Revealing the Potentials of Earthen Shell Design Using Form Finding Techniques


Elif Yapıcı,[1] Özlem Tüz[2]
[1] Mersin University, Mersin, Turkey
[2] Mersin University, Mersin, Turkey
[1] elifyapici@mersin.edu.tr
[2] ozlemtuz@mersin.edu.tr, ozlemtz@yahoo.com

While construction technologies and building materials are developing continuously, providing users' comfort requirements for the cities and buildings we live in, being in harmony with the natural environment and how the constructed environments will or will have to change in time after they are built also how they will affect the natural environment during the construction processes are crucial issues to be considered.

Although it is possible to create or modify a construction material like polymer-based materials these kinds of materials are neither adequate for building healthy spaces nor degrade, while aging, in a desirable way. Therefore, the aim of this study is to discover the potential of natural materials, by considering earthen structures, which have great importance in terms of designing healthy spaces and ecological sustainability.

This paper demonstrates the possibility of generating examples of earthen architecture, which can be built by blocks or pouring, using different construction systems, or by adding different additives in order to improve the structural or thermal performance of the material, through architectural form-finding methods. These methods are can be followed using computer-aided design programs and enabled innovations in construction technologies.

Keywords: Earthen Architecture, Shell Design, Form-Finding, Computer-Aided Design

1 INTRODUCTION

Computer-aided design programs and innovative production techniques (for example 3D printing) have the potential for the design and construction of earthen architecture. Even earthen structures have known as weak to seismic actions; it has been changed in time thanks to innovations in formwork and material technology. There are only a few studies about earthen shell design (a shell constructed from compressed earth blocks exhibited at La Biennale di Venezia, the 15th International Architecture Exhibition in 2016) which designed considering vertical loads of the structure [1], the other example found on the literature investigates again the masonry shell structure but considering also the lateral loads by using computer-aided design programs [2] but it is obvious that considering the environmental challenges we have been facing since the industrial revolution, we should and will rethink earthen architecture and there is still a lot to discover about. Before discovering the future possibilities, we should reconsider the state-of-art of earthen architecture to reveal this potential; so this paper discusses how to design an earthen shell through a form-finding method by handling the formwork and reinforcement techniques since it is necessary to know for any architectural design; how it will be constructed and will come into existence.

2 FORM-FINDING TECHNIQUES

There are many ways to generate a form; by creating continuous surfaces (soft meshes, double-curved shells or hyper paraboloids), using modularity and accumulation (interlocking units, irregular units), deformation and subtraction (twisted blocks or porous spaces), creating algorithmic patterns (tesselated planes or Voronoi surface) or triangulation (Penrose patterns or faceted lofts) [3] (Fig. 1). These techniques are being used by designers along with each other or separately but when it comes to designing a shell it should be considered that shells are form-active structures while transferring their loads to the ground [4]. In ancient times people have discovered the load-bearing behavior of shells by creating arches, vaults and domes. These basic forms are being used even today because of their durability and beauty also their limitless variations and being researched about the basic principles behind them. The earliest research was about these form-active structures' main element; the arches. In the 16th century Stevin illustrated how a chain takes the shape of the forces that affect it by using hanging weights on and later in the 17th century Hooke and Wren used the inversion of this hanging chain model to design a non-funicular form, a dome [5].

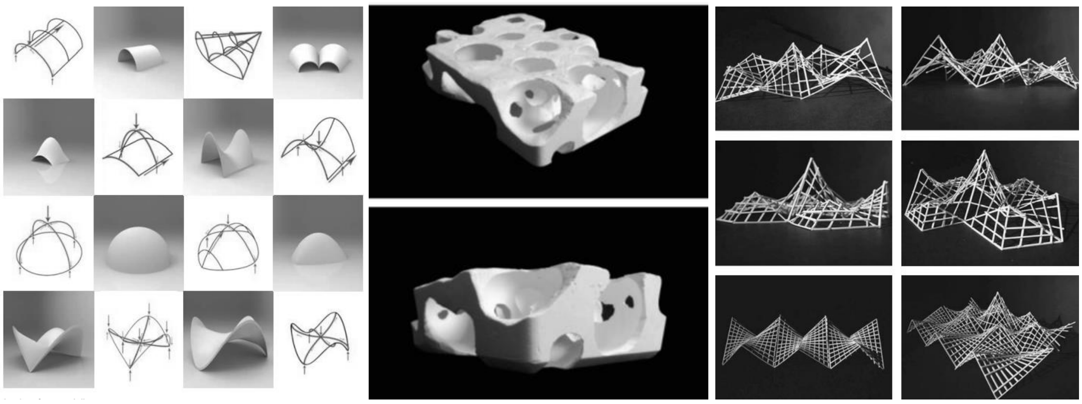

Fig. 1: Some examples to generative form finding techniques; creating continious surfaces, deformation and subtraction (Agkathidis, 2015).

Since the inversed hanging chain modeling was discovered in order to design non-funicular forms, they have been used by many architects including Antoni Gaudí one of the masters of all times and a great example of it can be the basilica he designed in 1883, La Sagra da Familia (Fig. 2). However this technique hasn't been improved in order to resist lateral loads yet, only one research [2] found in the literature that considers seismic loads using the hanging-chain method in two planes while designing a masonry shell structure and shows that; it is possible to estimate the lateral load will affect the structure so finding a form will resist it in the same way just like it resists to gravity by using computer-aided design programs (Fig. 3).

Fig. 2: Hanging chain model of Gaudi and the modeling of La Sagrada Familia both from the exhibite in Casa Milà (From personal archive).

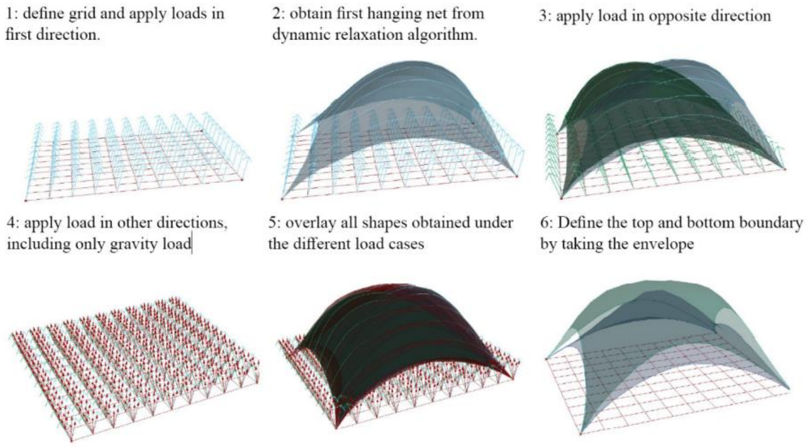

Fig. 3: Form finding process step by step for a shell with square plan simply supported on the four corners (Michiels et al., 2017).

3 FORMWORK AND REINFORCEMENT IN EARTHEN ARCHITECTURE

3.1 Formwork

Despite there being a vast variety in the production of earth and construction techniques differing to the cultures also the chemical composition of earth depending on the place, the majority of the earth-building techniques can be grouped, considering the manner of forming and strengthening the material as; sculpted earth, molded earth, rammed earth, and compressed earth (the technique used in preparing the blocks) [6]. The rammed earth process begins with soil selection that has an appropriate ratio of sand, gravel, and clay; the soil is usually being provided directly from the site and then poured into usually wooden formwork that can resist forces caused by the compaction of the soil [7].

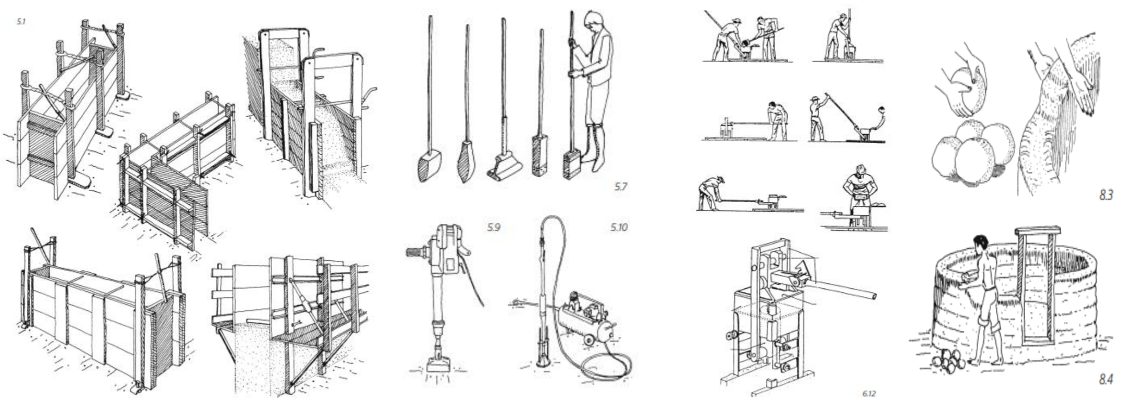

Fig. 4: Earthen architecture's construction techniques; rammed earth formwork and tools, production of compressed earth blocks and sculpting earth by hands (Minke, 2006).

The compressed earth block production has started with manual and motor-driven mechanical presses with heavy iron lids that presses the earth into molds and today these mechanical presses have electric, diesel, or gasoline-powered engines that make use of hydraulic compression to produce thousands of blocks per day and have attachments which include earth-blending machines, hoppers, and loaders [7]. Another technique that can be more efficiently used for earthen shell construction is wet sculpting. It is a primitive technique thus it is simple cause no tools are required to work with earth (especially for the kind of earth that includes more clay and is called "loam") [8].

Fig. 5: Houses constructed with wet sculpting technique in Ghana (left), a ceiling design to molded earth which can be constructed pouring mineral loam in formwork of textile stressed by cables (Minke, 2006).

The easiest way to make a wall of lightweight mineral loam is to simply pour it into a formwork by preparing the mix in a forced mixer (it is even possible to use an ordinary cement concrete mixer in which the loam is being poured over the aggregate while it is turning) then the formwork is being simply left open on one side for the upper portion of the wall, the mix is being thrown into it and tamped and the surface of the walls made with this technique need only be plastered with a single thin layer [8]. These two techniques (molded earth and wet sculpted earth techniques) (Fig. 5) have more potential to use in shell structures since compressed blocks are usually more proper to use for masonry structures and rammed earth is a technique that works by applying vertical forces to the earth. Besides these two techniques have more potential to use different kinds of formwork like textile formwork which is cheaper and more flexible to use even though there is a designed example to it (Fig. 5), still it is not found another or applied example in the literature. Also, despite there is a study that investigates the performance of adobe bricks using the 3D printing technique and since 3D printing can be used with computer-aided design programs, there is no other example in the literature that investigates the potential of additive manufacturing in earthen architecture yet [9] (Fig. 6).

Fig. 6: 3D printed cob cylinders' production from a robot arm.

3.2 Reinforcement

As mentioned before earth is being reinforced; with various types of aggregates or fibers in various proportions, different shapes, chemical compositions, capacities for water thermal or mechanical properties. A decrease in density is being observed with the increase in aggregate or fiber content, as reduction of shrinkage cracks. Ductility is always being improved with increased plant aggregate or fiber content (dependent on Young's modulus) and both tensile and flexural strengths depend on the shape of the plant particles: they are being improved when fibers are used. Earth has a high capacity to balance air humidity, and this capacity is also being increased by the addition of plant aggregates or fibers. Thermal conductivity decreases with the addition of plant aggregates or fibers and because of the decrease in density of the material [10] (Table 1). So all of these properties of the material are modifiable, can be optimized to correspond to the users' needs and there are also studies to improve the seismic behavior of the material by using bamboos, polymer meshes or ropes [11].

Table 1: Chemical and mechanical properties of plant particles used in earth construction materials (Laborel-Préneron et. al., 2016).

Type	Composition (%)			Elastic modulus (GPa)	Tensile strength (MPa)
	Cellulose	Lignin	Hemicellulose		
Hemp fiber	64	4	16		
				21	1077
				34	900
Wood aggregates	50	16–33	7–29		
Flax fiber (Harakeke)	61	8	27	21	805
	81	3	14		
	60	3	16		
Jute fiber	72	13	13		
				10–30	400–800
Kenaf fiber	70	19	3	136	1000
Diss fiber					100
Coir	43	46	0.25		
				3	150
	41	27	22		144
	21	47	12	10–40	73–505
Oil palm fiber	49	23	21		
Date palm fiber				5	233
Sisal fiber				18	580
	65.8	9.9	12	15.5	472
				15	363
	73	11	13	15	347–378
Banana fiber	26	25	17		

4 CONCLUSION

Rethinking the earthen architecture has great importance by the means of both ecological sustainability and providing users' comfort in today's and future environmental conditions. Future possibilities of earthen shell design are waiting to be discovered through computer-aided design techniques and innovative production or material technologies. Considering the form of a shell, wet sculpting and molding are two production techniques that are utilizable and developable since they also offer more than compression-only structures unlike the compressed block technique. Especially the molded earth has the potential to use different formworks like textile which has the advantage to create a form; flexibility. These potentials can be used, as mentioned above, by strengthening the earth's structural or thermal performance using reinforcements like; plant aggregates and fibers, bamboos, polymer meshes or ropes. Also it is possible to use computer-aided design programs that can predict the behavior of the structures so the principles of form-finding techniques that have been used to create shells since they have been improved can be useful to design a shell that is resistant to both vertical and lateral loads will affect it. So all the advancements in architectural or computational methods of design and construction are available today and can be used considering also the things been learned from the past.

5 REFERENCES

[1] Block, P., Van Mele, T., Rippman, M., Paulson N. *Beyond Bending Reimagining Compression Shells*, DETAIL Business Information GmbH, Munich, 2017.
[2] Michiels, T., Adriaenssens, S., Jorquera-Lucerga, J.J., *Parametric Study of Masonry Shells Form-Found for Seismic Loading*, Journal of the International Association for Shell and Spatial Structures 58(4), 2017.
[3] Agkathidis, A., *Generative Design: Form-Finding Techniques in Architecture,* Laurence King Publishing, London, UK, 2015.
[4] Engel, H., *Structure Systems,* Published by Hatje Cantz Verlag, Germany, 1997.
[5] Adriaenssens, S., Block, P., Veenendaal, D. & Williams, C., *Shell Structures for Architecture,* Published by Routledge, New York, USA, 2014.
[6] Kraus, C., 'The fitness of earthen architecture', *Earthen Architecture: Past, Present and Future – Mileto, Vegas, García Soriano & Cristini (Eds)*, Taylor & Francis Group, London, UK, 2015.

[7] Rael, R., *Earth Architecture,* Published by Princeton Architectural Press, New York, USA, 2009.
[8] Minke, G., *Building with Earth: Design and Technology of a Sustainable Architecture*, Birkhäuser – Publishers for Architecture, Kassel, Germany, 2006.
[9] Alqenaee, A., Memari, A., *Experimental study of 3D printable cob mixtures*. Construction and Building Materials Volume 324, 21 March 2022, 126574.
[10] Laborel-Préneron, A., Aubert, J.E., Magniont,C., Tribout, C & Bertron, A. *Plant aggregates and fibers in earth construction materials: A review*. Construction and Building Materials 111:719-734, May 2016.
[11] Fuad Abdulla, K., 2019. Innovative Structural Enhancement Techniques For Adobe Masonry Structures, Doctor of Philosophy (thesis), The University of Manchester, The Faculty of Science and Engineering.