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Fused Deposition Modelling Formworks for Complex Concrete Constructions

Roberto Naboni
CREATE Group - University of Southern Denmark, ITI, CAE | Denmark | ron@iti.sdu.dk

Luca Breseghello
ACTLAB - Politecnico di Milano | Italy | breseluca@gmail.com

Abstract

Concrete is undoubtedly the most employed material in constructions. In principle it allows to build complex architecture, where form can be for the realization of complex shapes. However, the biggest limitation of its use is explained by the demanding process needed to create free-form casts, it often limits its potential to obvious geometries. With the aim of overcoming current limitations, this paper explores the use of additive manufacturing to create formworks for concrete elements. The case study of a complex column is here utilized in order to develop an approach for advanced molds, where pressure levels, fluid dynamics of concrete and disassembly are integrative part of the design process. In conclusion are presented recommendations for further development at larger scale.

Keywords: Digital concrete, Casting, Additive Manufacturing, Digital Fabrication, Construction Method

INTRODUCTION

Concrete is one of the main materials used for constructions, which in principle allows for the realization of complex shapes. However, the biggest limitation of its use is explained by the demanding process needed to create free-form casts, which often constraints its potential to discretized geometries. When we look at history of constructions, many studies have been conducted to go beyond this limitation, among them Erwin Hauer with his intricate facade surfaces with modular concrete blocks, (Hauer 2004), and Miguel Fisac with his roof system allowing wider spans and higher structural performance (Fisac 1966).

DIGITAL FABRICATION IN FORMWORK MANUFACTURING

The ability of the fluid concrete mix to fill almost any shape when placed into a closed volume has not yet been fully exploited in constructions. In fact, the rapid development of digital design tools allows to conceive dramatic architectural forms which could take advantage of concrete full potential (Naboni et al. 2015), but a little relation exists with the primitive modes of production used in concrete construction nowadays. Despite the flexibility of the material, and the advances in design and modelling, no efficient solution has been developed yet for the production of complex concrete architectural forms (Lloret et al. 2015).

Given the need of bridging this gap, formwork manufacturing can drastically benefit from the inherent advantages of digital fabrication, being already driver of innovation in different sectors of the construction industry. Currently, many researchers are contributing to the broad spectrum of the diverse innovative approaches to constructions with concrete and digital fabrication technologies. Each technique carries intrinsic advantages and drawbacks, which make them suitable for a specific context of application. Variables are geometrical, such as the level of formal complexity required, concerning production, such as the speed of production, but also more generally about the feasibility of the technique, looking at the costs of labour and the availability of resources in the construction area.

Nowadays, studies on formwork techniques have focused on developing solutions to make feasible high level of complexity and definition, supported and implemented by computational design. Concrete casting techniques of different typology are experimented (Fig.1):

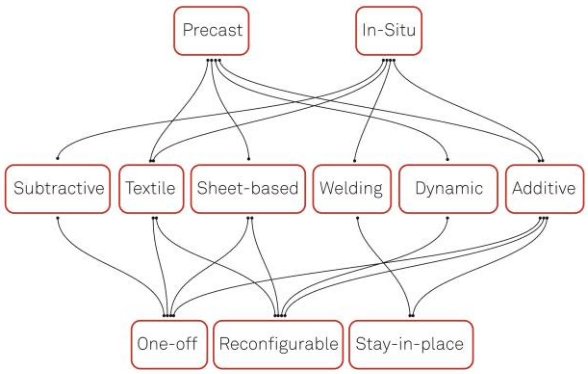

Figure 1: Overview of the state-of-the-art concrete formwork techniques and their diverse uses. Source: authors.

(1) *Subtractive*. Computer-numerically-controlled (CNC) machines have recently became one of the earliest and most widespread methods to produce freeform geometries in constructions, specifically formworks for concrete, by carving out material of expanded polystyrene foam (EPS) or wood (Clifford 2014, Liew et al. 2017, Brander et al. 2016).

(2) *Textile.* The building technology of fabric formworks can be traced back to Roman times, and throughout

history of constructions it resurfaced various times (Veenendaal et al. 2011). Fabric formwork is the building technology that exploit the use of structural textile membranes as the main material for concrete moulds. The material is highly flexible, hence deflecting under the pressure of fresh concrete, but if properly designed showing a excellent surface finish (Orr et al. 2012, Popescu et al. 2018, West 2009).

(3) *Thin-sheet*. Leveraging the advances in computational design and the easiness of numerically-controlled 2D cutting of sheets of material, it is currently being investigated the use of CNC or laser cut to produce moulds from thin sheets of plastic material. Origami folding techniques are used to design and bend the material after cutting, to shift from 2D geometry to 3D (Pigram et al. 2012, Kaczyinski 2013, Jackson 2015).

(4) *Bending & Welding.* A rarely tackled problem concerning concrete building fabrication is the placement of reinforcement: even geometrically simple concrete constructions require a high number of complex and accurately bent reinforcement bars (Reynolds et al. 2007). At different degrees, different research projects are addressing the issue by exploring robotic bending of the reinforcement bars, together with an semi-autonomous system for placing and welding them (Coffrasuisse 2017, Hack 2018).

(5) *Dynamic.* Tackling the issue of sustainability and economy of formworks, dynamic formworks are reconfigurable formworks which allows their reuse but also formal customisation. They can be distinguished between pneumatics systems (Kromoser, Hubner 2016), reconfigurable surfaces using pistons and microcontrollers (Bell et al. 2014), and slipforming, a well-known construction system for cores and bridge piers is now being explored using a delimited formwork that moves vertically through a 6-axis robotic arm and sensors to have feedbacks on material (Lloret 2016).

(6) *Additive.* Striving for the reduction of formal limitations and materials consumption in constructions, additive manufacturing has the potential to be a new disruptive technology in the field (Naboni et al. 2017). The challenge has been taken by directly 3D printing concrete (Khoshnevis 2006), or by printing formworks (Jipa et al. 2017, Morel et al. 2015).

ADDITIVELY MANUFACTURED FORMWORKS

Additive manufacturing has the potential to unlock freedom in design and optimisation in material organisation. Despite the fascination of early works and the prospect of a bright future of the technology, 3D printing can not be yet considered structurally reliable nor economically feasible in conventional construction works.

Hence, the idea is to exploit the advantage of material usage optimisation of 3D printing coupling it with a conventional material yet not fully unlocked in its possibilities such as concrete. This creates an interesting balance between an innovative fabrication technique, and a well-known composite fluid material able to adapt and fill every form it is poured into.

In this research, we are looking for a way to realize concrete constructions where multiple instances of complexity can be integrated. Firstly, allowing the realization of limitless curvature at any scale. Secondly, permitting the realization of interconnected geometries with different topological degrees. Lastly, introducing the possibility to characterize external surfaces with different textures. In response to this, the research focused on developing a novel casting technique based on the use of Fused Deposition Modelling (FDM).

METHODOLOGY

The methodological procedures involved in this work are: *Initial Investigations* on additively manufactured formworks. The information gained, are then supporting the definition of *Design Principles for FDM formworks*. As proof of concept, a *Column Design* is developed in order to integrate principles into a functional prototype. In this process, material feedback is studied in terms of *Hydrostatic Pressure* and *Concrete Fluid Simulation.* These two critical aspects are integrated by developing intuitive digital tools for their early evaluation in the design process. An approach to design and fabricate *Reusable Formwork* is illustrated, an important aspect for the overall sustainability of the approach.

INITIAL INVESTIGATIONS

The design of the formwork needs to address different complexities. Firstly, it requires a stiffness high enough to withstand the hydrostatic pressure generated by the fluid concrete. Initial tests investigates the performance and behavior of corrugations on the surface of the formwork as strengthening elements. In general, corrugations proved to be effective and adaptable to most formal complexities. A series of small-scale prototypes have been casted in order to examine the influence of the depth of the corrugation to the resistance of the formwork and to the quality of the final manufact. Moreover, tests have been conducted to optimize the printing routine, but also to test different plastics, different compositions of PLA (Fig.2), ABS and PP, and cementitious admixtures.

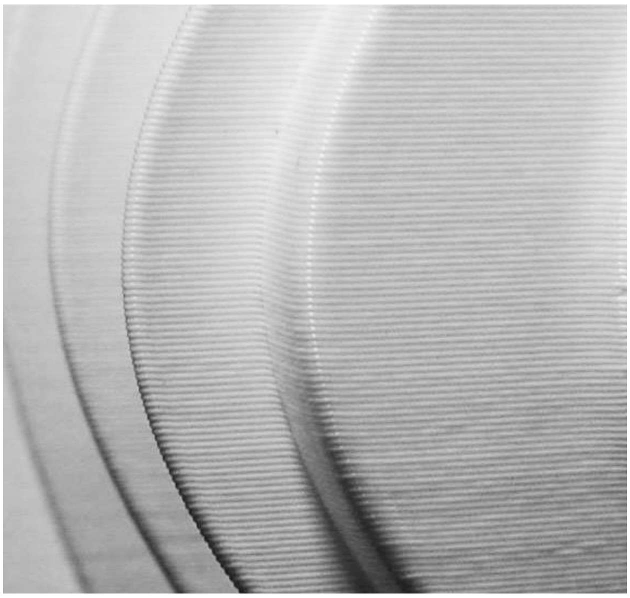

Figure 2: Detail of corrugations of 3D printed formwork with PLA. Source: authors.

The second important matter to be addressed is the removal of the formwork when the concrete has hardened. During the first phase of testing, working on small-scale objects and with reduced quantities of concrete, the formwork has been developed as a monocoque element to be easily melted using a commercial heat gun (Fig.3). This operation has high limitation at different levels: the formwork obviously becomes impossible to be reused, the energy and heat required to melt plastics at a large scale becomes unsustainable, generating toxic fumes and deteriorating the concrete reducing its mechanical properties. Another approach is that of printing distinct elements, segmenting the overall formwork into parts, that can be assembled and disassembled with the prospect of being reused.

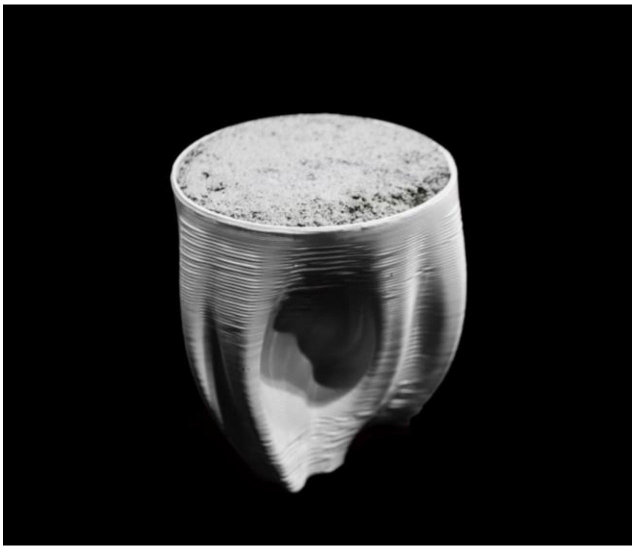

Figure 3: Example of monocoque formwork which requires heat to be removed. Source: authors.

Together with these issues, as mentioned earlier additive manufacturing is bringing an unprecedented freedom in designing topologically complex geometries. The initial tests aims at challenging the various opportunities provided by the technology, to test limits and complications that may arise. *Doubly-curved* surfaces requires extra labour at a high cost with conventional production methods, while additive manufacturing makes them accessible with very few constraints; similarly, *intricate topologies*, considered as complex geometric configurations of matter, e.g. cellular structures, hollow forms, interlocking geometries, can be hardly manufactured with conventional fabrication technologies, but they can be fabricated as much as simple geometries with 3D printing; a series of tests focused also to *surface finishing*, to the evaluation of the peculiar layering of 3D printed parts as well as the high scale of definition of the technology, which allows to think of patterns and surface variations in the order of millimeters.

DESIGN PRINCIPLES FOR 3D PRINTED FORMWORKS

The research aims at developing a 3D printed system for concrete casting which allows high complexity and shape definition. This investigation is conducted in an experiment-based manner: subsequent tests aim at refining fabrication techniques and incorporating performative aspects in a process which connects final design goals to the automatic generation of advantageous 3d printed casts. The process is branched into several complementary phases.

COLUMN DESIGN FOR FORMWORK

Dealing with complexity in form, also requires formworks to address such complexities. It is here presented the design, evaluation and fabrication procedure of a 100cm proof-of-concept test column, which means to exploit the potential of 3D printing for concrete formworks, but also the necessary reinforcements that the container needs to react to material pressure. Hence, the design of the column is the result of the interaction between the topological complexity unlocked by additive manufacturing and the criticalities arising from the process of optimisation of the formwork. Along with the design and manufacturing of the prototype, a set of digital tools for the analysis of the model and the optimisation of design and manufacturing processes are developed.

The fabricated design, in scale 1:3, is developed through an iterative process that builds on the initial explorations. As shown below (Fig.4), a 100 cm cylindrical column with a 15 cm diameter is the starting point for the design (A). A second iteration (B) implements a variable radius in the column, making it thicker in its central part and thus generating doubly curved surface. To increase the degree of topological complexity of the column, a twisting hole is being carved out of the previous iteration. Hence, the resulting volume (C) is a highly intricate geometry, which as further described in the next paragraphs presents higher pressures, hence stresses, when the fluid material is poured. The final configuration (D) features a series of corrugations, which, as mentioned before, are strengthening the form as much as the formwork.

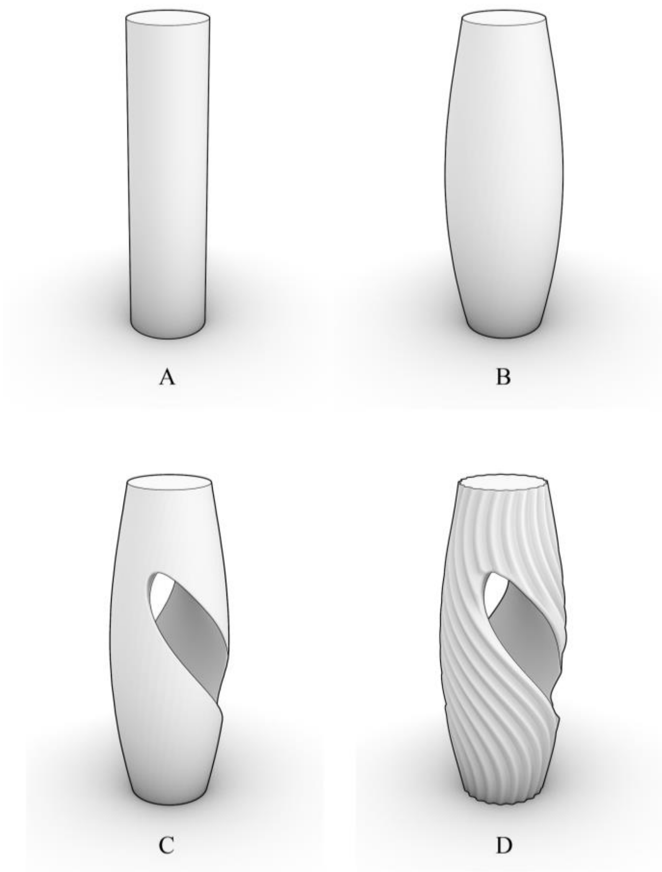

Figure 4: Design iterations: A. Cylindrical 100 cm column; B. Curvature complexity added; C. Topological complexity added D. Reinforcement corrugations. Source: authors.

MATERIAL FEEDBACK FROM HYDROSTATIC PRESSURE

Predictive models are fundamental instruments to the understanding *a priori* of material's behavior. Specifically, the two main issues related to the shaping of concrete are the fluid behavior of the mix during the process of pouring and the structural resistance of the formwork to the pressure applied by the cementitious mix (Fig.5).

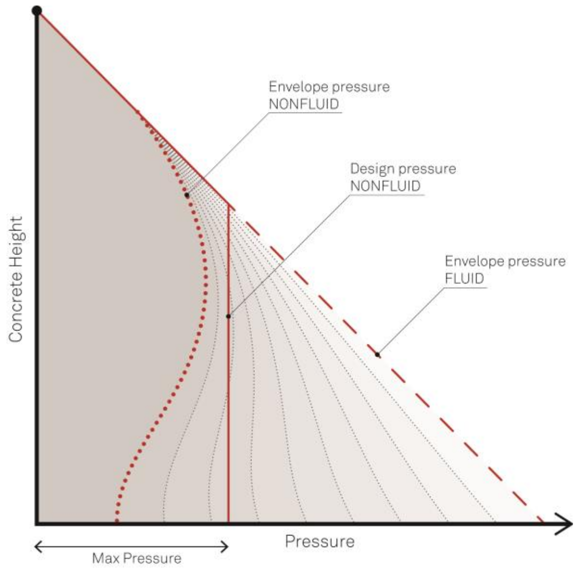

Figure 5: Typical and assumed distribution of concrete lateral pressure on formworks. Source: authors.

One of the predictive analysis tool that has been carried deals with the understanding of how the *pressure* of the fluid material is distributed on the 3D printed surface of the formwork. This can certainly induce breaking of the plastic material, or lead to elastic or plastic deformations, which would not ensure sufficient precision, particularly in the case of complex detailing. A custom algorithm written in C#, run in Grasshopper and relying on the Kangaroo live physics engine has been developed to access and preview this behavior. The simulation studies the fluid at rest, when the formwork is completely filled. Hence, the equation for lateral formwork pressure provide only the maximum to be used for design. Given the fluidity of the chosen material, the system can be assumed as quasi-hydrostatic (CIRIA 2003), where $p = \rho gh$. Local pressure is then proportional to material density, and to the height of the fluid or plastic concrete from top of the placement to the point of consideration in the form. In fact, the hydrostatic pressure is defined as the pressure exerted by a fluid at equilibrium at a given point within the fluid, due to the force of gravity. Therefore, it increases in proportion to depth measured from the surface because of the increasing weight of fluid exerting downward force from above.

Specifically, the force computed and applied through the Kangaroo engine, pushes each vertex of the mesh to the average of the normal directions of its corresponding faces, with an intensity given by the previously defined proportion. Doing so, the deformation of the mesh follows pressure pattern, hence it gives an intuitive suggestion of the the behaviour of the formwork under the stress of a self-compacting concrete.

The examples (Fig.6) below illustrates the behavior under these system of forces for different formal configurations. Example A e B presents a smooth surface, and a linear increase in the pressure distribution along the height of their boundary surfaces. Test C, which presents a twisted perforation in the central part of the form that influence the pressure behavior, highlights a concentration of pressure in certain areas. The last iteration, D, presents the addition of reinforcing ribbings all around the surface, which have the bifold purpose of strengthening the column but also to give much higher resistance to the printed formwork.

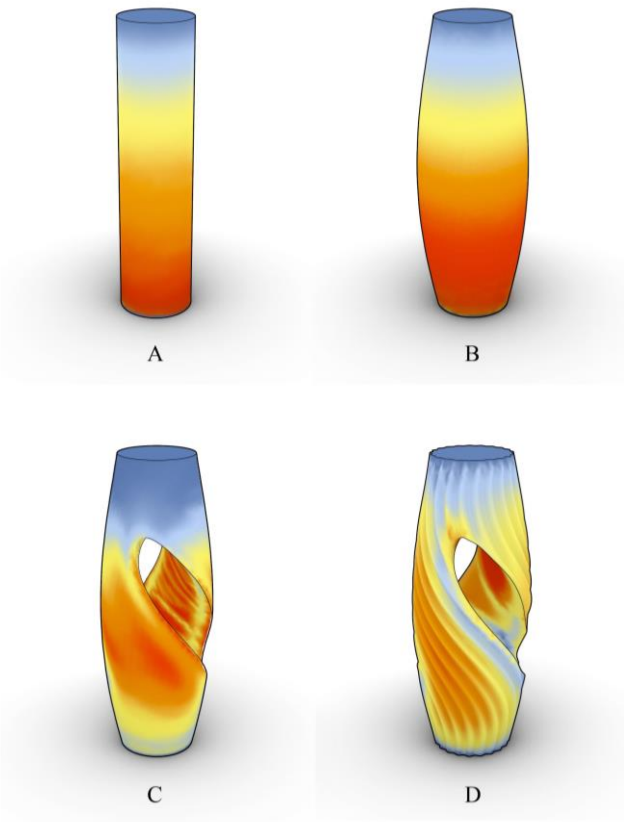

Figure 6: Pressure mapping on incremental design iterations for a 100 cm tall column. From A to D, features are added to improve formwork resistance to hydrostatic pressure, but also to challenge it with higher levels of design complexity. Source: authors.

MATERIAL FEEDBACK: CONCRETE FLUID SIMULATION

Initial tests have demonstrated that the cementitious mix is not easily pourable in topologically complex and highly detailed geometries. Fluidity of the material is a relevant discriminant and necessary condition to fill such geometries, being it able to flow into the form and to take the shape of the 3D printed formwork. Furthermore, the material has to be self-compacting, due to the difficulties of an eventual vibration process. Even if the level of viscosity can be very low, such materials can present a non-isotropic and non-linear behaviour while pouring. Hence, in order to be able to have a complete and precise filling of the formwork, it is important to be able to have a prediction through simulation on how the concrete fills the 3D printed envelope.

It is here presented a method for the simulation and assessment of the flow of cementitious material in the formwork (Fig.7). Houdini, a 3D animation software developed by SideFX, based on procedurals logics and widely spread in the computer graphics industry. The software has powerful engines for physics, dynamic and volumetric simulations, making it very suitable for the simulation of material behaviours and collisions. In particular, Houdini contains a *FLIP* (Fluid Implicit Particle) fluid solver, a hybrid between a *volumetric* (voxel-based) engine, with predictable results yet computationally inefficient, and a *particle system*, computationally fast but unpredictable: a FLIP system calculates particles movements in an adaptive grid with defined characteristics. Being computational time and power required are barriers in the use of particles systems for simulation of fresh concrete flow (Mechtcherine et al. 2014), the improved speed of computation of FLIPs can guarantee a relatively fast simulation yet with a relevant resolution providing informative indications about the behaviour of the fluid.

The developed procedural routine allows to control the simulation in its three constituent elements: the formwork, the concrete pump and the cementitious mix. Any generated or imported mesh can be set as rigid container, i.e. formwork, of which it is possible to control its characteristics, such as friction, elasticity and temperature. Parallelly, a source of emission, i.e. pump, can be defined in its position and dimension, but also the volume of material (particles) it pours and their velocity of emission. The emitted particles, i.e. the concrete mix, are defined by the combination of a set of variables, some specifically related to the engine, e.g. particles separation and dimension, which determines the resolution of the simulation, and other characteristics related to the material itself, such as temperature, density, friction and viscosity.

The output of the simulation allows to evaluate the rate of filling of the formwork and the eventual non-homogeneous distribution of the semi-fluid material in the mould. Specifically, the simulation produces a time-dependent animation which provides information about different parameters in play. Shown in the figure below, the visualisation of the local velocity of the fluid at different time frames allows to assess how this is flowing in the shape and to identify eventual bottlenecks that prevent it to fill completely the formwork. Parallelly, a 3D mesh of the concrete filling the mould is provided.

Figure 7: Visualisation of local velocity vectors relative to the cementitious mix, showing its direction and intensity of movement. Together with that, a 3D mesh shows the material filling the mould. Source: authors.

PRINTING VARIABLES: PRINTING ANGLES FEEDBACK AND OPTIMIZED TOOLPATH

On the one hand, 3D printing bring a vast amount of freedom in design and fabrication, allowing to think beyond the limitations of conventional manufacturing methodologies. On the other hand, FDM printing technique brings its own disadvantages and limitations. One of the most relevant is the fact that, being the material deposited in a semi-molten state, the angle between one layer and its previous one should be carefully controlled so that a sufficient amount of material is always present for the molten material to be supported. To be able to have a direct real-time feedback, a digital tool has been developed in C# and implemented in Grasshopper in order to asses the printing angle of each layer. This allow visual and numerical control over this parameter during the modelling phase, reducing timing and possible errors or large angles which would cause bad printing quality or even failure in the manufacturing process (Fig.8a). Taking the normal direction at points at a defined resolution on the surface, is calculate the angle that intercuts between this vector and the printing plane. The limit safe angle is usually considered 45 degrees, but in most cases 60 degrees can be printed without losing too much quality. With bigger nozzles these angles can be more extreme.

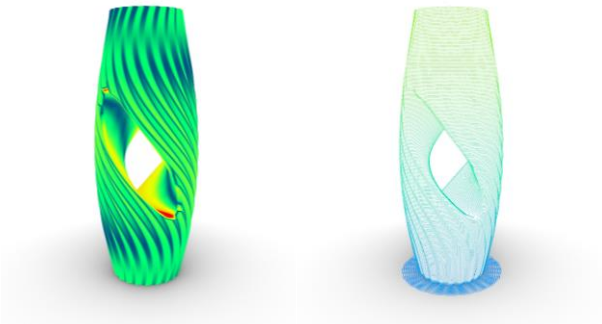

Figure 8: a: visualization of real-time printing angles feedback, where red is over 65°; b: visualization of the optimized printing toolpath. Source: authors.

Common slicing software are conceived and built on the typical dimensions of 3D printers, and they disregard some important aspects that instead are crucial for a large scale production process. In fact, often passing from one layer to the next one, or from one part of the print to another one not continuous, the printer has to travel, i.e. move without printing, and this become very time consuming when printing with a large-scale machine. Moreover, given the large amount of material that is constantly extruded and the dimension of the printing nozzle, it is still hard to precisely control the flow of material when travelling.
To have a better control over the printing toolpath, over the machine movement and the amount of material extruded, a custom parametric routine for the definition of the slicing pattern and the generation of the .gcode have been realized into Grasshopper and C#, relying in part on a the script generated by WASP (Fig.8b). This routine translates into a set of tools which can be used by users that starting from a 3D digital model are able to control the multiple parameters, from speed and height of the layers, to those more detailed which are crucial in the context of large scale printing, such as the orientation of the curves, the start and end position of each layer and the travel paths. Everything is then translated into machine language and automatically saved as a .gcode file.

REUSABLE FORMWORK

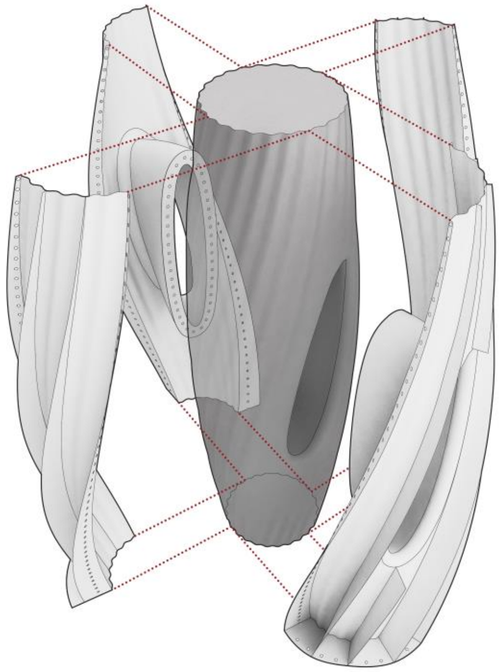

Figure 9: Exploded view of the 3D printed formwork. Source: authors.

Current approaches for 3D printed formworks are melting and wasting the produced cast as a one-off product. As mentioned earlier, this makes the technique highly inefficient, wasteful and economically not feasible. Furthermore, a prolonged exposure of the concrete to a source of heat is likely to reduce its mechanical properties.

Hence, it is here presented a component-based cast able to be assembled and disassembled prior and after pouring, making it easy to open and also 100% reusable for multiple releases (Fig.9). Segmenting the geometry into mountable and removable elements requires considerations regarding the procedure, so to avoid having geometric obstructions in the unmounting phase. The exploded view in figure 8 shows the four components that joined results in the final column form and how each of them can slot in and out before and after the release and hardening of concrete.

The target to develop a scale-independent system creates the need for conceptualizing a novel type of joinery which can address geometric complexity while being convenient in terms of site assembly. Moulds are assembled by a quick joining technique which ensure the realization of seamless shapes and avoid material leaking. The necessity of printing fast for the technique to be feasible, requires higher printing layers, hence lower resolution, which is still abundantly within the accepted limits for the realm of constructions (2-3 mm), but puts a limitation when dealing with details and joinery during fabrication. To avoid the necessity of dealing with small scale elements, the approach is to use threads to ensure a continuous joinery that allows ease of use and permit to have a distributed loading without heavily reinforcing the structure.

Figure 10: Complete formwork joined through sewing. Source: authors.

At the edges of each part of the formwork, a larger offset on the outer side of the mould was made in order to host a series of holes evenly spaced at 2cm distance. Each component having corresponding sewing surfaces, the components can be easily stitched from outside, providing the cast block's surface continuity without any interruption caused by the joinery system (Fig.10, Fig.11). With the concept of sew 3D printed elements' coming into play, the system gains a new feature that reduces the labor cost and provides easy assembly without skilled workers.

Figure 11: Detail of sewing joinery. The method ensures a constant pressure over the edge, avoiding any leakage and ensuring a non-visible seam on the concrete surface. Source: authors.

Figure 12: Casted column after disassembly of the formwork. Source: authors.

RESULTS

The developed research integrates computational design and traditional concrete constructions technique. The development of an applied case study has been instrumental to develop and verify the necessary set of tools to predict and optimise all the design that might influence the quality and precision of the manufacturing of a precast concrete element through a FDM process.

Throughout the development of an applied case study, different findings have emerged. It was proven that FDM can be suitable for mold-making of intricate geometries, with different levels of complexity involved. In particular, for small objects, shell-based printing have been sufficient in preserving precision and mold integrity.

Part of the results involve the development of intuitive tools for designers, in order to have a direct feedback on some problematic aspects, such as pressure of the concrete on the formwork, and distribution of the concrete in complex geometries. The tools have proven to provide a visual aid for the design, by highlighting zones that can be problematic, eventually driving the design into feasible solutions.

The making of the column has allowed to develop a specific approach to mould making with FDM: successful segmentation for complex geometries allow to produce multiple elements; the sawing joinery allows for a low-tech solution that is easy to put in practice and efficient in use. Finally, the produced concrete column has shown that areas of difficult accessibility demand the use of self-levelling concrete, as vibration is difficult to apply.

DISCUSSION

As the research goal is using FDM printing technology for the manufacture of construction systems, the work here presented is a preparatory stage that aims at developing a set of digital and technical tools, testing them at a smaller scale with conventional mid-size 3D printers. Hence, for a full scale development of the technique a series of considerations have to be taken into account:

- Development of accurate simulation of the pressure that the formworks will need to withstand;

- Rigorous studies on the formwork material, as scaling the process will imply more pressure from the concrete as well as longer printing time, hence requiring a further optimisation of the manufacturing process by means of efficient layer extrusion and material resistance;

- Studies on the relation between the features of the cementitious mix, i.e. fluidity, compression and tensional strength, and the casting of complex geometries;

- Improvement of the joinery system, in terms of resistance to the pressure and applicability at the larger scale.

Finally, to imagine applications in real buildings, will be explored the possibility of introducing rebar positioners in the design, to be printed integrally with the formwork.

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