Form Exploration with Optimized Three-Dimensional Printed Architecture
(Paper)

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Abstract
There is a fundamental relationship between architecture, structure and construction technology. Besides ideology change, the main reason behind the change in architectural form is new structural analysis tools, new material discovery or the invention of new construction methods. Additive manufacturing techniques will change the construction methods of the future making it faster and more cost-effective. New modeling and analysis technologies such as voxels, will enable unprecedented forms and structure optimization beyond what is currently possible.

On one hand, designers' creativity has depicted truly remarkable novel forms despite the technical limitations of the current Additive Manufacturing technology to produce such forms or to achieve usable multi-story buildings. On the other hand, the cost-effectiveness and speed of production of the technology have been a reason to produce three-dimensionally printed architecture that is a replica of what could have been produced with conventional or mass production methods, using same productions techniques and reinforcing the building material the same conventional way, which defies the purpose.

This paper explores the architectural form opportunities with currently available materials and AM techniques without resorting to conventional constructions methods or forms. The research explores possibilities of form achieved with a widely used material such as ordinary concrete, a material that is limited in its ability to create horizontal floor slabs which prohibits the making of multi-story buildings. The research is composed of three stages:

First, generating a form using the voxel technique, where two-dimensional images are used to generate three-dimensional geometry.

Second, the resulting geometry is structurally analyzed against typical loading conditions, with the use of ordinary concrete, a material that can be used to 3D print the depicted structure.

Third, the resulting structural analysis is optimized for minimum use of material, resulting in an unexpected architectural form.

The resulting forms are used as building blocks for hypothetical architectural structures.
The main objective is to achieve a usable multiple floor buildings possibilities with structurally optimized three-dimensionally printed forms.

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Form Exploration with Optimized Three-Dimensional Printed Architecture

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Abstract

There is a fundamental relationship between architecture, structure and construction technology. Besides ideology change, the main reason the architectural form change is due to better structural analysis tools, material discovery or invention and advancement in construction methods. Additive manufacturing techniques will change the construction methods of the future making it cost-effective and achieving faster delivery. New modeling and analysis technologies such as using voxels, will enable unprecedented forms and form optimization beyond what is currently possible.

Despite the technical limitations of the Additive Manufacturing technology to produce usable multi-story buildings, designers' creativity depicted remarkable but unattainable forms. On the other hand, the cost-effectiveness and speed of production of the technology produced three-dimensionally printed architecture that is a copy of what would be produced with conventional or mass production methods.

This paper explores the architectural form opportunities with current materials and AM techniques. The research explores possibilities of form achieved with a widely used material such as concrete, without reinforcement, a factor that limits the ability to create horizontal floor slabs and prohibits the making of multi-story buildings

1. Introduction

Architecture form is a function of the structure system, and as architects, we are always interested in novel architectural forms which are usually a product of new structural systems or analysis capabilities. As the modern movement based its form shift on the advancement of structural steel and reinforced concrete, today's additive manufacturing technologies and advanced structural analysis tools would again reshape the architecture form.

"… the particularities of structural form can be closely related to spatial functions and to conceptions of space. We can thus interpret structure as being part of an integrated design approach in which we cannot completely explain, understand, or appreciate structural form without recognizing its strong co-dependence on the particular character and use of the architectural space. It is of importance to note, however, that any gross deviation from what can be considered to be a reasonable concern for mechanical requirements should not be the result of random, uninformed, or thoughtless design, but rather of carefully considered ideas related to other design imperatives" [14]

Additive manufacturing is a technology that is transforming the industry including the AEC industry. The technology promises a novel way of producing buildings that are economical and fast. With the new technique of depositing layers of material to construct three-dimensional forms, comes new form possibilities that were prohibitively expensive with the traditional building methods based on modular repetition and mass-produced parts.

Since the industrial revolution, mass production was the process with which manufacturers were able to significantly reduce the price of production, making product cost very competitive to consumers. The 20th-century development was marked mainly by the mass production market. Architecture like everything else has benefited from this trend which availed parts that contributed to the construction industry; such as construction equipment and assembly lines of doors and windows.

However, this did not change the form of the produced architecture. The building technology that shaped the form in the turn of the 20th century did not change, in an interruptive way, the main lines of the architecture form. [5]

Possibilities are endless if the gap between the technology and the structural properties of the used materials can be closed (Figure 1).

With the introduction of computer modeling, the limits for creative forms has been elevated significantly, allowing previously “difficult to draw” forms to be economically realized, albeit within the boundaries of conventional construction methods. The introduction of additive manufacturing has stretched the limits even further with the promise of achieving complex shapes not possible with conventional methods.

Figure 1. 3D printed buildings for Mars (www.marscitydesign.com).

Despite the promising traits, the structural limitations of the current processes and materials might impose certain form restrictions on the resulting architecture. Unlike the imagery that is depicted as 3D printed buildings, the current structural limitations give an entirely different form typology.

One significant restriction that has to be overcome is the tension force which requires reinforcement in concrete. Without a practical way to add reinforcement to any building material with properties suitable for 3D printing such as concrete, it is difficult to imagine some specific shapes especially horizontal flat slabs covering large spans.

Many research projects have addressed similar issues, and partially resolving the problem in some ways. In their research project “The smart takes from the Strong,” [10] managed to fabricate a concrete slab that can have the adequate load-bearing capacity. Their approach explored the synergy between the geometric flexibility of 3D printing sand formworks and the structural capacity of concrete. It allowed the production of composite components with properties superior to either individual material [10]. The result of this project indicates possibilities for achieving a horizontal slab that can be used as another floor slab, but without addressing the vertical support.

Other projects, such as VULCAN [7], utilized materials other than concrete, in this case, it was plastic, to realize full scale three dimensional printed usable spaces, yet sacrificing the possibility of having a usable horizontal surface as a first floor.

Since there are many economic benefits in using AM technology, it is possible to get some form insights of what can be achieved with current limitations. This research is exploring the form possibilities when utilizing non-reinforced concrete as a material to build vertical support and provide horizontal surface above providing a usable space within and potential of adding a second floor.

Utilizing the analysis capabilities of Autodesk project Monolith, an optimized form of 3D printable structures were produced as an exploration of form possibilities.

2. Background

2.1. Autodesk Monolith as an experimental platform

According to the software website, Monolith is a voxel-based modeling engine for multi-material 3D Printing. Besides its ability to generate form using geometry description and preset functions it also can create form that is derived from image blend and sweep, enabling a novel way to generate forms that adhere to different set of rules than currently possible, such as having a particular shape cross-section at certain height and a different one at another enabling a sort of a loft operation with an unprecedented level of control and detail.

It also enables "Topology Optimization," which the maker defines it as: "… a form-finding solution which uses static analysis to determine the optimal distribution of material within a volume based on a loading/support condition. It is a process which seeks to find the optimal load path for a particular loading condition and boundary volume. By defining the constraints of the system, the optimization process will attempt to numerically optimize the distribution of material so that it meets the prescribed performance targets." As mentioned on the software web page at monolith.zone

While doing this, the process alters the form of the support element, resulting in new visually unexpected forms.

If the original form is proven architecturally to support the required load and be aesthetically appealing according to our historical standards for aesthetics in architecture, the deformation resulting from the optimization process will challenge that.

In reality, the optimization process produces unexpected results. Few questions arise;

- Should we accept the optimization process aesthetic results?
- Can we control the process to generate what we would consider aesthetically appealing?

And another more profound question;

- What will it look like?

- How will it affect the usability of the generated space?

2.2. The current state of the technology

Lately, the possibility of utilizing the AM technology to produce full-scale architecture has been tested. Up till now, few full-scale examples were demonstrated. In May 2016, the city of Dubai launched the world's first "functional" 3D printed office building of 250 square meters (Figure 2).

A structure of a single floor with all amenities printed in 17 days, and “assembled” on site in two days. The goal of the project, as mentioned by officials, is to push the envelope on technological development, innovation, and creativity. The machine responsible for printing out the office building is a massive warehouse size printer that stands at about 6 meters tall, 40 meters long and 13 meters wide. The resultant building form, despite being slightly unconventional, still respect the traditional building shapes of vertical walls and horizontal slabs.[5]

In January 2015, another firm in China produced a 5-story residential house and the world's first 3D printed villa (Figure 3). The villa measures 1,100 square meters and comes complete with internal and external decorations.

Figure 2. Dubai first 3D printed office building.

Figure 3. 3D printed villa in China (3ders.org)

Other successful full-scale projects have utilized different production techniques such as VULCAN, the world's largest 3D-printed architectural pavilion (Figure 4) [7]

But the project that most lends its form aesthetics to actual optimization process while maintaining a functional role would be the "The bridge" project (Figure 5), which began by the Joris Laarman Studio and Petr Novikov and Saša Jokić from the Institute for Advanced Architecture of Catalonia (IAAC) to be placed across the Oudezijds Achterburgwal canal proposed for Amsterdam.

Figure 4. VULCAN, the world's largest 3D-printed architectural pavilion by Lei Yu et al.

Figure 5. The bridge project, by Joris Laarman Studio, proposed for Amsterdam.

3. The experiment:

To explore form, an investigation with a small structure of dimensions 4*4*4 meters was conducted. The scale of the structure qualifies it to be a room module, either a standalone or part of a larger building. Some difficulties, discussed later, prohibited larger scale tests.

3.1. Choosing building material:

The reason to select concrete:

The structural properties of concrete are well known and well-studied. Concrete has high strength in compression and more importantly has no useful tensile strength. Concrete is also the only primary structural material commonly manufactured on site; it has no form of its own. The suitability for injection through a nozzle while in the liquid state makes concrete a viable material to demonstrate the technology. Large format full-scale 3D printed architecture examples have used concrete, albeit no disclosed details about the mix. It would be safe to assume that concrete can be adapted successfully to be three-dimensionally printed.

However, without reinforcement, and due to the binding moment, it would be technically challenging to achieve horizontal elements out of concrete.

This experiment assumed the following structural properties for analysis:

Young's Modulus of Elasticity = 40 Gpa

Poisson Ration = 0.15

Density = 2400 Kg/m3

The loading conditions of the two test were identical using 10000 KN on the horizontal part of the form, and constraining the four lower corners of the structure in x, y, and z.

3.2. Exploring the analytical results of the software

Starting with a proven form that can create an enclosure with compression stresses only, a cross-vault was tested in the analysis module of the software. The form was created using the “image sweep” function (Figure 6).

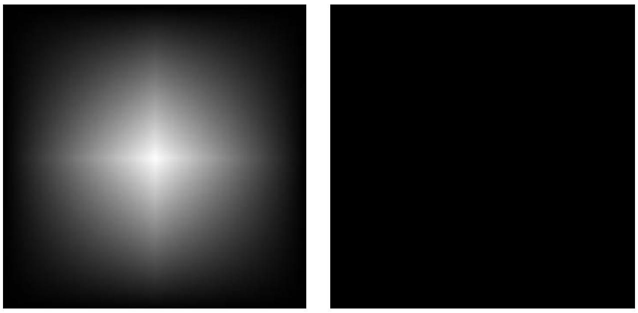

Figure 6. Base and top images used to generate the starting geometry.

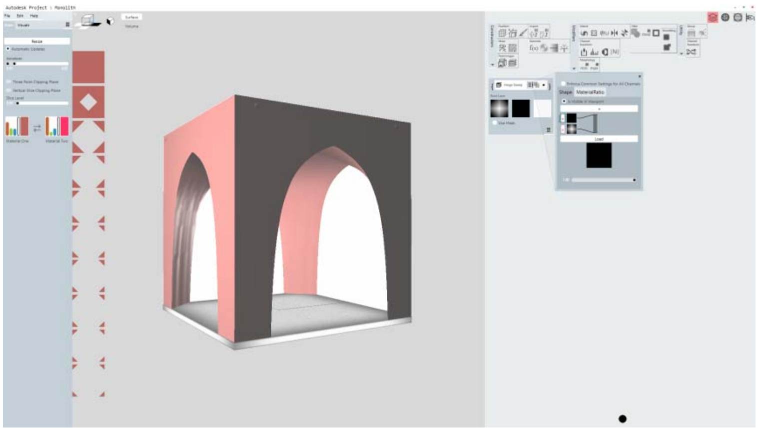

Figure 7. The generated form of a cross vault before optimization.

Then, a generic loading test situation that is very close to a cross vault was also tested using the optimization module of the software. The two approached produced forms that are close to each other.

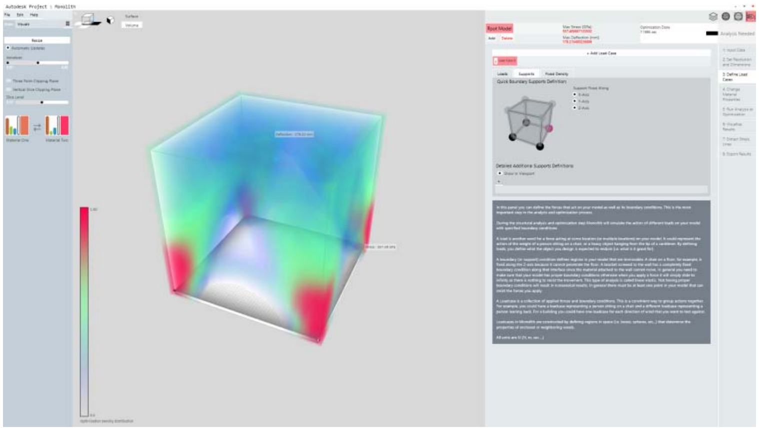

Figure 8. Loading and support generic test would also produce a cross vault.

3.3. Applying variations.

Different variations of the images that when swept creates the geometry were tried. The conditions of the tests were to have a form that includes:

- a possible usable internal space
- openings that can act as windows and doors
- a top horizontal level that can act as a second floor, or at least
- provide small span ranges that can be crossed by with other materials such as wood board without the significant need for extra support.

3.4. The results

Case # one:

Continuous optimization of the cross vault geometry created a four-legged structure that optimized as per the use of the construction material yet preserving the internal enclosure of usable space as well as a horizontal roof (Figure 10).

The architectural visualization of the resulting form (Figure 11) is depicting a multi-story structure with different variations of the scale of the unit.

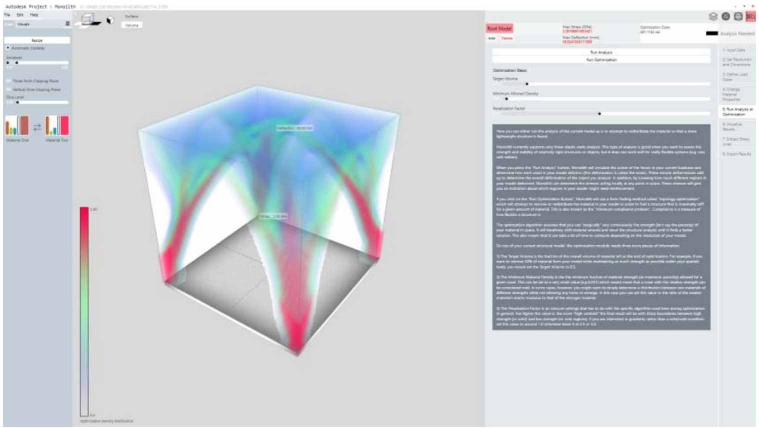

Figure 9. Loading and support generic test would also produce a cross vault.

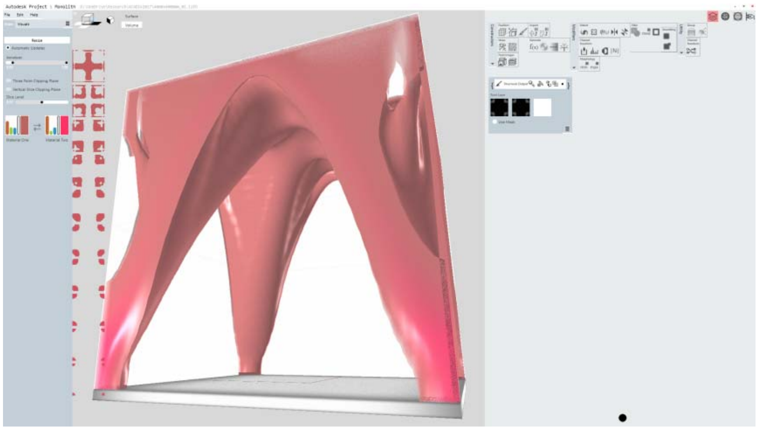

Figure 10. Loading and support generic test would also produce a cross vault.

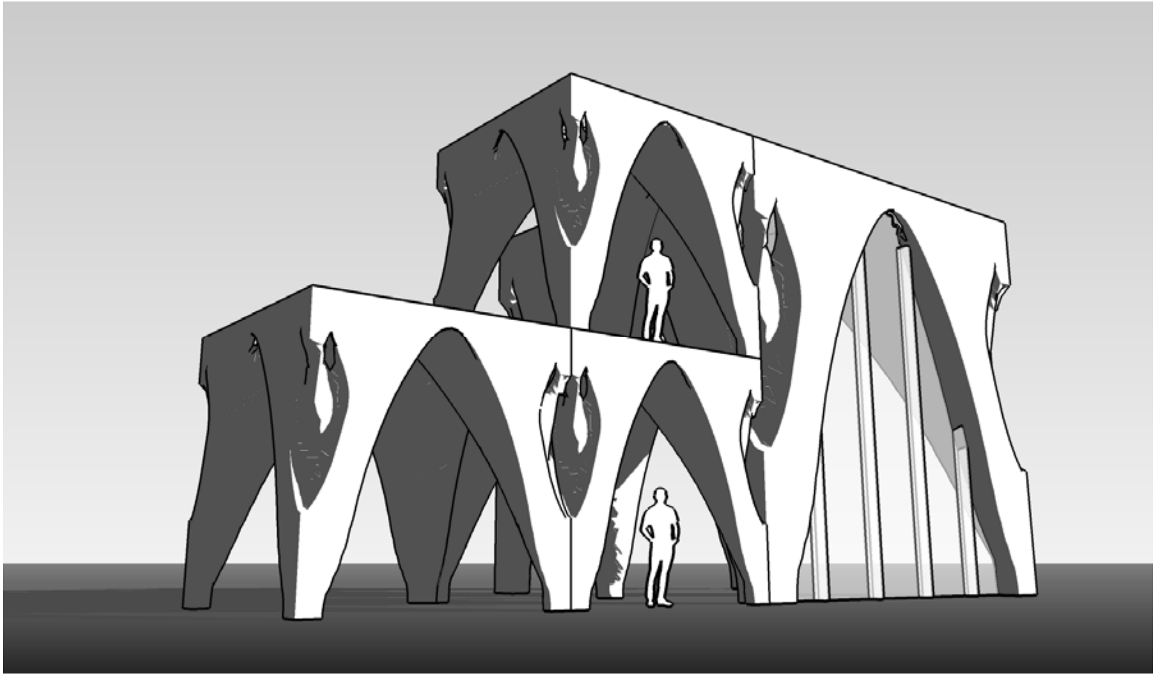

Figure 11. Loading and support generic test would also produce a cross vault.

Case # two:

The creating images (Figure 12)

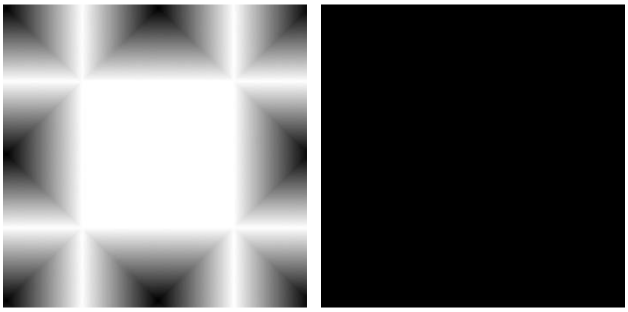

Figure 12. The images swept to produce the 3D structure in case two.

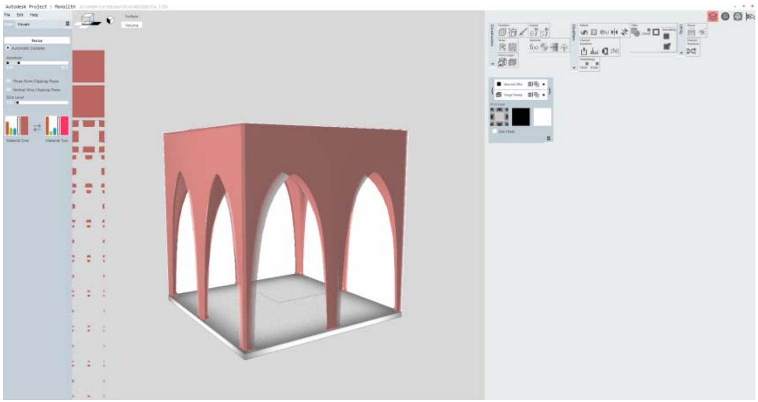

Figure 13. The resulting structure of the swept images for case two before optimization.

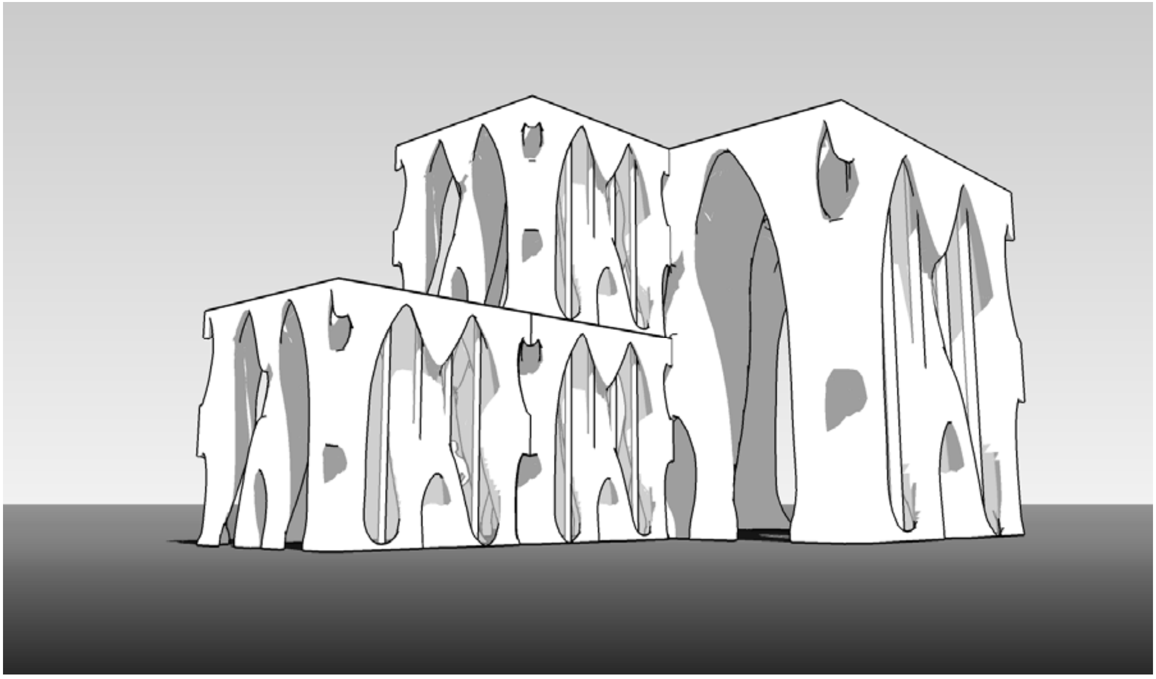

Figure 14. Architectural visualization of the resulting optimized structure of case two.

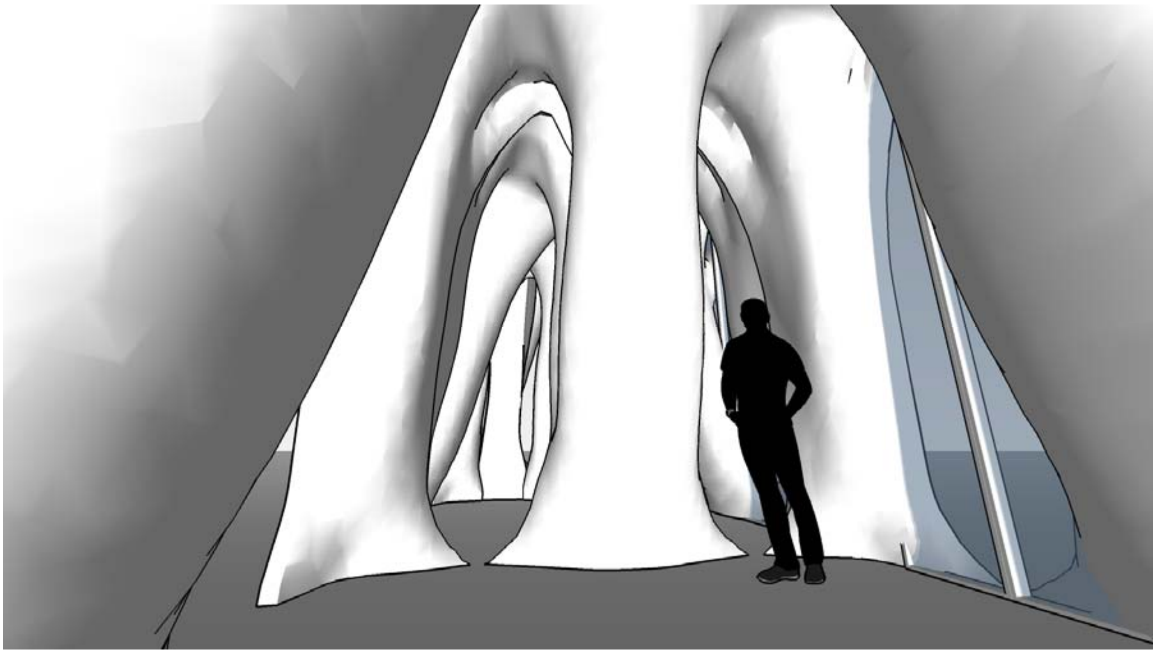

Figure 15. Interior visualization of the resulting optimized structure of case two.

More variations: in this variation, a completely solid top was replaced by a different possibility that would create a structure with spans that can be crossed by other materials such as wood boards, or stone slabs.

Case # three:

The creating images (Figure 16)

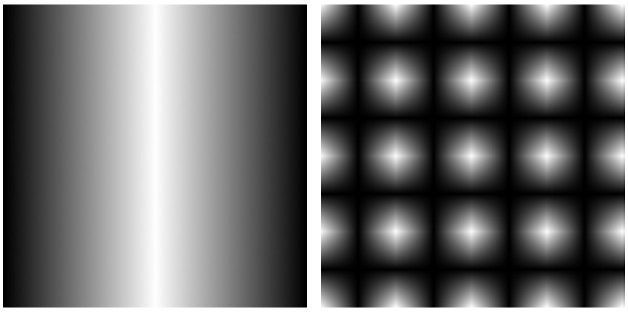

Figure 16. Architectural visualization of the resulting optimized structure

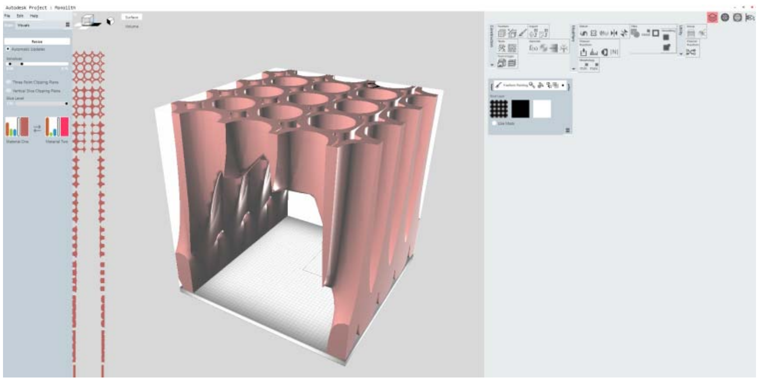

Figure 17. The form resulting of images used for case three.

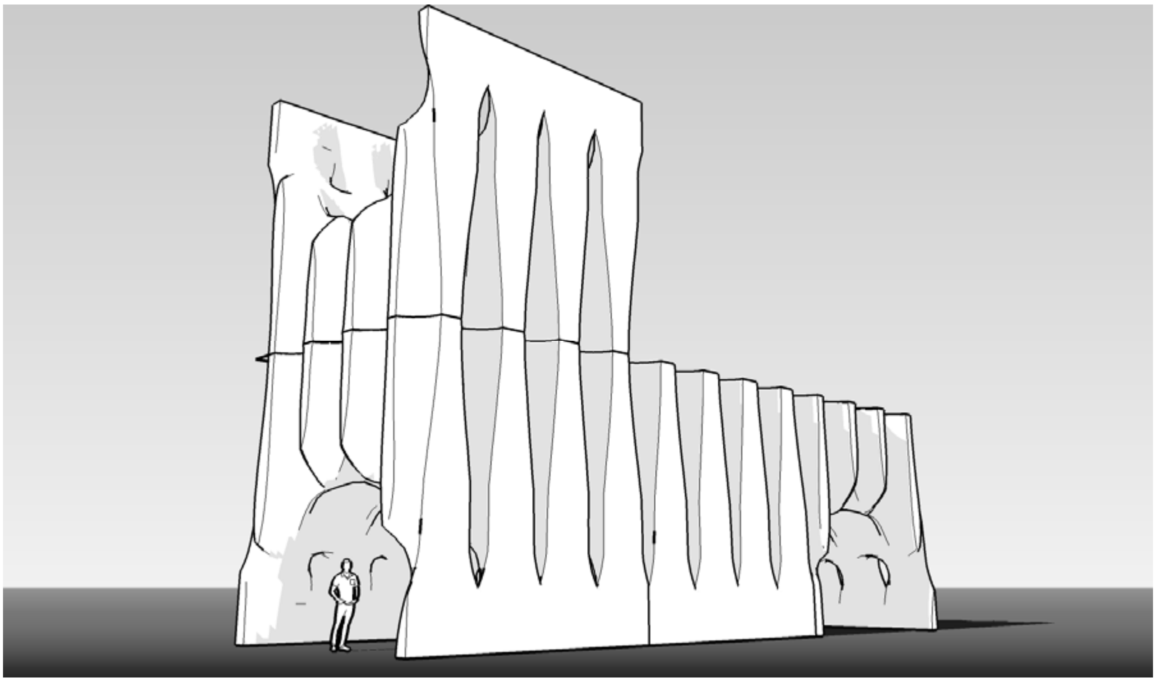

Figure 18. Architectural visualization of the resulting optimized structure of case three.

4. Discussion:

Producing traditional looking buildings with the AM technology would be one dimension of utilizing it. The real potential would be to produce a new form following the new rules of production. Since the optimization process of the structure cannot predict the resulting form, this opens an excellent opportunity for a novel form vocabulary never used before.

The approach generates some dilemmas though, are we seeking 3D printing for productivity or novelty?

The other concern is about the approach to form, should we envision complex form that cannot be achieved by conventional manufacturing techniques, then develop methods to achieve it? Or envision a form that follows the physical boundaries and the structural properties and limitations of material and technique, and explore its possibilities?

This research sought the latter approach, trying to imagine what is possible first.

Many difficulties were faced due to the novelty of the test tools. The rough interface of the program and the unexpected behavior along with scarce documentation made the testing difficult. Issues with the resolution and proper scaling, as well as computing power required to run the analysis and the optimization of parts, also added to the difficulties.

5. Conclusions

There are potentials in utilizing the AM technology in construction; from speed of construction to economy, it is crucial to capitalize on such technology and benefit from it. The resulting form should be guided according to the designer intentions. However, it should also follow the physical limits of the used material.

Form exploration with new analysis tools opens a new horizon for architecture.

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