Light formwork for earthen monolithic shells

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Elizabeta Šamec
University of Zagreb

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LIGHT FORMWORK FOR EARTHEN MONOLITHIC SHELLS

Elizabeta Šamec (1), Akash Srivastava (2) and Stephanie Chaltiel (3)

(1) Faculty of Civil Engineering, University of Zagreb, Croatia

(2) Indian Fellow, Domaine de Boisbuchet, Lessac France

(3) ETSAB UPC, Barcelona, Spain

Abstract

The ongoing research in project *Small scale robotic manufacturing for large scale buildings,* developed through the *Innochain* network by Stephanie Chaltiel, is investigating how robotic fabrication enables construction of earthen monolithic shells in near future context. Introduction of small-scale robots (drones) in to the building process revives building of earthen shells in general by minimising labour intensive tasks, leaving more time and budget for skilled work.

By describing two case studies, paper sheds light on robotic fabrication process and timeline of the construction, as well as constraints related to architectural and structural requirements according to usage of different lightweight formworks and drone deposition techniques. The paper discusses role of pneumatic and wooden formwork, since the replacement of conventional scaffolding by use of flexible formwork is very interesting research subject [6, 7 and 8], enabling additional savings regarding the material, cost and time necessary for the construction. According to results of case studies the paper highlights key inferences to govern future physical experiments towards successful development of Bioshotcrete construction technique for earthen shells.

Keywords: light formwork, pneumatics, earthen shells, drones, digital fabrication

1. INTRODUCTION

Raw earthen structures are recognized by literature as traditional structures made from the mix of natural soft materials (clay, sand, marble powder, fibres, etc.). Although large scale inhabitable unbaked pottery is long known, for example the Musgum domes in Cameroun, due to intensive manual work it still has non-legitimate status in some European countries. Today when sustainability in construction becomes crucial, earthen architecture is being reconsidered, due to its little ecological footprint; both during construction and period of use.

The paper aligns to the research [1] carried out by Stephanie Chaltiel in the project *Small scale robotic manufacturing for large scale buildings*, a part of the *InnoChain* network. The project develops Bioshotcrete construction technique [2] that consist from the sequential layering of different types of mixes of clay and fibres over the temporary lightweight formwork using drone spraying technology, consequently leading to building a self-standing shell.

With aim to revive building of earthen architecture in modern context, this research imposes few objectives [3]. Firstly, to use non-cement based mortar, enabling construction with natural material that has unique combination of thermal insulation and heat storage properties. Clay is the most widely available primary material and it can be used in geographically diverse locations, making it extremely suitable to build temporary shelters (refugee camps and disaster zones). The traditional way of applying clay on formwork is relatively non-uniform, laborious and time-intensive process. Therefore, second objective is to minimize intense manual labour. This can be achieved by implementing robotic fabrication processes i.e. developing on-site digital fabrication strategies using small-scale robots. The last objective is to minimize formwork – the objective that this paper shall deal with elaborately.

2. BIOSHOTCRETE TECHNIQUE

The wattle and daub is a traditional earthen architecture technique consisting of coating layers on both sides of the lost formwork (made out of flexible intertwined branches) until sturdy envelopes are reached at the end of the curing time. The technique is applicable but contains very labour intensive manual tasks. For other materials, like concrete, more sustainable solutions are developed through the past, like shotcrete. Therefore, team of robotic experts, architects, engineers and drone specialists explores how to use the robotic techniques for digital fabrication in order to combine traditional procedures of building with earth and modern needs for efficient and fast construction. The research resulted in development of Bioshotcrete technique for building large scale monolithic earthen shells [2].

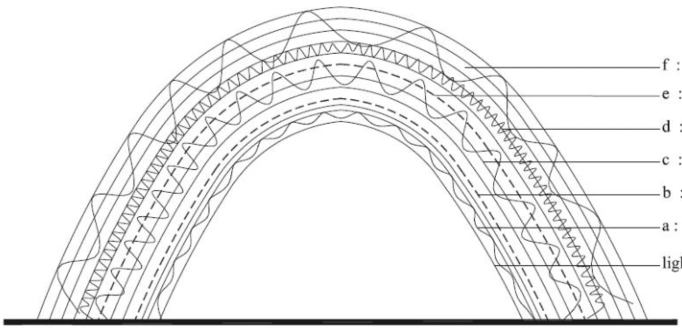

Figure 1: Cross section – succession of applied layers (based on [3])

The technique consists in projecting paste-like matter, composed of carefully formulated different clay mixes, following precise and customised deposition sequences over a temporary formwork. By modifying the proportion of each ingredient in the mix (grains, fibres, clay, water, etc.) different consistencies, levels of viscosity, elasticity and stickiness are obtained [3]. The protocol of clay mixes deposition is heavily dependent on the formwork provided, the deposition apparatus and the robotic actions. Three main layers [3] can be identified as seen from the Figure 1:

i. Liquid layer for the initial spray – contains high percentage of plaster to form a thin solid crust to replace formwork action and enables its easy removal

ii. Viscous and fibre layers – high in sands and fibres to gain thickness without overloading the delicate formwork and to absorb moisture
iii. Dry layers – contain increasing sand diameter and grain size to provide volume and thickness to gain stability and ensure structural performance

The integration between matter and robotic actions depends on spraying device, material container and process of feeding the deposition apparatus until self-standing shell is completed [3]. Monolithic shells are chosen as structural system for this application, due to their ability to exhibit advantageous load-bearing behaviour resulting in spanning a large footprint with least possible material. Since the flights taken by the drone spraying matter need to be optimised, enabling the structure to be erected in least possible time span; the smaller cross section of the structure is thus a crucial parameter.

3. FLEXIBLE FORMWORK FOR THIN SHELLS

In last years, huge carbon footprint caused by concrete industry (31,654 million tons of concrete produced per year according to [4]) is forcing us to reconsider building shell structures as possible way to use concrete properties to their advantage, reducing the needed cross section. However, producing a formwork and scaffolding for such geometry specific structures is very material and labour intensive. Replacement of classical wooden formwork with different types of flexible formworks (fabric, pneumatics, etc.), has a history in concrete construction [4, 5]. New types of flexible formworks, like cables in combination with membranes or knitted material, are recently the research topic of great interest [6, 7]. Today, development of digital fabrication technology can help expand and transform existing construction methods for shells, and potentially offer more sustainable building solutions and usage of different materials [8].

In this research a series of experiments with flexible formwork were conducted. On the beginning a robotic arm fitted with a mortar hand sprayer (8L capacity) connected to air compressor was used to deposit a variety of clay mixes [1, 3 and 9]. As formwork, fabric stretched between compression elements was used until the structure reached self-standing condition and formwork was removed. Due to restrictions of a robotic arm [3], like reaching capacity of the arm, the cost, size and impossibility to bring such heavy apparatus in remote sites, further experiments were concentrated on using drone for spraying matter. With introduction of drones in to the building process necessity for scaffolding or any height limit of the structure (up to 25 m) disappeared, enabling further cost and time benefits for the project. Two real scale case studies using drone spraying for building earthen domes were conducted in 2018. Case studies will be presented and compared, with emphasis on used formwork and matter deposition techniques.

4. CASE STUDY 1 – LARGE SCALE TEST DRONE SPRAY OVER PNEUMATIC FORMWORK

In Drone Centre Barcelona, large scale outdoor experiment was conducted by depositing clay mixes on to the pneumatic formwork [2]. Deposition was made with custom made drone, that has 4 engines (each 20hp), carrying container of 5 to 35 kg capacity. It was piloted by automated flights using GPS systems, with 1 cm precision. As formwork, affordable prefabricated 4m inflatable dome was used (Fig 2A). Pneumatics bring following benefits in to the building process of earthen monolithic shells: reduced time for the montage, lesser "skilled" manpower deployment on site, negligible transportation, price reduction by multiple usage with ability to gain different shapes and textures, etc.

Except from beneficial properties, many of the existing pneumatic formwork systems struggle with process-related inaccuracies with respect to the reference geometry and the thickness of the final structure [5]. Behaviour of pneumatic structures is inherently nonlinear. They acquire their primary load bearing capacity after undergoing deformation which, even under small pressures, may be very large [10].

Figure 2: Tests made on pneumatic formwork (from [2]) - A) installation of pneumatic formwork B) matter deposition C) deformation under matter weight and deposition pressure

Regarding this case, pneumatics bring problems related to deposition of the material during the drone spraying. The membrane, becomes deformed when material with a comparatively high density is applied. With the drone carrying large amount of material and depositing it at once (Fig. 2B, 3A) the deflection from excessive pressure present during this non-constant deposition is very large (Fig. 2C). The weight of the material and pressure under which it touches the flexible surfaces cause hard control of shell geometry, resulting in deviations from the designed structure and variable shell thickness. The accurate geometry for such a shape dependent structure is highly important especially if small thickness of the shell is desired due to lesser number of spraying flights needed.

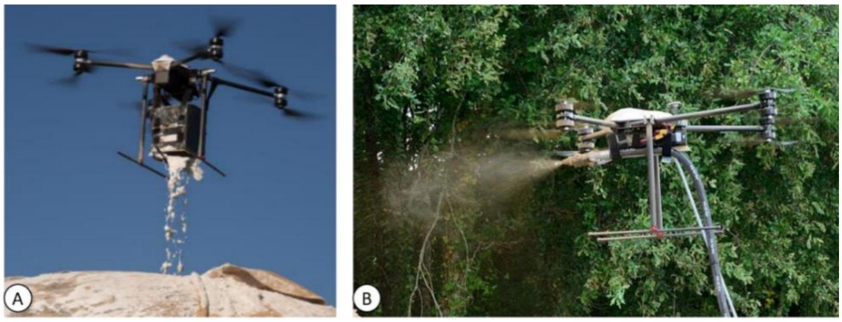

Figure 3: A) Drone carrying container with clay mix (from [2]) B) Drone with pipe connected to matter mixer and water

Therefore, the challenge is to achieve a very gentle and continuous deposition to avoid sagging and deformations. In order to accomplish that, research was concentrated on the development of the drone with ability to carry supply pipe, design and production of customised spraying devices and fitting options on the drone, allowing to vary pressure and other drone spraying parameter [2]. Drone was modified to carry pipe connected to a matter mixer with water on the ground (Fig 3B), enabling constant material feed, and helping to efficiently coat large surfaces with more homogenous coating of clay mix. After being tested indoors [10], new available spraying technology was tested for the first time on a real scale structure during the second case study.

5. CASE STUDY 2 – LARGE SCALE TEST DRONE SPRAY OVER LOST LIGHT WOODEN FORMWORK

The goal of the case study was to build in 5 days, a permanent inhabitable monolithic earthen shell in real size. The location set for the case study was a bucolic farm in south west of France. The weather conditions (min./max. temperature: 11/33 degrees, avg. rainfall 11 mm [11]) remained varied during the entire duration of study. Due to short duration of workshop, the Bioshotcrete technique had to be adopted and instead of numerous clay layers necessary to build the body of the structure, cross section was achieved by using small jute bags filled with hay, then sprayed by 5 layers of clay. The construction was divided into two parts (Figure 5) i.e. manual construction of formwork and body of the structure (3 days) and application of clay layers using drone spraying (2 days).

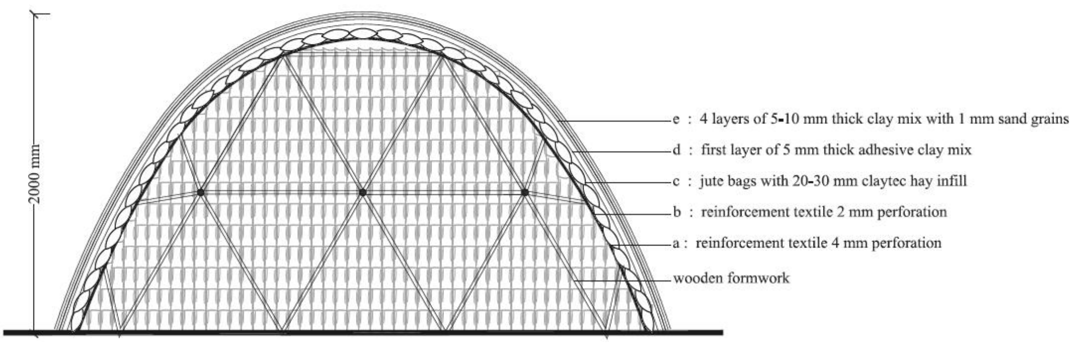

Figure 4: Cross section of the CS2 dome –modified layers for faster thickness gaining

The formwork was built as the 2m radius wooden geodesic dome anchored to the concrete ring of one feet cross section. The wooden members were joined with simple snap-together connectors, made of UV resistant plastic, manufactured by *Hubs* [12]. On to the wood, jute fabric was fixed acting as a surface to attach around 1800 jute bags filled with hay. The bags are connected to fabric in two points on the top of the bag using zip ties. The bags are laid out like tiles, with 1/3 overlap necessary to transmit the load from top to the bottom of the dome. Overlap was also preventing potential movement of the bags caused by wind generated by the drone. The jute bags were selected as easy to use prefabricated elements, and hay as the natural filling material with low mass and characteristics necessary to preserve benefits of earthen architecture. The size of the hay is 2 to 3 cm, the hey is then big enough not to drop out of the bag's perforations, and small enough to stuff the bag with right compaction. However, the first ring laid on the bottom of the dome was filled with coarse sand and aggregate (1-2 cm) to avoid moist and water suction from the ground and to provide a solid base to the dome. Although bags enabled fast generation of cross section thickness, the attachment process became the most intense manual process of this building procedure. The wooden formwork subsequently stayed as a lost formwork, due to reasons explained further in this chapter. The application of clay on to the build structure was done in 5 layers – the first more viscous layer and 4 layers containing clay with small grain size sand of less than 1 mm and linen fibres. Each clay mix deposition corresponded to mix of 8 bags of 8 kg of clay with water (a proportion of 12 l of water per bag), corresponding to 1 cm thickness to cover 25 m^2. The application method using drone enabled work in the regions unapproachable to the team otherwise, without extensive scaffolding on site. The process was spread over 36 hours with intervals of drying between each spray of the next layer. Additional two layers of special paint containing sealant are applied on the end to make the dome waterproof but still "breathable".

Figure 5: CS2: A) installation of wooden formwork, B) attachment of hay bags, C) formwork detail, D) drone spraying

Upon the successful construction of the dome in 5 days (Fig. 6A), the dome unfortunately collapsed after four weeks. Detecting possible reasons of the collapse is critical for future experiments. Initial assessments upon inspection concluded on particularly three main reasons for the failure of the structure. Firstly, the prefabricated PVC hub failed, the wooden element connected by plastic hinge (ball) to the hub (socket) snapped out (Fig. 6C). The reason is probably the working principle of joint for fast fabrication (snap together ball and socket) that is not solid enough. New version of 3D printed hubs with a locking cap is now available and should be used in further experiments with light wooden formwork. More importantly, the joint has failed because the earthen structure itself did not start to work in compression, since thickness of projected matter should have been at least 25 cm and cover all the bags. With time to apply more layers, thickens of structures cross section would enable to sustain structures own weight independently from the wooden skeleton. Lastly, it was not possible to provide 1 month of rain protection for the dome, and the weather conditions altered the curing time needed for this technique to work. Since curing was interrupted and the thickness was not sufficient to cover the bags; textile and hay have a tendency of holding on water, thus the dead load may have increased due to the pouring rains.

All these factors were taken into consideration for the subsequent case study carried out in London [13] (Fig. 6C). At first, the weight at the top of the dome (top 5 triangles) was reduced by replacing all hay bags with a plastic sheet. The sheet allowed enough daylight within the dome, while also eliminating any possibility of water entering from the top. Thereafter, the entrance to the dome was kept smaller while also providing additional poles as support frames. Thirdly, the hubs in this case were 3D printed, functioning much better with a locking cap. This resulted in a stronger skeleton and thus giving a longer life to structure.

Figure 6: A) Finished dome sprayed with paint for waterproofness, B) Failure of prefabricated hub, C) London dome

6. CONCLUSIONS

The Bioshotcrete aims to incorporate alternate bio materials, advanced digital fabrication techniques and drone automated fights within the construction industry in the upcoming years.

The CS1 showed us that usage of pneumatic formwork for such future construction process is worth investigating, but due to used deposition technique emphasis is still on the large deflection problem. There are several insights gained in the CS2 that could help in dealing with mentioned problem in future experiments. By using the latest drone spraying technology, for the first time more pressure control and consequently thickness control is gained. This is very important for any light formwork used, but especially relevant for potential decreasing of currently problematic large deflections of pneumatics. By enabling the pilot to control pressure and angle of spraying in future experiments, even more thickness control can be gained, important for further improvement of the method.

Through CS2 it is confirmed that the minimal thickness of layer applied on the formwork is 0.5 cm and maximum 2 cm. Therefore, for the 3 m high dome, build using original Bioshotcrete procedure and by using pneumatic formwork, expected thickness of the cross section would be 10 cm. In that case, additional jute between clay layers needs to be added serving as reinforcement. This conclusion will be confirmed true next physical experiments.

In both case studies it is proved that the drone spraying technique allows to reach and coat different parts of the structure without the need for a scaffolding or a crane, as a huge benefit for cost and timeline of the project. New spraying technology even enables efficient spraying of lower parts of the dome, where spray angle is almost 90 degrees.

Further exploration of geometry and structural analysis are necessary to derive future full scale tests for shells with optimal structural performance. Monitoring formwork's displacements (wooden or pneumatic) is regarded as necessary to gain more inside on formwork behaviour during the construction process. For the overall understanding of pneumatic formwork's behaviour, development of numerical model that would consider air and load pressure as nonlinear influence would be beneficial. The climatic conditions while spraying clay over the pneumatic formwork can play a critical role in its overall construction. While the air can get cooler or warmer as the time of the day progresses, it can contract and expand the formwork, which can develop cracks on the layers applied.

As in former case studies [9], iterative geometry analysis of the constructed shell would enable more control over degree of deformation. Numerical model of the shell can provide results for analysis of displacements, utilization and stress lines, enabling to evaluate the fabrication process in terms of structural performance. Also, obtained stress lines can serve as guide lines for placement of additional reinforcement.

7. ACKNOWLEDGEMENTS

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