Generative tool to support architectural design decision of earthbag building domes

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Abstract

The interest in earthbag dome construction (also known as sandbag, superadobe or superblock construction) is increasing as a world consciousness develops to achieve the planet's equilibrium for sustainable living. The main objective of this research is to develop a parametric tool to help architects modeling virtual earthbag domes from ideation to construction phase. This challenge has been addressed by adopting an experimental methodology that explores parametric generative design with the use of visual programming language (VPL). In this paper we present the development of a tool for the ideation level including features that allow for the calculation of material quantification. The usability of the tool was validated by earthbag constructors and architects.

Keywords: Visual programming language; Earthbag building; Superadobe; Sustainable architecture; Generative design.

Introduction

This research aims to facilitate the virtual modeling of earthbag domes by architects. It is a part of a PhD study that previously classified the constructive variation on the application of earthbag techiniques (Santos & Beirão, 2016). It is also an indirect way to encourage the adoption of ecological materials used in ancient construction techniques into our current construction practices.

In face of the finitude of natural resources and accelerated environmental degradation, it is pertinent to associate the use of new technologies with the development of these kind of projects because they cause less damage to the environment.

Earthbag is also known as superadobe, sandbag or superblock. It is the construction technique where the walls are built out of stacked bags filled with earth, with barbed wire layered between them (Hart, 2015; Hunter & Kiffmeyer, 2004; Minke, 2009;). These constructions are durable, strong, climatically efficient, and formally flexible (Hunter & Kiffmeyer, 2004). They are composed with renewable and reusable resources, hence promoting sustainable development (Barnes, Kang, & Cao, 2006).

Although earth construction is a low environmental impact recognized solution, the existing software tools are still limiting factors in this specific type of project. Considering this, we formulated the hypothesis that the virtual modeling of the domes could be aided by a parametric tool specially developed for the purpose. "CICERO" (Creative Interface for Constructing Earthbag Resource Objects) is a parametric generative dome design tool developed with the use of a visual programming language (VPL) that generates earthbag designs taking in consideration the technology's geometric limitations hence guiding the designers towards consistent solutions.

Methods

The research adopted an experimental methodology exploring the advantages of parametric generative design with the use of visual programming language (VPL systems). The VPL code was developed by resorting to a Computer aided design (CAD) software that most of architects already use, to generate designs of earthbag domes in a known environment, faster and more effortlessly.

The methodological procedures were:

a) Collecting from existing literature an extensive set of earthbag building technical characteristics.
b) Identification of the main parameters for the generation of earthbag domes.
c) Development of a parametric model able to generate the earthbag dome and associations.
d) Create a web-based platform to implement tests online.
e) Submit the tool to architects with experience in earthbag construction to experiment the tool and answer an inquiry, to validate the tool.
f) Evaluate the survey and their results.

Data collection

To develop the VPL code for the earthbag dome construction, two general steps were necessary in the first place.

Firstly, a data collection overview to identify the technical rules was done identifying constructive constraints and general characteristics of earthbag domes.

Secondly, we devised a way to insert all technical variables into the code parameters. The goal was to provide a tool where the user could provide inputs and receive an interactive response from the model. The identified inputs refer to: Bag size, curvature arch, radius of the dome, quantity of smaller domes to assemble around the first one, distance of the smaller dome to the center, the angle to locate the small domes and finally their radius.

Inputs

The tool inputs are inserted resorting to number slider interfaces. These sliders were predefined, constrained to specific limitations that resulted from the overview of structural constraints of the constructive technique.

BAGS

The purpose of the bag is to retain the earth during the process. Polypropylene bags are more recurrently used; however other kinds can be seen like burlap. Polypropylene is the cheaper alternative and is not as environmentally toxic as the polyvinyl chloride (PVC) (Wojciechowska, 2001); besides, it can be recycled.

The wall width is the variable with greatest influence on structural safety (Canadell, Blanco, & Cavalaro, 2016), then the bags chosen must be bigger than 12 inches (30,48cm) (Hunter & Kiffmeyer, 2004). Khalili suggests a roll of 14 to 16 inches (35,56 to 40,64cm) wide Superadobe tubing (Khalili, 2008). After an overview about bag sizes available to purchase, there were extracted the sizes that match with those structural constraints: 40, 50 and 60 centimeters wide bags after compaction.

RADIUS

For a self-supporting single dome, the ideal interior diameter suggested by Khalili is: 2,5 to 3,5 meters (Khalili, 2008). However, new studies simulated a diameter of 6,0 meters (Canadell et al., 2016; Hunter & Kiffmeyer, 2004).

ARCH CURVATURE

The earthbag dome is a solid revolution of a catenary arch and works with the force of the gravity, rather than against it(Khalili, 1986). The dome section was studied observing a hanging chain under tension, once it is reversed is under maximum compression(Khalili, 2008; Wojciechowska, 2001).

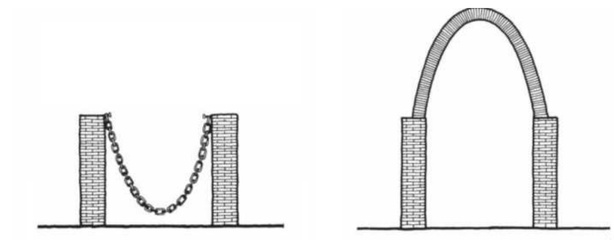

Fig. 1 - A hanging chain in tension is reversed to become a catenary arch (source: Khalili, 2008)

There were studied two kinds of arches already validated by theoretical studies as a better structural design for earthbag domes: The pointed arch and the variable arch (Canadell et al., 2016). The variable arch is more steepen aiding extra stability to structure (Hunter & Kiffmeyer, 2004).

During the construction, it is required two cords as a compass to define the geometry, the center compass to adjust each layer and the height compass to design the arch curvature (Fig. 2).

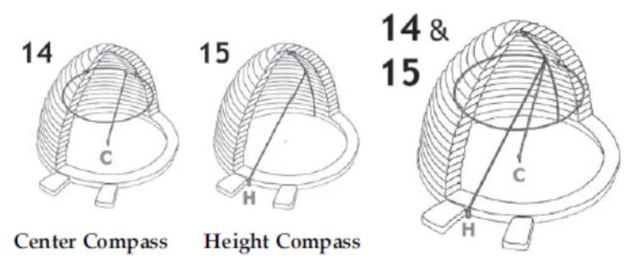

Fig. 2. Association of compasses to create the dome shape (source: Khalili, 2008)

For the pointed arch, the compass must be stacked touching the entrance door covering a cord equivalent to the diameter. For the variable arch, according to literature, the distance (d') to stack the cord to the dome entrance can be increased up to 1,50m (Canadell et al., 2016).

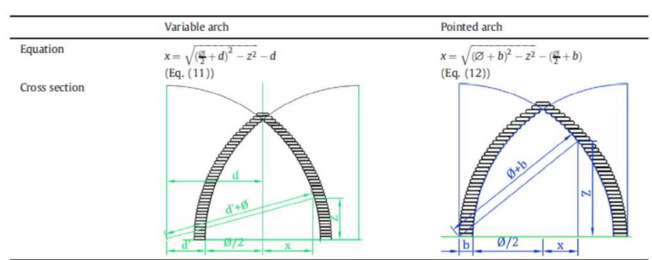

Fig. 3. Kind of dome designs and their equations for possible arch curvature in height (source: Canadell et al., 2016)

Based on the arches curvature equations (fig. 2), it is possible to find the dome height and design the dome section.

APSES (CLUSTERING)

To achieve a bigger area, it is recommended to build several interconnected domes than a bigger one (Hunter & Kiffmeyer, 2004).

It is also a good structural strategy, building additional semi-domes (apses), assembled around a big central one acting as buttresses, like in the historical Byzantine constructions (Cowan, 1977).

These associations are build interlocking bags by overlapping alternate rows. The apses will work as a buttress, for the larger dome adding stability to the overall design (Cowan, 1977; Khalili, 1986). Together they will counterbalance each other endlessly and permanently.

It is recommended to insert at least one third of the apses projection inside the cluster to work as a buttress.

-**Summary Inputs Board**

Table 1: Summary Inputs Board - Table 1 shows a summary of the inputs.

Variables	Numerical values	Unity
Bag Size (compacted)	0.4 - 0.5 - 0.6	Meters
Curvature Arch	1 to 1.5	Meters
Dome Radius	0.75 to 5.00	Meters
Quantity of apses	0 to 5	Integers
Radius of apses	0.75 to 5.00	Meters
Distance (apses to center)	≥0	Meters
Angle location (apses)	0 to 360	Degrees
Rotate apses	0 to 360	Degrees

Outputs

BUILDING HEIGHT.

If the radius is known, the height of the building can be extracted by resorting to basic trigonometry, with rectangle triangle proportions. (Fig. 3) Then the height is given by the equation height= $\sqrt[2]{(bag + 2*radius)^2 - (bag + radius)^2}$.

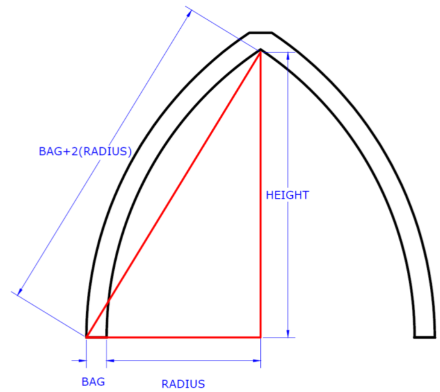

Fig. 4 Diagram of equation to find building height.

VOLUME OF EARTH

The volume of earth consumed in the construction was extracted from the 3D model. However, it is necessary to calculate two variables: the relation between the compacted and uncompacted soil and the composition plus percentage of soil mixture. As the conditions can change according to each site, the final user has to do this calculus.

The volume extracted from the model regards the compacted mixture when the soil particles are pressed together. Thought, for calculating the amount needed in the construction process it is necessary to calculate the uncompact mixture quantity when the soil is loose and mixed with air and water between soil particles.

The trivial praxis in quantification engineering calculus is to add 40% to discover the uncompact soil volume.

As bags contain soil, any soil type can be used, except highly organic soil, increasing the chance to use on-site material (Calkins, 2009). However the ideal mix for earthbag construction is approximately 30% of clayed soil and 70% sandy soil (Calkins, 2009; Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004). Most of the world's oldest remaining earth constructions were built with this soil mix ratio. Sometimes it is not possible to achieve the ideal ratio depending on the site soil; in such a case the builder needs to insert different proportions of natural hydraulic lime.

LAYERS

After the tamping process, the layers lose height up to 12 cm (Geiger, 2011). After the conclusion of higher layers, the underlying rows can flatten down also. They can variate a little between themselves.

For empirical studies, it was defined that, considering representations necessities, the height of each earthbag layer must represent by the rate of ten centimeters (Hunter &

Kiffmeyer, 2004). Then, to identify the number of layers the equation is given by dividing the total height by 0,10 meters.

BARBED WIRE

Two threads of 4-point barbed wire are applied between the layers along the entire length of the wall to increase bag to bag friction and overall stability (Geiger, 2011; Hart, 2015; Hunter & Kiffmeyer, 2004; Wojciechowska, 2001). The wire combined with the woven polypropylene fabric add a high tensile strength to the structure.

SURFACE AREA

Knowing the total external surface is important to calculate the quantities of coating material to protect the structure. The materials can variate according to each project. However, it is often used chicken wire to wrap the entire dome surface providing adhesion more adherent surface for materials like stucco, earthen plaster or even cement plaster (Hunter & Kiffmeyer, 2004).

Results

The code structure provides a generative design interface, based on changing the input variables bounded by the known structural constraints and generate a volumetric model together with the necessary constructive information outputs, namely those informing material quantities which enable the calculation of construction costs.

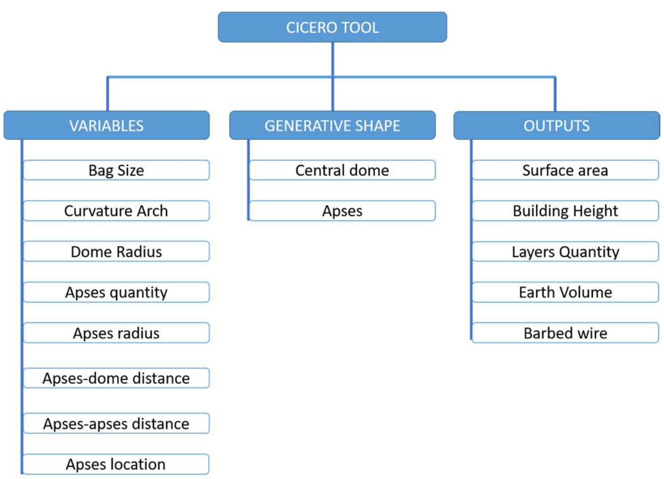

Fig. 5 -Generic code diagram

The CICERO tool was designed after some preliminary code prototypes based on a systematic literature review process and several trial implementations until an idealized usability was eventually achieved. There is a rectangle box interface on right providing the variables, or the inputs to be changed per each project by the user. On the left side there is the generated 3D model providing the constructive information as outputs. They are given in real time to help decision making while the creative process is under development.

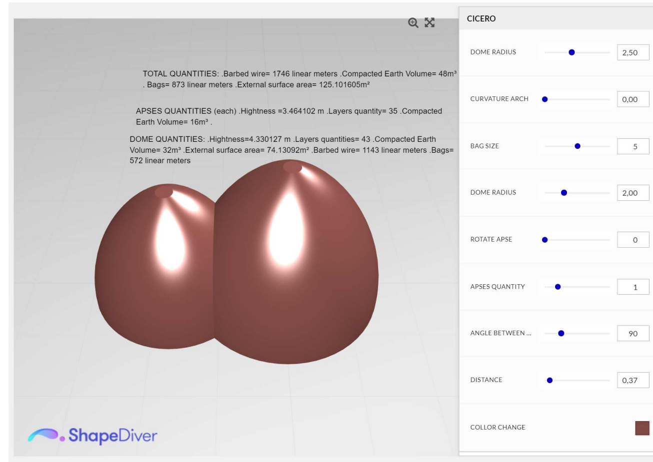

Fig. 6 -Cicero tool

Validation

Later on, an evaluation was made with online users, using the shapediver platform to host the tool (Fig. 6). In this way, the users did not need to download anything, and they could do the entire procedure online.

The tool was embedded in a website (www.cicero.earth) with a video-tutorial and an inquiry to answer after its use. The inquiry was available in English and Portuguese and was divided into three larger categories: user characterization, user interaction and subjective suggestions for improvements.

The website was disclosed aiming at experts in earthbag construction and planning for validating the technical data, the tool usage and establish a general profile of the target audience for the final tool.

It was also necessary to collect data from lay people (not just from experts) to evaluate the tool user experience.

User Characterization

There were sixteen people, with different nationalities, recruited for the research sample. The age variations were: 44% between 26 to 35 years, 37% between 36 to 45 years, 6% between 46 to 55 years and 13% over 66 years old.

Five of them were specialists with planning, had constructive experience in earthbag buildings and still work in this field. One works in Europe, two in Brazil, and two in the United States. One with less than five years of experience, Two with five to seven years, and two more than ten years. Two usually plan by hand, and three use CAD software. When it was asked how much time they usually need to design a virtual volumetric model, most of them answered differently: two never did, one needs minutes, one needs hours and one needs days.

There was one retired in the sample, all the other persons were architects, designers or professors in these fields. Two of them did not know about earthbag construction before this research, the others learned it in University, books, workshops, websites, video programs and manuals.

User interaction

There were three exercises to evaluate the tool performance for time and comprehension of the tool, and ten objective questions and based on the 10 Nielsen's heuristics (Nielsen, 1995).

The exercises were designed to recreate three different known volumetric dome models, extracted from literature (Fig. 7). It was given technical images and respective information to feed the tool. After finishing the experiment, they were requested to sign how much time they took to design the virtual model.

The exercises were given in an ascendant difficulty scale, where they needed to change more variables and to generate more complex domes clusters. Eighty eightpercent, did the exercises in less than ten minutes using CICERO. Only two people took more time to do them. The first because he was doing other things during the exercise, the second was a Brazilian and said that he had difficulties to understand the parameters in English and had to check their translation first.

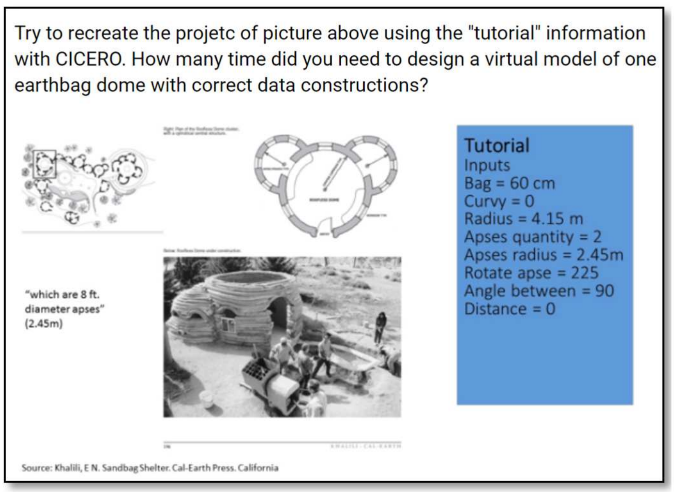

Fig. 7 – Example of the exercise given to validate the tool

The heuristics questions are unformal guidelines to evaluate the user interaction. They regard: visibility of system status; match between system and real world; user control and freedom; consistency and standards; error prevention; recognition rather than recall; flexibility and efficiency of use; aesthetic and minimalist design; help users and documentation.

All fourteen people answered this part. All heuristics parameters were well ranked in evaluation (more than 85%). The only parameter that took less was about the help documentation, where just 69% said it was enough for their CICERO understanding.

Suggestions

The last comments and suggestions given by the participants were: insert in Cicero additional data regarding buttressing (besides the included apses), openings and safety factors; improve the explanation on the parameters with auxiliary documentation; insert the measurement units in the parameters and finally translate the tool for other idioms.

Conclusion

The results of the validation process confirmed the hypothesis that the use of a parametric modeling tool could improve and aid the design of earthbag domes providing new useful tools to the users. The user can create complex models, with one or more domes associated by just changing a few numeric variables, receiving the construction specification outputs, in a short period, with high efficiency. As a practical contribution, this tool is expected to help architects to design earthbag building domes, in an easier and faster way while generating automatically the necessary documentation for construction. Additionally, the generated model provides also 3D models that can be used together with digital fabrication tools to fabricate models that are otherwise difficult to fabricate. Finally, we also expect that the use of this tool may increase the promotion of this form of sustainable building. Future work includes improving the tool by embedding it in a BIM environment.

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