures on-site; (ii) application of small/medium-scale systems to produce small building components to be assembled. Secondly, the best AM technology can be selected on the basis of the availability, costs and geometric limitations of 3D printing.

(c) In the third stage of the conceptual design process, all the geometric limitations of 3D printing must be known and taken into consideration. The construction of angled or standard overhangs, bridges, bores and channels, excessively thin wall thickness and too small elements might not be correctly printable, strictly depending on the specific AM system and its characteristics. The thickness of the nozzle, the extrusion method and the material employed highly affect the geometry of overlapping layers. Once all the geometrical limitations are known, the designer can effectively realise the concept of the component or construction. In the end of the conceptual design, the draft of the component is defined together with the target performance to be reached (e.g. functional, structural, and thermal characteristics in order to satisfy minimum regulatory standards and user comfort).

> Note that the designer generally has fewer geometric limitations in conceiving various small components to assemble at forming large-scale structures.

2.2 Parametric Modelling

Parametric modelling belongs to the family of computer-aided design (CAD) concerning the use of computer-based software to aid in design processes. On the other hand, if compared with other tools, parametric modelling is able to build geometry by exploiting mathematical equations operated with visual scripting. This process provides the ability to change the shape of the model's geometry immediately when specific dimension values are modified. Consequently, once the conceptual design of the model is ready, it is necessary to identify all the dimension values that need to be parameterized (e.g. thicknesses, lengths, heights, curvatures, and parameters that define any internal fillings). The aim of parametric modelling is of basic importance since it establishes the flexibility and adaptability of the ideated component and allows fast customization, analysis and optimization of the final product. In addition, the achieved parametric 3D model can operate in synergy with specific performance analysis software. For this purpose, an iterative process can be set up to adjust the dimension values and improve the performance until the printability is reached and the target performances are satisfied (Sect. 2.4). A correct execution
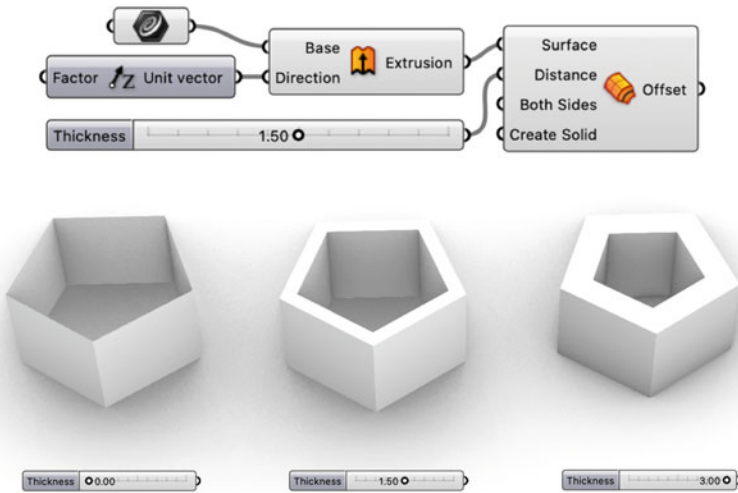
Fig. 3 Example of a parametric model with a parameterized thickness (Grasshopper software)

of the parametric model makes the subsequent phase of the iterative adjustment of dimension values simpler and more effective.

Operatively, the parametric modelling is carried out by using specific software (e.g. Rhinoceros and Grasshopper). In these tools, 3D modelling is achieved by using specific *components* (hereafter written in *italics*) to be dragged onto a canvas and adequately connected between them. Figure 3 shows how an example of a parametric model is generated starting from a pentagonal shape. The pentagon is firstly extruded (with *Extrude* component) in the Z cartesian direction and secondly, an *offset surface* is applied by parameterizing the thickness (one-dimension values only can be varied in this example). In the end of the process, the parametric model allows to easily change the thickness dimension values. In particular, the figure shows three configurations obtained by setting different thicknesses of 0, 1.5 and 3 respectively.

2.3 Slicing

For the 3D printing process, analogously for other digital fabrication technologies, a connection between the digital environment and the real physical one is necessary. This connection can be achieved through computer-aided manufacturing software (CAM) that generates a toolpath (in an alphanumeric language) to provide the machine with the processing instruction. For additive technologies, the CAM procedure to convert a 3D model into specific instructions for the printer is called "slicing". Indeed, the process operates a "slicing" of the three-dimensional model to obtain a set of layers re-creating the geometry. The output of the *slicing* is called G-Code and
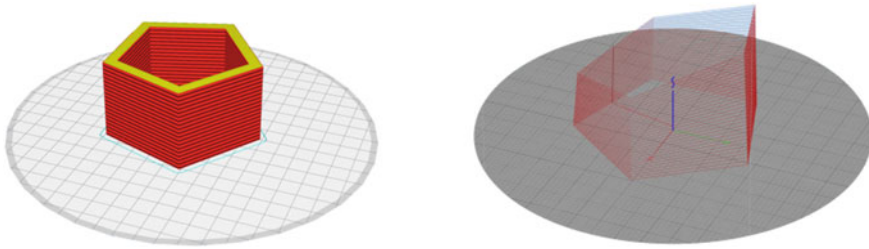
Fig. 4 Automatic (left) and parametric (right) slicing of a simple 3D model

consists of instructions for the 3D printer that can create the object in the physical environment by producing successive layers of material. During the slicing process, numerous printing parameters can be defined such as the layer height (related to final component resolution), the pattern of the internal fill or the parameters related to the printing supports.

In this section, two possible approaches are specified to set the slicing: (i) the automatic slicing by using specific software (e.g. Cura, Simplify3D or Slicer3D) and (ii) the parametric slicing to directly draw the printer toolpath.

The software to achieve automatic slicing are very fast and user-friendly but are also limited to specific algorithms. In fact, even if this software allows to change of numerous printing settings, the tool path is automatically generated by the program and cannot be entirely decided by the user. On the other hand, "parametric" slicing overcomes the drawback of automatic slicing and gives the user full control of the procedure. In this way, the creation of the G-Code is entirely controlled by the user without randomly generating infill or tool path as in the case of the more traditional slicing software. To provide an example, by using this tool it is possible to create toolpaths that are not planar to the printing plane (an option not yet available in slicing software). Figure 4 shows the slicing process obtained for an example geometry (the same of Fig. 3) obtained both with an "automatic" (left) or "parametric" (right) slicing that allows not planar layers.

2.4 Performance and Printability Simulation

The performance analysis is fundamental to achieve functional, structural, and thermal characteristics in order to satisfy minimum regulatory standards and user comfort. For this purpose, another benefit of parametric modelling is the ability to create ready-to-use input files for powerful performance simulation software (e.g. Abaqus). Typically, such software are based on finite element method (FEM) analysis that can be used to obtain solutions on a broad spectrum of engineering problems including thermal, structural and acoustic investigations. In the proposed five-step approach, the FEM is used in synergy with parametric modelling by setting an iterative procedure. The objective is to adjust the parameter of the model until the
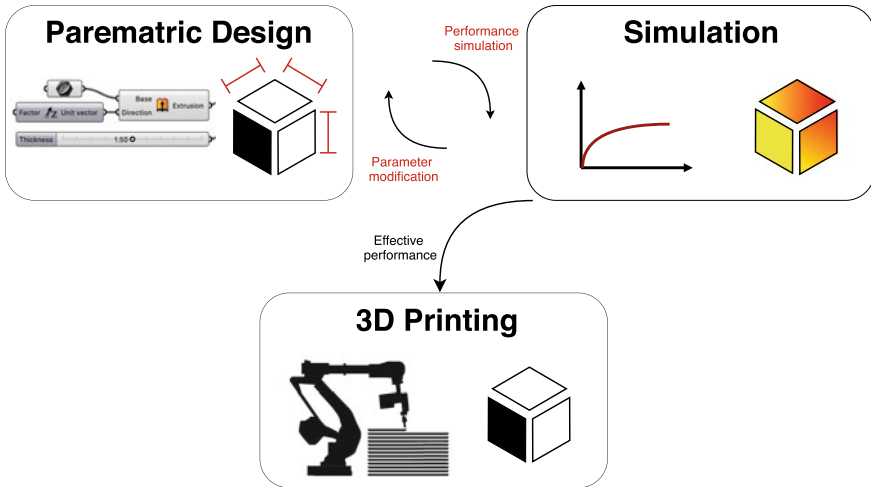
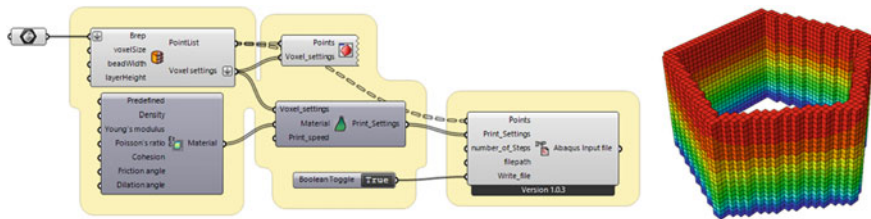**Fig. 5** Iterative process for performance simulation and parameter adjustment

Fig. 6 The connection between Grasshopper and Abaqus software for FEM analysis

minimum performances defined in the conceptual design are satisfied. Such operation is simpler and faster if the parametric model allows changing all the key parameters influencing the performance of the component. Figure 5 schematizes the iterative process for performance simulation and parameter adjustment.

In addition, Fig. 6 shows the components used in Grasshopper to connect the model with Abaqus software and run a printability simulation (a ready-to-use file for Abaqus is generated in Grasshopper). The resulting FEM analysis concern a printability simulation of two different configurations of the thickness (same example of a pentagon extruded shown in the previous sections).

2.5 3D-Printing and Prototyping

The last step of the proposed procedure concerns the effective 3D-printing of the designed object. Even if the previous phases are carried out in a workmanlike manner,

negligence in the final phase can compromise the quality of the result. Indeed, the products derived from 3D printing of viscous materials can be classified in three categories: (i) High-quality products meeting aesthetic, functional and structural requirements; (ii) Medium quality products not meeting aesthetic requirements with details not appreciable; (iii) Insufficient quality products not meeting aesthetic, functional and structural requirements, totally or partially collapsed.

To this aim, the current subsection provides a useful overview of the critical issues that can arise throughout the modelling and printing process. In particular, Fig. 7 shows 4 main fields that can generate criticalities: (I) Printing material, (II) Printer settings, (III) Design or (IV) Slicing. Every field is divided into more specific features affecting the results of a 3D printing process. In turn, each feature is associated with a specific effect derived. In the last part of the figure (on the far-right side), possible solutions to correct the wrong features are proposed. In the following discussion, a letter (**bold in brackets**) associates every specific feature (in **bold**) of the figure with the connected description.

Material features: The most important feature of the material employed is its viscosity (**a**). This feature leads to formal three-dimensional variations of the product and to its natural sagging as soon as the layers are deposited on top of each other. In this case, to solve a problem of a "too fluid" material it is possible to induce heat during the printing process or including additives in the mixture can be necessary to accelerate
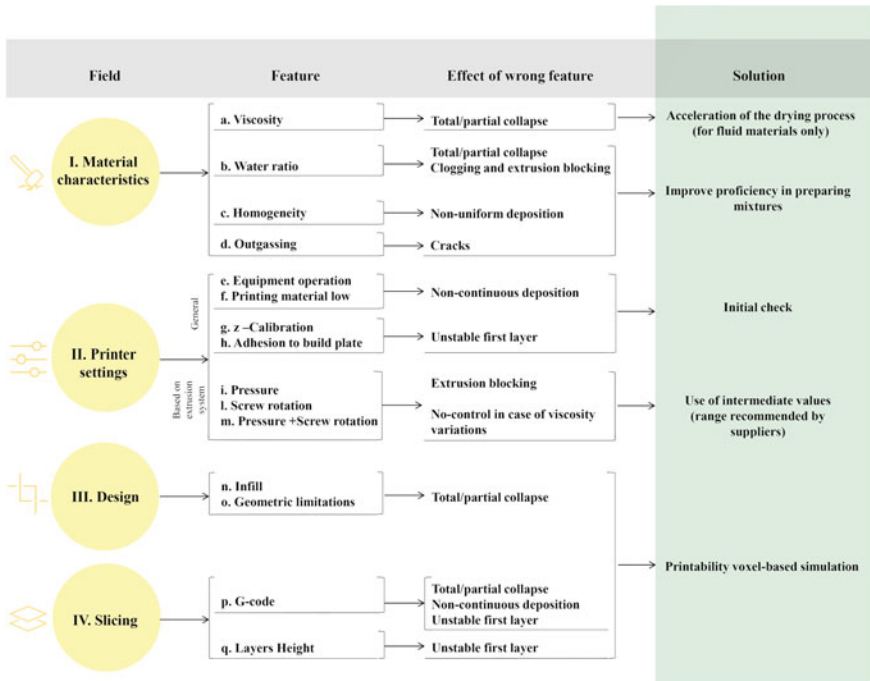

Fig. 7 Overview of possible criticalities during 3D printing

the hardening process. In preparing mixtures, the water ratio is also crucial (**b**). Indeed, the material can result too solid or liquid according to the quantity of water introduced and respectively being less extrudable or tending to collapse immediately after extrusion. The mixture needs to be homogeneous and outgassed as well (**c**, **d**). Different consistencies and the presence of trapped air in the mixture may result in the printing of a product characterized by superficial defects such as cracks or that tends to collapse. Wrong features, in this case, can be avoided by preparing a mixture in a workmanlike manner with a suitable quantity of water, well-pressed and mixed.

3D printer settings: during the printing process, equipment failures (**e**) or material depletion (**f**) can occur. If the operations stop for some reason, the parts already printed get wasted or recycled and the 3D-printing process has to restart from the beginning in order to be continuous. Moreover, the origin on the z-axis needs to be well calibrated (**g**) and the extruded material must adhere to the build plate (**h**). Difficult adhesion is due to the different nature of viscous materials compared with the materials of which the plate is made. Wrong settings cause unstable deposition of the first layer with the consequent collapse of the entire extruded structure. Equipment full checks before launching a 3D printing process are considered to be indispensable. For what concerns the specific extrusion system employed, it is necessary to set proper values for piston pressure (**i**), screw rotations number (**l**) or both (**m**) in hybrid systems technologies. In case of viscosity variations and to prevent extrusion blocking, the use of intermediate values among ranges typically recommended by suppliers is suggested to be able to intervene on these settings during printing. To give an example, if the maximum pressure allowed by the machinery is being used and it is necessary to have a greater quantity of extruded material (e.g. the material is too dense) it is not possible to make this correction during the printing process by further increasing the pressure.

Design: the project of the infill structure determines the quality of the product. Inadequate infill regions (**n**) as well as the extrusion of "not printable" geometries (**o**) can lead to the total or partial collapse of the structure.

Slicing: errors in G-code (**p**) can produce an unstable deposition of the first layer and non-continuous deposition or total/partial collapse of the structure. Furthermore, layer height (**q**) needs to be well configured in order to avoid the fabrication of low-quality products in which the details are not appreciable.

In general, an effective FEM printability simulation (proposed in Sect. 2.3) should detect errors and prevent total or partial collapse during the 3D-printing processes.

3   The Five Steps Applied to Clay Bricks with Complex Infill

In the building sector, the possibility of creating **small components** to be assembled on-site can be very effective both for achieving customised design and high performances. The flexibility of the 3D printing can be useful to get complex geometries as in the case of the hi-performance clay bricks of Sangiorgio et al. [9]. In particular,

this section shows how the proposed five iterative steps have been applied to obtain clay bricks with complex internal filling geometries [9].

3.1 The Conceptual Design of Complex Bricks

The first stage of the conceptual design concerns the review of available AM technologies. Among the available technologies, in the case of 3D printed brick, the preliminary review focuses on Material Jetting exploiting clay material. During the first screening, the range of 3D printers of the Wasp company (Italy) is selected for the closeness of the supplier to the used laboratory (FabLab Poliba, Bari, Italy) and for economic convenience. In the second stage, since the proposed application concern the production of small/medium-scale building components, the machine Delta Wasp 40,100 for clay is selected. Indeed, such a machine represents a good compromise among availability, costs and geometric limitations of 3D printing (typical of a delta printer) [10]. In the third stage, the conception of the new printable bricks is defined by considering the limits of the selected machine. Beyond the limits of the selected 3D printer, two ideas guided the design: (i) The observation of the traditional and widespread external shapes and internal wall thickness of the brick; (ii) The use of periodic minimal surfaces to generate the complex internal configuration of the bricks.

Note that the periodic minimal surfaces are geometries well known for the high mechanical performances also used in ceramic 3D printing. To this aim, such geometries are selected to be integrated into clay bricks [11].

3.2 Bricks Parametric Modelling

The purpose of the parametric modelling in the case of 3D printed bricks is twofold: (i) reach flexibility and adaptability of the elements allowing for a quick change of different periodic minimal surfaces as filling geometries; (ii) connect the parametric modelling with an accurate FEM analysis software in order to simulate the brick printability.

For the first purpose, the obtained visual script allows for quick modify the dimension of the brick (length, width and height), the number of minimum surfaces that can be inserted in the brick, and the thicknesses of the infill and of the external walls. In particular, the script is divided into four clusters of components in order to achieve *external shell generation* and thickness, *infill generation* exploiting the minimal surfaces, *infill thickness* and *finalization* of the brick respectively (Fig. 8). For the second purpose, the connection of the parametric modelling to the simulation software is achieved with Abaqus (FEM analysis software) through a plug-in named *VoxelPrint* for Grasshopper [12]. The components of *VoxelPrint* allow to create a voxelization of the designed geometries (convert the geometry to a set of identical
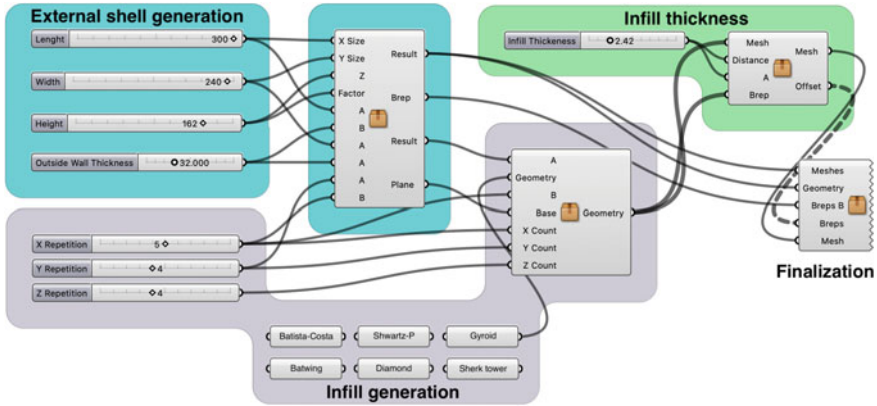
Fig. 8 Visual scripting (with clustered components) to generate complex bricks

finite elements) and consequently achieve a ready-to-use input files for simulation in Abaqus [9].

3.3 Slicing Software

In the 3D printing of the proposed clay bricks, a specific path of the extruder is not necessary. Consequently, among the two slicing processes described in Sect. 2.3 the simplest approach, based on common slicing software such as Cura, is chosen.

The key parameters selected for the slicing include a layer thickness of 1 mm printed by a nozzle of 2 mm diameter and a printing speed of 30 mm/s.

3.4 Simulation to Verify Infill Printability

With the aim of achieving a printable brick with a complex infill exploiting minimal surfaces, an iterative process is set to adjust the dimension of the parametric model until the cells of the brick result printable from simulation. The parameters are varied by respecting the limitation of the Italian regulatory [9]: the minimum thickness of the external walls (external shell) is 1 cm while the thickness of the internal walls is considered to be at a minimum 0.8 cm. In addition, the external shell of this first prototyping is 15 × 12.5 × 9 cm.

Starting from the lowest values of internal fill thickness (0.8 cm) and the number of cells (which cause the total collapse of the bricks) the iterative process led to an increase in the number of cells up to 4 × 5 × 5 and an internal thickness of 3 mm. Indeed, to provide an example, Fig. 9 shows the analysis of the internal geometry
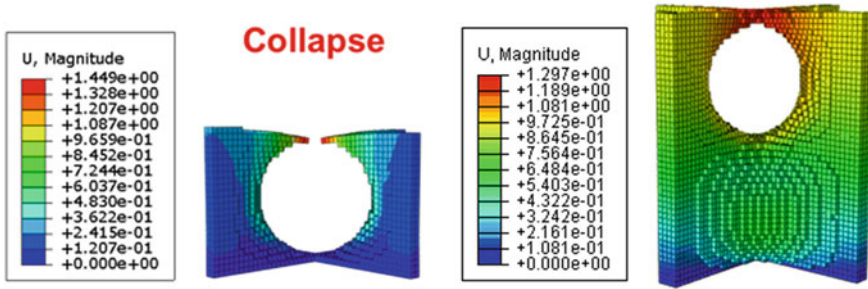
Fig. 9 Brick cell collapse or cell perfectly printable

of "Sherk Tower" that collapses with a thickness of 1.5 mm and became perfectly printable with a thickness of 3 mm.

3.5 3D-Printing and Prototyping

In conclusion, the prototypes of the bricks are printed by using a Delta Wasp 40,100 for clay by respecting all the suggestions proposed in subsection 2.5, specifically for obtaining a suitable viscosity of the printing material. To sum up, Fig. 10 shows the Slicing in the software Cura, the 3D printing and the final brick.
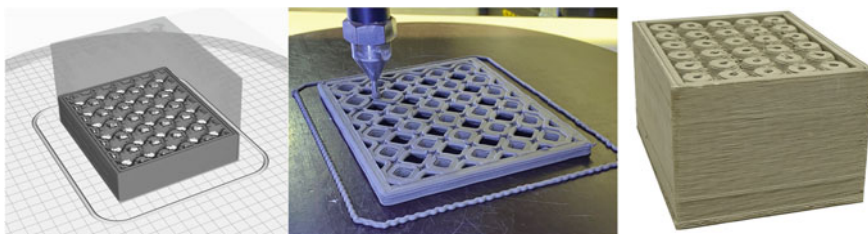
Fig. 10 Slicing in the software Cura, 3D printing and final brick

# 4 Design of a Support-Free 3D Printed Nubian Vaults

Large-scale 3D-printing of viscous materials is becoming relevant in the research sectors of space and post-disaster architecture for giving the opportunity to extrude local earthen resources. The aim of this section is to propose a preliminary approach for 3D printing structures entirely made of raw earth. Due to technological limits in 3D-printing overhangs [13], structures are typically combined with traditional flat roofs in which just vertical walls or columns are additive manufactured. 3D-printing of roofs is a challenging process, and temporary or permanent supports may be necessary. However, the use of supports made of materials different from the locals should be avoided in extreme environments. In fact, the design and transport of formworks could be expensive and the realization hard or dangerous for workers. In the course of history, several techniques of masonry have been developed for building massive structures without the use of supports, such as Nubian vaults, Catalan vaults, and Persian vaults [14]. Considering the similarities between additive manufacturing and masonry, especially in compositional and structural fields [13], a further goal of this section is to determine a suitable strategy for closing 3D-printed structures by applying masonry constructive principles with a focus on the Nubian vault.

4.1 The Conceptual Design of Nubian Vaults

The Nubian vault is a characteristic structure of the ancient region of Nubia composed by raw-earthen bricks held together by mortar. The bricks were assembled to form arches inclined at an angle of 45 degrees in relation to the level of ground. In this structure, formworks are not needed since each added layer is supported by that previously printed and already stable. Such construction principle has been reworked to be used in 3D printing with raw earth. In particular, the prototype has been conceived for being realized in the rural area of "Malandra Vecchia" (Abruzzo, Italy) and is inspired by the traditional earthen architecture present in its surroundings. In the forms, the project reminds of the "hut archetype" (Fig. 11, left). The innovative technological "hut" is thought to be made of inclined layers. Two components can be observed: (1) the part 1 is characterized by hut-shaped layers tilted at 45°, (2) the part 2 works as support for the tilted part and is composed by layers extruded horizontally.

4.2 Vault Parametric Modelling

Also in this case, the aim of the parametric modelling is allowing quick changes in the model in order to optimize it and conduct a FEM analysis for the printability simulation.
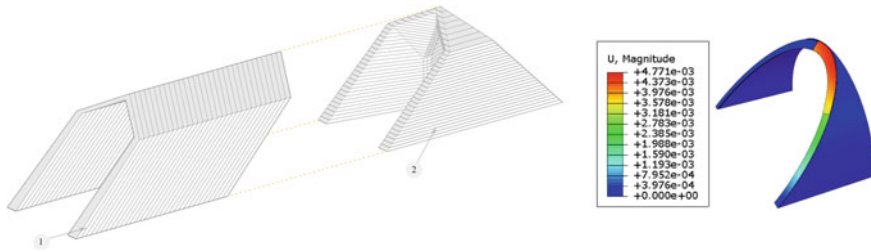
Fig. 11 Components of the nubian vault prototype and FEM printability simulation

Parameters consistently affecting the performances of the prototype are: (i) width of the span, (ii) height of the ridge line, (iii) height of the eaves line, (iv) angle of inclination of the hut-shaped layers, (v) angle of inclination of the sidewalls, (vi) thickness of infill, external walls and roof.

4.3 Parametric Slicing Process

The printing process is of basic importance in this case, consequently, a parametric slicing process is set in order to draw an effective toolpath. Indeed, this method allows the creation of 45° inclined toolpath and enables different printing settings such as layers height and infill regions for each part of the prototype.

4.4 Performance Simulation

In order to verify the performance of the inclined toolpath, a suitable FEM simulation (Abaqus software) is applied by investigating the deformation trends of the layers (according to the executed slicing). The right part of Fig. 11 shows the deformation of the upper layer (heavier in the central part of the arch) that remains acceptable to ensure printability.

4.5 3D-Printing and Prototyping of the Vault

In the last phase, the effects of the correct slicing method can be noticed by printing a prototype and verifying the application of Nubian vault principles during production. Figure 12 shows the small-scale tests to simulate both the 3D printing with horizontal and inclined layers performed at "Fablab Poliba" Digital Fabrication Laboratory and by using a WASP Delta 40,100. The prototype realized with horizontal layers shows several printing criticalities (it collapses on the top and does not allow for
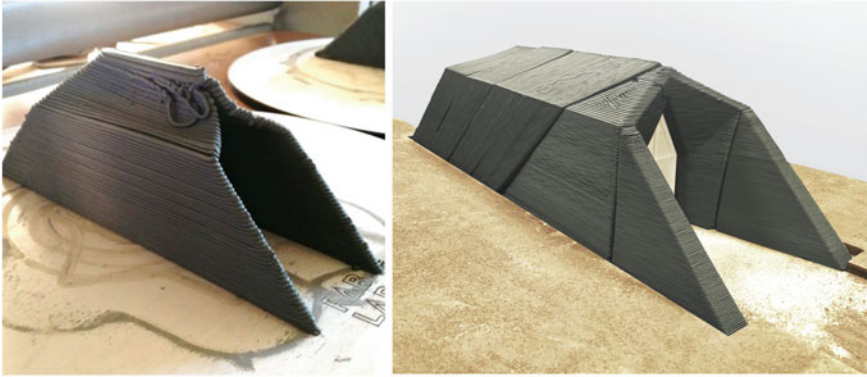
Fig. 12 The prototypes with different slicing methods: horizontal and 45° layering

Fig. 13 Render of the application of the 3D printed Nubian Vault in Malandra Vecchia (Italy)

the full closure of the structure) while the inclined layers are perfectly printable. In conclusion, Fig. 13 shows a rendering of the application of the Nubian vault in Malandra Vecchia, a fraction of the municipality of Casalincontrada, (Abruzzo, Italy).

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