Architectural Engineering Graduation Studio

SHELTERRA

Reconfigurable Masonry
Settlements for Refugees

Research Paper

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RECONFIGURABLE MASONRY SETTLEMENTS FOR REFUGEES

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ABSTRACT

July of 2021 marked the beginning of a massive internal conflict in Afghanistan, resulting with the reinstated power of Taliban across the country. The radical change in the regime and the vast destruction of people's homes and cities led to a steep increase in internal displacement and the total number of Afghan refugees inside and outside of the country. This research looks into the possibility of using local earthy materials and modular dry-fit stacking construction for the shelters. It studies different methods that are used to approximate the shapes of the polyhedral modules. With these findings this paper attempts to answer the research question: "How can we design a set of a few polyhedral cells with which we can make many variations of modular shelters?" By doing that, the study concludes with the clear plan of action and research needed to complete the design of these modules and shelters.

KEYWORDS: *Computational design, Topological design, Shelter design, Modular architecture, Funicular structures*

I. INTRODUCTION

Afghanistan has a long history of domination. It was influenced by many conquerors and suffered civil wars. All of which challenged the lives of the Afghan population, destroyed homes and cities. In July of 2021 Taliban regained control of the country after almost 20 years through a series of armed attacks on various regions and politically important cities. This was accompanied by many horrible events and massive destruction. According to UNHCR (United Nations High Commissioner for Refugees) Afghan refugees constitute to one of the largest refugee populations in the world of approximately 2.2 million people, with more than 600,000 being forced to flee since January 2021 (2021). At the same time, the IRC (International Rescue Committee) calculated the rise of people internally displaced by conflict in Afghanistan of 73% (2021). The data of IDMC (Internal Displacement Monitoring Centre) shows the total of 80.5 thousand people displaced only in August (2021). On top of that, the COVID-19 pandemic adds more health risks. Combination of all these disasters left the Afghan people with minimal levels of safety and low chances of survival without the urgently needed humanitarian aid, including shelters.

The Department of Economic and Social Affair of the UN (United Nations) formulated 17 Sustainable Development Goals (SDG's) in 2015. Goal 11 states: "Make cities and human settlements inclusive, safe, resilient and sustainable" and one of its targets focuses on "building sustainable and resilient buildings utilizing local materials" (2021). The design of reconfigurable shelters follows these guidelines by not only providing a safe space for refugees but also by utilising the locally mined earth to form the compressed blocks. Several historic types of traditional Afghan housing were constructed from "clay mixed with chopped straw" (Nawid, 2020, p. 1218). This material is not only easy to find in the Afghan soils but is also simple in use and has several properties that make it very suitable for the climate.

The envisioned design for this study is inspired by historic compression-only structures, such as arches and domes. The more intricate example of such architectural forms are muqarnas. The spatial geometrical transitioning by the means of stacking various modules used in traditional muqarnas acts as a base for understanding the methods for this research and further identifying the design plan for the shelter modules. By studying these methods this paper will focus on formulating a computational method for procedural design of the shelter (blocks).

II. RESEARCH FRAMEWORK

2.1. Problem statement

The recent economic-political catastrophe in Afghanistan requires urgent need for shelter to aid and protect the affected people. The existing shelter designs shown in the catalogue of UNHCR (United Nations High Commissioner for Refugees) are hard to transport, especially due to the geographical positioning and current political situation of Afghanistan (2016). In addition to that, these shelters are prefabricated and not designed taking the specific needs and opportunities of Afghanistan into account. This makes their use less affordable, less sustainable in materialization, more time consuming in transportation (and possibly assembly) and therefore not compliant with the 11th Sustainable Development Goal of the UN. Furthermore, any additional glues/nails/hinges needed for usual construction would create similar problems.

By taking inspiration from traditional muqarna structures it is possible to envision the desired shelter dimensiality and structure. However, a further understanding of the available generative methods is needed in order to be able to create the framework that would allow to design the blocks for the compression-only shelter structure.

2.2. Objectives

The main objective of this research is to formulate a methodological procedural framework for designing the polyhedral blocks, that could be assembled without additional glues or adhesives in order to form a funicular vault-like structure. With the help of computational topological design principles this framework will describe high-tech design steps to be taken for creating the blocks that can be implemented with the least additional means, such as complex machinery and therefore have a low-tech construction as a matter of assembly.

2.3. Research questions

Following the posed problem statement and the objectives of the research, the main research question is formulated as following: *How can we design a set of a few polyhedral cells with which we can make many variations of modular shelters (funicular spatial shell-like structures made of a set of dry-stacked polyhedral blocks)?* customization.

III. SCOPE

This paper focuses on various approaches to the solution of the posed question by describing the different types of tessellations. It identifies three main variants: 2D, 2.5D and 3D tessellation. It further looks into the form finding and shape optimization algorithms, namely Dynamic Relaxation, Force Density Method and Graphic statics. This is needed for better understanding of the processes in order to be able to apply them in the further stages of the blocks design and approximating the structure by the means of topological polyhedralization.

Geographically, the research discusses the shelter design for Afghanistan. However, the generative nature of the design makes the blocks easily reproducible. This means, that the project can be applied in other countries with the similar climate conditions and available earthy materials. Also, the stacking composition can be adjusted to the specific needs of the people, which allows for affordable mass customization.

IV. METHODOLOGY

This research is exploratory in nature and focuses on collecting qualitative data about the various generative methods that could be used to design the polyhedral blocks for the shelter. Two qualitative research approaches are applied to conduct this study. The first one is the grounded theory, which follows a rich data collection on a chosen topic for inductive procedure development. The second one is the action research, which combines the theoretical knowledge with the possible practical application in order to be able to answer the research question and design the working framework for the shelter block design.

The main method used to complete the research is the literature study and analysis of other secondary sources on the methods that are chosen. Another method applied during the later stages of the research is hand sketching. This is done for a preliminary study of form and dimensiality of the blocks, pattern and tessellation possibilities investigation, better visualization of the spatial concept design for the vault-like shelters and sketching of further research and design processes.

V. TYPES OF TESSELLATIONS

5.1. 2D tessellation

Tessellation is an "arrangement of shapes fitted closely together with no spaces in between, especially in a repeated pattern" (2022). A 2D plane tessellation is also commonly referred to as tiling. There are many ways of generating a pattern or tiling a 2D plane. Because of the nature of the design project, being an architectural structure where the dimensions and sizes of spaces need to be able to be researched and defined separately, it is more convenient to use the method of substitution tiling. This will allow "fitting" the tessellation into the desired shelter footprint and also a higher blocks variation possibility by creating multiple types of prototiles. Hence, it will provide for a larger number of customization variations.

5.2. 2,5D tessellation

The 2,5D tessellation method, also known as the Lego method, starts with the 2D plane tessellation. Afterwards, the resulting pattern is navigated to the chosen highest point (commonly the geometrical center of the plane) and the outlines of the blocks are picked with the idea that these blocks should overlap each other so that they can be stacked on top of one another. The outlines are later creating the 3D blocks. Because of their design method, they can be stacked into a 3D structure. A schematic representation of this method can be seen in Figure 1 below.

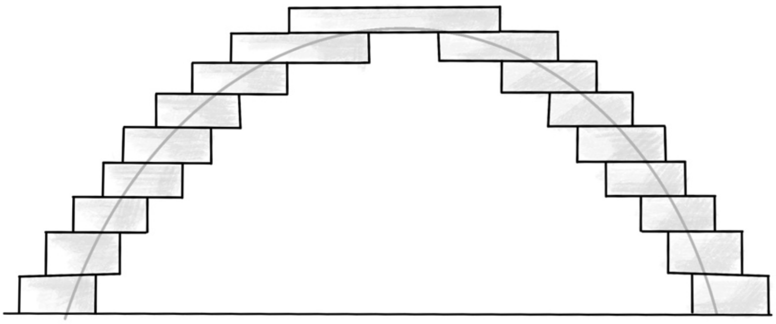

Figure 1. 2,5D tessellation method

5.3. 3D tessellation

The 3D space tessellation method is sometimes referred to as the gothic method. It can be used to create structures by filling the space with the polyhedra, in which all cells are congruent. In order to find the final vault-like spatial shell structure, a force diagram dual to the polyhedral cells is analyzed and the "extra" are taken out. The 3D tessellation method is described in a scheme shown in Figure 2 below. This approach wasn't chosen to complete the design of the reconfigurable shelter. It is very different in methodology and design processes from the 2,5D approach. The latter was picked because of the possibility to start working in the 2D plane and have a better understanding and control over the design of the stackable blocks.

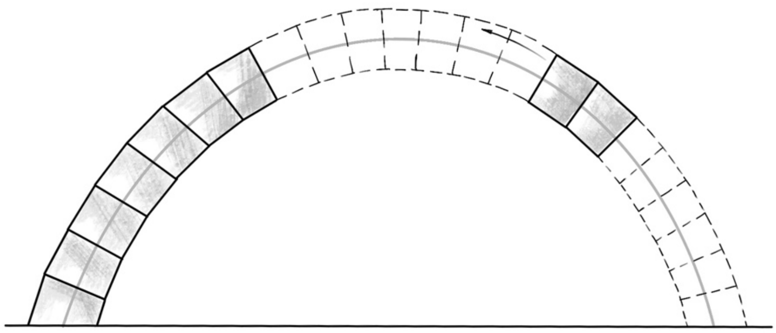

Figure 2. 3D tessellation method

VI. Form finding and shape optimization

6.1. Dynamic Relaxation

One of the methods for computational form finding is Dynamic Relaxation. It is used in order to find the geometry of the structure where the forces would result in equilibrium and is usually used for cable or fabric structures. However, the structures that are in equilibrium in tension also result in equilibrium in compression if reversed upside down. Structural designers like Heinz Isler were renowned for the experimental approach to shell like compression only forms by hanging and freezing the cloth to later reverse it and get a perfect funicular structure (Kotnik and Schwartz, 2011). The same idea can be applied for shape optimization of the shelter. Firstly, a dual graph of the blocks is composed. After that it can be mirrored with the XY plane and analyzed in tension with the help of the Dynamic Relaxation method. After adjustments and gaining the equilibrium, it can be mirrored back.

6.2. Force Density Method

The Force Density Method (FDM) introduces a new term – force density, which is a ratio of the force to the length of the branch of a net structure (Schek, 1974). Two problems can be solved with this method: the preliminary assessment of the structure and the possible load paths investigation (Bruggi, 2020). This method is used for generating solutions with the help of a system of linear equations. It is generally used to design the cable net structures. However, Adriaenssens et al. (2014) explain how the introduction of the loads make this method allow the form finding of synclastic structures, which are suitable for the shell structure design. A huge advantage of this method is the ability to materialize the resulting structure completely arbitrarily.

6.3. Graphic Statics

Graphic statics is based on two diagrams: the form diagram and a force diagram. The first one shows the geometric layout of the loaded structure and the forces applied to it. The second one represents the equilibrium of forces between the structure. The main useful property of this method is the ability to observe direct transformations on one of the diagrams while adjusting the other. This feature creates the possibility to design the structures by simultaneously using both, the form and the forces (D'Acunto and Konstantatoub, 2020).
This method has extended into the 3rd dimension thanks to the progression in the field of computer aided design. Within the 3D graphic statics there are two main approaches: the polyhedron-based approach and the vector-based approach.

In the polyhedron-based approach, each polyhedron is represented as a spatial truss. Each node of this truss has its concurrent edges. The internal axial forces of the concurrent edges of each node of this truss can be represented visually with the surface area of the face, that is perpendicular to that force. Repeating this graphic representation to every truss member concurrent to the node results in a closed cell. The same applies to each node of the initial polyhedral. These cells have a dual relationship with the spatial truss, where each node corresponds to a cell and each edge corresponds to a space.

In the vector-based approach, the form and force diagrams are constructed from the cycles of vectors. For a structure in static equilibrium, vectors that are parallel to the bars of the spatial truss that are concurrent to the node are scaled to generate a closed cycle of vectors. This procedure is repeated for every node, resulting in a series of the closed cycles of force vectors (force polygons). All of them can be later combined into one vector-based diagram.

VII. Results

After studying the various approaches and methods to design the polyhedral blocks for a funicular vault-like structure, a clear procedural framework can be formulated. A step-by-step plan of the further actions to complete the design of the blocks is the following:

1. Define the dimensiality of the shelter projection on the 2D plane (plan)
2. Make a 2D tessellation with the chosen pattern using the substitution tiling
3. Find the dual graph of the tessellation
4. Mark the apex vertices on the dual graph, which belongs to the faces incident to the apex vertices on the tiling
5. Run the shortest path traversal from the apex vertices to the vertices that are incident to the walls
6. From each link on the traversed paths mark two faces in the original/primal tiling and create a 3D Lego-like block out of them
7. Scoop out some excess mass out of these Lego blocks and shape them as Muqarnas pieces

VIII. Conclusions

In conclusion, the research question is answered by designing a framework for further form finding of the polyhedral blocks, with which it would be possible to construct a funicular dry-stacked vault-like shelter in Afghanistan. This procedure will be followed in the next steps of the project and further developed into the master graduation design project.

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