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Digital fabrication phasing for monolithic shells

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Abstract

The digital formulation of monolithic shell structures present some challenges related to the interface between computational design and digital fabrication techniques, such as the methods chosen for the suitable parametrization of the geometry (Bravo, M., 2013) [1], the optimization criteria of variables, the translation of the relevant code for digital fabrication, and especially the phasing related to the matter becoming material within the digital fabrication process.

This paper exposes the process for the implementation of new digital and physical methods for monolithic shells design and construction using digital fabrication techniques combined with enjoyable manual craft. It explores the potential of carefully recalibrating the phasing between digital parametric modeling formulation and simulations with the physical translation aiming at renewing shells construction processes, in terms of the time it takes to build them, the optimization of materials and labor, and the feasibility of the dweller to be involved during different phases of construction. In addition, it will highlight significant changes that digital fabrication can engender in the use and the resulting aesthetics. (Huijben, Van Herwijnen, Nijsse, 2011) [2].

The paper will feature 2 case studies, detailing the steps required to take advantage of the circular data flow involved in digital modeling techniques, matter characteristics, structure distortion, and digital fabrication tools using robotics (Block, Veenendaal, 2015) [3]. It will explore examples implemented with an easily mounted temporary or lost formwork, and the methods of 3d scanning iteratively or in real time, so the form in progress can inform the system when at a later stage the fabrication tools will be depositing the material. The potential of integrating sensors and radars used in the car industry to create new protocols of construction will be explored, such as having a set rule between the angle of extrusion and the level of material's viscosity. New interfaces between 3d modeling programs will be presented (such as rhino and robotic fabrication - Kuka prc for example -) and the resulting novel monolithic shell construction experiments will be revealed.

Keywords: Digital modeling, digital fabrication, optimization, parametric modeling, monolithic shells, earth structures, robotic fabrication, removable formwork.

1. "Monolithic mud shells and digital fabrication: concepts and referents"

Shell structures have been used in architecture since ancient times because of their many advantages, such as self-supporting properties, wide spans without internal supports, unobstructed interiors, and undeniable aesthetic qualities of the enclosed spaces. Shells implement the principle of "resistance through form" (Eladio Dieste, 1996) [4], using geometries with curvatures or folds that result in active surfaces or membranes. The strongest type of shell is called "monolithic" because "it's commonly built as a single cast and act as a single unit [5].

The use of mud for shell construction is a modest but relevant referent that can be found in ancient traditions, advocating the use of local materials, basic construction techniques, and highly sustainable practices and methods. Some references include: the *Nubian vaults (Sudan*), the *Harran Beehive Houses* (Turkey), and the *Musgum mud huts* (Cameroon), among others [6]. They are constructed with small lumps of sticky clay thrown by hand one on top of another following immaterial trajectories as geometrical guides, with simple and repeated motions.

Often referred as 3D printing, additive manufacturing is now implemented at diverse scales and techniques for earth construction. Among them, robotic fabrication is taking a relevant place where two main strategies can be found: extrusion and spraying.

Extrusion is conducted through a nozzle by which the paste like material is deposited, achieving complex geometries, but heavily restricted to the size and characteristics of the deposition apparatus. Some important initiatives in clay extrusion include Andrea Graziano "*Co-de-it*" in the "*inFORMed clay matter*" research project, that explores 3d printing using a 6-axis robotic arm. Extrusion for 3d printed objects is under investigation in the research "*G Code Clay*" (by Rael San Fratello) using various clays (porcelain, bmix, terra-cotta, and recycled clay). The Italian firm Wasp works with a clay mix (clay, sand, and fibers), for their recent large-scale experiments. Several experiments with extruded paste like materials are being conducted at Iaac [7].

The spraying technique deposits material through a nozzle under pressure, and has a long history using shotcrete (both wet and dry concrete mix), widely used in a variety of construction applications including civil works, pools, and buildings [8]. Spray concrete was extensively explored in shin shell structures lifted by pneumatic formwork patented as the *Binishell System* (Bini and Fontana, 2014) [9]. In addition, fabric formwork has been widely explored with *concrete* (Hawkins et al., 2016) [10], a technique that has recently been recovered using concrete spray applied on a temporary fabric formwork with metal mesh reinforcement (Veenendaal and Block, Philippe, 2014) [11]. Although this work is clearly different from mud spraying, it presents some opportunities for the automatization of its placement, as seen in the work in 2016 from *AA Visiting School in Stuttgart*, where robotic spraying with fabric formwork was tested. Mud digital fabrication using spray is only recently being explored, influencing and shaping many workshops, like the *Smart Geometry* preliminary experiments from the *AA visiting school Lyon* (co-led by S.Chaltiel and MP.Placais in collaboration with Wilfredo Carazas earth aspecialist from CRATerre laboratory) from 2012 to 2015 at the *Grands Ateliers de lÍsle dÁbeau.*

Despite that the findings of these experiments are modest and incipient, the appearance of digital technologies unveils a potential use of spray 3d printing techniques for monolithic mud shells construction, and this paper explores the suitable methods and protocols for its implementation.

2. "Phasing 3d printing techniques for monolithic mud shells"

The use of mud for shells requires that the mechanical properties of the material must be considered, to achieve a self-supporting condition from its inception, therefore two items are fundamental. Firstly, a support system must be in place prior to applying the material. Secondly, placing of the mud must ensure the continuity of the layer to achieve a "monolithic" condition. These properties become highly critical for thin shells because they work with a reduced material thickness and exhibit a more fragile condition.

Preliminary experiments in 3d printing of clay monolithic shells reveal that one of the most deterministic factors is related to the protocol established in a sequence to complete the process of 3d printing, which has been denominated "phasing". The organization of this critical time-based sequence must be properly defined and formulated, following these steps:

- Design Proposal / Form Finding
- Formwork Setup
- Material Preparation [Mix - Type of sprayer – Trajectories]
- Deposition [Robotic Spray Deposition]
- Optimization [3d scanning - Export Scan to 3d model - 3d model optimization - Re-adjusted spray]
- Curing time and formwork removal [temporary, lost].

Details of each step are provided in the description of the case studies.

3. Case studies: "Two cases of digital fabrication for monolithic mud shells"

The implementation of digital fabrication techniques for mud monolithic shells has been explored in two workshops implementing singular "phasing" protocols. The first example explores simple shells, and the second includes perforations in the surfaces, and several other changes, which are detailed below.

3.1 Case Study 1: SMART GEOMETRY WORKSHOP.

4-days workshop. April 2016, Gothenburg, Sweden.
Cluster: "*Mud, Textiles and Robots for large structures*"
Participants: 10
Cluster´s tutors: S. Chaltiel and A. Dubor.

2.1. Design proposal / Form Finding:

The design proposal was to construct an earth monolithic shell by robotic spray fabrication and manual craft. Three structures were fabricated with a base of 1m x 2 m, ranging from 1m to 2m in height. The proposed design must be based on the use of concave arches, considering the differences between peripheral and internal arches (Fig. 1).

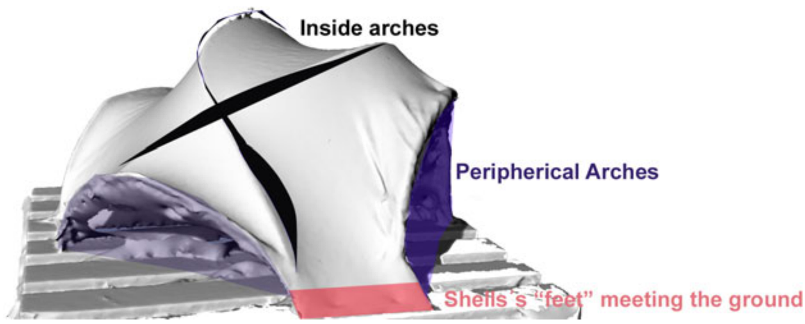

Figure 1: Defining distinctive areas of the earth shell in progress: peripheral arches, inside arches and shell's feet. [Stephanie Chaltiel, 2017]

2.2. Formwork set-up:

Temporal stability during construction is provided and it's composed of the following parts:

1) Self-standing bending arches in clusters of 2 or 3 willow branches, of 2cm in section and about 3m in length, were used to define the peripheral arches and inside area of the structure. Sufficient contact for the arches along the surface meeting the ground was provided with a plywood board surface with drilled holes to insert the bending rods (Fig. 2).

Figure 1: Setting up of the main formwork arches where the pulled fabric will then be mounted. Smart Geometry 2016. [Photo by the participants of the cluster].

2) An elastic membrane (Lycra) stretched by hand on top of the bending rods create a temporary formwork defining a tense minimal surface. It allows quick adjustment by hand, greater flexibility for different forms, quick and easy removal of fabric elastic formwork, and controlled smooth finish once the process of drying is completed.

3) Pouring the spray mud mixed with fibers (strips of jute) while the clay layers are still wet, to generate lost formwork that will merge with the clay mix over time, creating an assembly of interlocked materials.

2.3. Mix Preparation:

The clay mix is slightly different at each successive layer, using a varied composition of clay (binder to hold the mix together brought from Barcelona and extracted from Terruel), sand (aggregate that provides bulk and stability), and fibers (reinforcement that helps to hold the mix, control shrinkage, provides thickness and flexibility, natural straw of 3 cm were used). Three layers were proposed (Fig.3) with the following proportion:

- Mix "Base" mixed with water also called ¨barbotine¨ in French which consistency is similar to choclate mik. (1U clay, 1U hard sand);
- Mix "Fibra 1" (1U cay, 1U sand, 1U fibres);
- Mix "Fibra 2" (1U cay, 1U sand, 2U fibres).

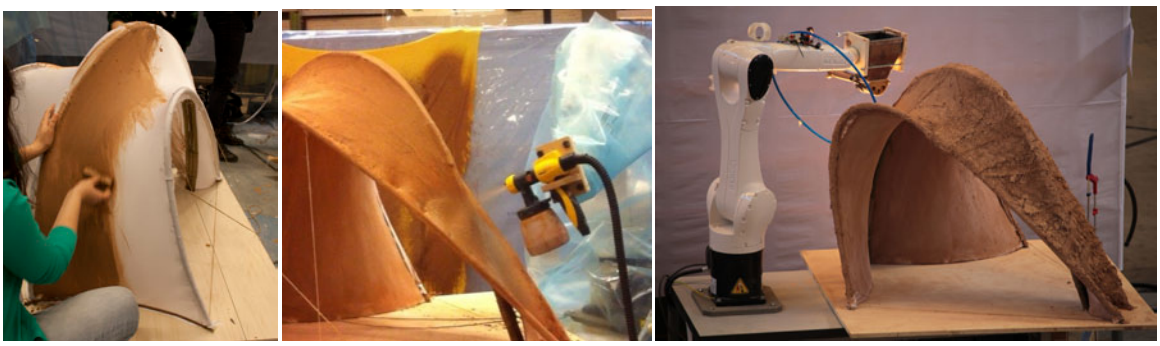

Figure 2: Application of first layer "base" or ¨barbotine¨ (left); Clay mix spray on successive layer (center); Wagner heavy paint sprayer connected to the Agilus Kuka robot containing clay mix and spraying in progress. Smart Geometry 2016. [Photo by the participants, 2016].

2.4 Deposition [Robotic Spray]

Robotic spraying constitutes a crucial step as it allows greater level of homogeneity and the application of thinner layers at each coating, and it's dependant on the sprayer type used. Two types were attached to the robotic arm:

- A Wagner sprayer for heavy paint is used to spray the first layer (wet clay mix containing only clay, sand and water). The sprayer handle was modified so that it's constantly in ON mode, therefore turning on and off can be controlled digitally when the air compressor connected to the robots. This sprayer is made with plastic detachable parts, which made possible to 3d print one part of the nozzle and making the opening slightly larger to avoid any clocking of the mix.
- A concrete hand sprayer (approx. 20 cm sizee) made of stainless steel was used connected to the Agilus robot for the application of the following layers containing clay, sand, water and fibers. The nozzles were made of a little board containing 3 holes, a new little board with larger 3-2 cm diameter holes was laser cut to allow more material to be sprayed.

The robotic control uses 2 Kuka Agilus of 1m reach, controlled through Kuka Prc Grasshopper. The end sprayer tools were modeled in Rhino and included it into the Kuka PRC definition (Fig. 4), where the default drill was replaced with the end of the sprayer, placed at the same location and direction in the 3d space. Calibration of the distance between nozzle and fabric formwork was tested, and set at 20cm for the best homogeneous finish, and trajectories were proposed.

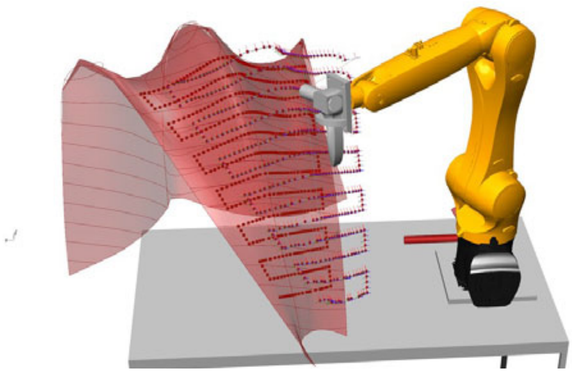

Figure 3: Continuous Robotic trajectory in Kuka PRC Students´s work. [Smart Geometry 2016].

With Kuka prc the robotic trajectory simulation can only be checked with visual simulations, not in the code, so manual tests were conducted on the spray technique, speed, geometry, following the curves of the structures or spraying in horizontal lines from left to right, which proved to be the most efficient in terms of homogeneous finish. Also, the movement freedom of the robot is limited as if the rotation to be below 45 degrees (Fig. 5), to avoid the mix to fall out of the sprayer.

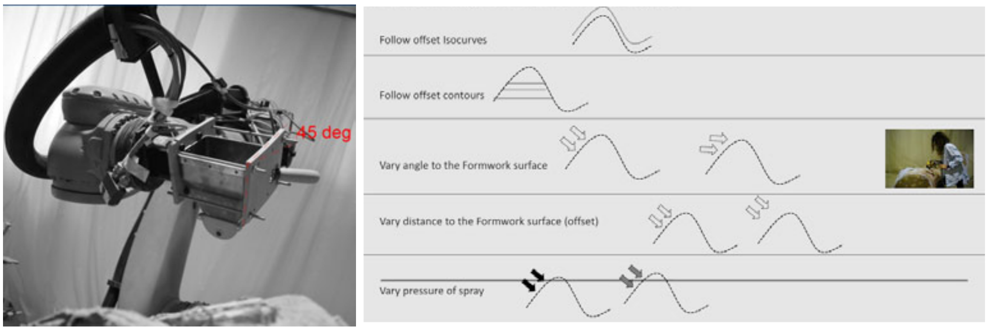

Figure 5: Sprayer ready for Robotic spraying at fixed angle of 45 degrees (left) and parameters for robotic spraying (right). [Stephanie Chaltiel, 2017].

2.6 Optimization

The 3d scan of the shell in progress is done using Agisoft software from digital images in a highly contrasted environment, or a Kinect motion-sensing device. The scan must be done to test their deformation at two stages: 1) Before any material is applied; 2) After the 2 first layers of clay mix are applied to highlight the sagging on each rib side. So far, this process has been done iteratively but not in real time.

The 3D spatial data obtained from the scan generates a very detailed mesh that, when exported into Rhino 3d needs it's simplified and cleaned up using Grasshopper plug-ins, to detect triangles, reduce their number and close the mesh. The optimization for the 3d model is performed using Karamba, a parametric structural engineering tool embedded in Grasshopper plug-in, that is able to perform finite element calculations, which detects variations in the shell thickness. The 3d model optimization using Karamba simulations (Fig. 6) were to optimize two issues: 1) to vary the shell thickness precisely to use the minimum amount of material, and 2) To achieve auto-stability and integrity of the structure.

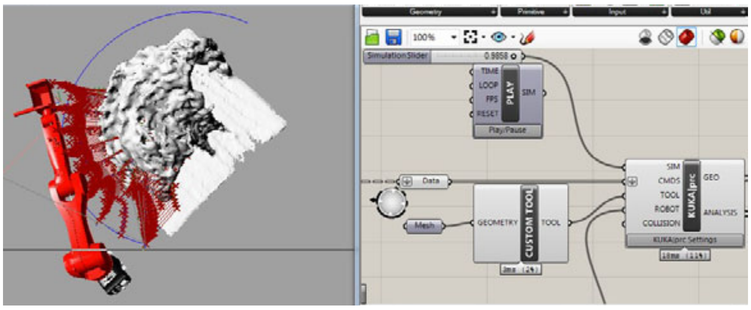

Figure 6: Robotic trajectory in Kuka prc spray on the 3d scanned structure modeled into a Rhino mesh (left). Grasshopper definition with custom tool box of modeled sprayer connected to the Kuka prc settings box (right).

2. 5. Final re-adjusted spray.

The main challenge of the re-adjusted spray is to rapidly correct the robotic spray trajectories aiming for the thinner layer and most homogeneous deposition, at a minimum distance of 30 cm away from the structure in straight horizontal lines. The structure reaches sufficient thickness in proportion to its height at approximately 3 cm thickness for 2 m height.

2.5. Drying time and formwork removal [temporary or loose]:

Drying time in between coatings must be ensured, and it was around 5 hrs but due to time constrains, the process was slightly accelerated with a manual hair dryer, decreasing it to 3 hours. Setting time can be verified manually by touching and knocking slightly on the structure.

The formwork removal must be executed carefully as follows: 1) Peeling of stretched fabric; and 2) Removal of branches. This process requires both strength and care, in order not to make the structure fragile.

3.2 Case Study 2: IAAC WORKSHOP "PERFORATED MUD SHELLS", May 2016.

May 2016 ; 25 hours seminar for first year master students (Term 3). IAAC, Barcelona, Spain.
Seminar Title: "*Phriends for Shells*" ("Phriends" was defined as the safe interaction between people and robots during structures´ fabrication progress).
Participants: 23
Tutors: S. Chaltiel, D. Stanejovic (robotic expert), Y. Mendez (assistant).

This seminar tested the digital fabrication of monolithic mud shells with perforations of increased thickness around the openings, producing five structures of 1.5m x 1.5m x1m (height) in size.

The formwork was set-up with a base made of plywood board, where the holes were used to include the bending rods. These rods were very delicate reeds and their behavior was very different, so it was more difficult to pull the fabric on the resulting arches and the robotic spraying needed to be very gentle. The openings for the perforations needed to be defined before applying the first coating of clay mix, and laser cut rings and triangles were mostly used to create those temporary formworks removed after the last layer of clay mix applied, so that the holes could be formed.

The material preparation of the mud mix was done in a large bucket and stirred by hand with an automated mixer for both fibrous and non-fibrous layers, with the limitation that the properties couldn't be constant in terms of air and water content. A Wagner heavy paint sprayer Flexio 590 HVLP, with external air compressor (kit part) was used, in addition to the manual concrete sprayer "Sablon" to spray the clay mix containing fibres (Fig. 7).

Figure 7: Concrete hand sprayer "Sablon" connected to Kuka robot wth fibrous mix spraying on the earthen shell in progress. Iaac seminar May 2016. [Photos by the seminar´s participants].

The robotic control with the openings was quite simple with the 3d scanning with Agisoft software included the lycra fabric with colour marks, so that the geometries could be more accurately 3d scanned. Only 2 - 3d scans of the structure in progress were possible at the following stage: 1) When the structure was only fabric and branches; and 2) After two first robotically applied clay mix layers. Each scan revealed that the shape was changing dramatically during the process, because wet clay mix is very heavy while sprayed into layers, so that robotic trajectories needed to be constantly recalibrated and reinserted into Kuka PRC software (Fig.8).

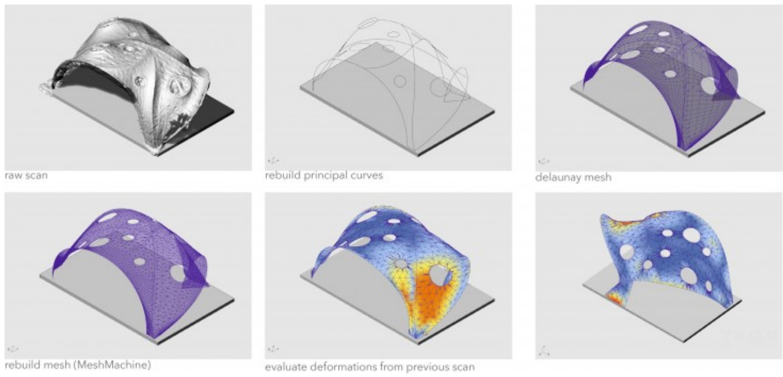

Figure 8: Rebuilt mesh from initial 3d scan before and after material application. Deformation evaluation between dry and wet structure. [Group 1, Iaac seminar, May 2016].

The 3d model optimizations using Karamba found the right compromise between perforations location on the mesh and thickness variation of the structure using the minimum of material possible for auto stability (Fig. 9).

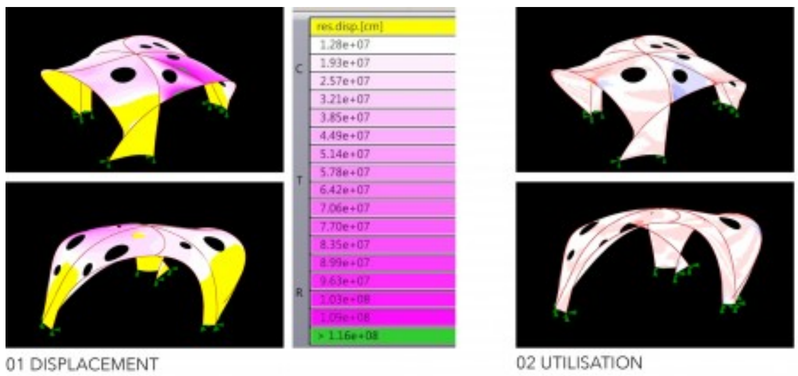

Figure 9: Karamba, Grasshopper, Rhino´s simulations on the resulting mud shell structure. Regions of the shell are defined by displacement and utilization criteria. [Students work from Iaac seminar, May 2016].

The fabrication process lasted 4 weeks, so more layers could be sprayed. The work was done indoors and the drying time was at least around 4 to 5 hours in between each spray layer. Before removing the temporary formwork of the lycra fabric and bending rods, the last layer of natural stabilizer was robotically sprayed. A highly viscous cactus solution was applied, prepared and cooked by Yessica Mendez (teaching assistant of the seminar). Once the shells reached at least 2 cm in thickness and all layers were dried, both lycra fabric and bending rods were removed (Fig. 10).

Figure 40: Resulting mud monolithic shell after formwork removal from Iaac seminar May 2016. [Photos by the seminar´s participants].

4. Conclusions: "Potential and limitations for 3d printing techniques for of monolithic mud shells".

The results of the proposed 3d printing strategies for mud monolithic shells confirmed the importance of establishing a correct "phasing", or a sequence that must be based on specific principles, parameters, and practices, that proved critical for its successful implementation.

The advantages of robotic spray for mud monolithic shells opens up an important field that could be expanded and explored, offering homogeneous and thin layers, the best finish are possible compared to traditional applications; minimum weight of the clay mixes by spray instead of extrusion; a higher degree of geometric freedom as the system doesn't need to be ruled by a vertical pouring of layers; and most importantly, the integrity of the monolithic shell seems to be achieved.

The main challenge of the formwork stage was to take full advantage of the tension and compression along the surface of the monolithic shell, so that while the minimum surface provided by the lycra fabric is still in place the structure works mostly under tension, and after the continued deposition of material on top adds weight until the structure is strong and thick enough, when the resulting shell works [mostly] under compression. The success of the fabrication technique could be observed after removing the initial fabric elastic formwork, revealing that that the thinner the layer and the more homogeneously applied mix on the fabric, the greater chance of survival of the structure, and the strongest is the resulting structure.

An important fact in this technique is related to the invisible properties of the clay mix, such as water and air structure which have significant incidence on the material application and constant stirring is recommended while the structure is being fabricated to avoid clay mix drying or changing consistency.

Robotic trajectories performed by Kuka robots were controlled by Kuka PRC and set by default. Only the trajectory of the end tool is the variable, while all the 5 other articulations just rotate to allow the overall trajectory of the end point of the tool (in this case the nozzle hole of the sprayer). However, sometimes some trajectories don't allow normal rotations of the 5 other articulations to happen when one member of the robot will collide into each other. Each of the 6-axis in the robot need to be coordinated while rotating and certain trajectories, that drawn on rhino cannot be achieved in reality.

In case study 2 (Iaac Seminar) the iterative robotic spraying around the perforations has proved to be important in reinforcing the structure in the weaker points. The junction between the shells edges and the ground were particularly important for the self stability of the structure as the perforated structures requires even more strength than the non perforated shells from Smart Geometry. It's still ambiguous whether it is best for the auto stability of the structure to have greater thickness around the openings and would require further digital simulations and physical testing to be able to draw conclusions.

Some of the research limitations involve the lack of structural testing performance in any of the models; the absence of real size prototypes; the exploration of the kind of most suitable geometry for mud shells, or the thresholds of diversion that can achieve self-standing properties, or the most suited foundations, or where to effectively put the perforations, have not been implemented.

Future investigations could experiment with inflatable formwork, where the unrolled pattern could be cut robotically after having been digitally simulated, and robotic spraying would happen earlier in the phasing. Specific tools could include in GH definition control, such as for example, knitting a fabric temporary formwork.

Both case studies demonstrated than iterative 3d scanning of the form in progress was key to the success of the resulting structure for the possibility of readjusting the robotic trajectories and actions while spraying. The protocol of iterative 3d scanning must be further explored, in order to include real time adjustments of the structure in progress, or even including some available technology used in the car industry. For example, tests can be performed where the robot doesn't only spray, but continuously 3d scan the structure at the same time.

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