Digital Tessellation and Fabrication of the ECHO shell

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Abstract

Complex forms, that in history have always been challenges for architects are now becoming familiar to people working at the edge between architecture and structural design. This is, in particular, true for free form shells design. Free form shells are today undergoing a wider adoption for both permanent structures as well as temporary structures [1]. These last are of particular interest, when they are conceived according to a logic of design for deconstruction, since they can respond to circular economy requirements [2]. This work explores the digital process from design to manufacturing of a shell that has the shape of sounds waves replicating like in an Echo. The structure is made of a sequence of wooden arches and a compact thin shell. The shell combines free form generation with planarization and tessellation processes, using hexagonal discretization. The hexagonal panels are CNC fabricated from 6 mm plywood and are connected together by ad hoc 3D printed joints. The arches follow the hexagonal shell patterns and are conceived as slices of shell continuity and replication. The overall structure is demountable, easy to transport and capable to be reassembled in short time, responding to the principle of design for deconstruction. The result is a neat clean space adapt to any exposition space.

Keywords: additive manufacturing, digital design, form finding, parametric modeling, tessellation

1. Introduction

In the contemporary scenario complex and freeform shapes represent a large portion of architectural solutions [3]. Impressive projects throughout the world carried out by important architects and engineers are evidence of a new way of designing. New technologies regarding the design and the fabrication are providing significant changes in architecture and total freedom in artistic expression [4]. This rising presence is due to multiple factors but firstly one of the key factors lies undoubtedly in the development of innovative methodologies associated with straightforward digital tools that affect each aspect of the design process, from the concept to the fabrication. Through the use of innovative techniques in the design first and then in the fabrication, it is possible to generate an optimized workflow that meets specific requirements in each design phase. Parametric modelling is involving all the aspects of the design creating a strong connection within the process. The interoperability with digital fabrication techniques is another demonstration of the countless potentialities that this new approach presents [5].

This paper presents a parametric approach to define an efficient shell structure, which will be digitally fabricated. In the following sections, the digital design is described in detail, from the form finding to the tessellation and planarization, up to fabrication of main components. All the digital design is carried out within Grasshopper® functionalities together with its powerful plugins. One of the key part of the all described process is the tessellation since it allows to discretize the original surface into flat panels, that will be CNC fabricated and assembled together by neat connection

2. Concept and overall methodology

The ECHO shell has been developed in answering the brief set by the international context within the IASS 2019 conference, which requires to develop a shell that is included in a volume 4x4x4m, that is lightweight and follows a logic of design for disassembly and can be carried around in 6 boxes. Our aim was to develop a space that has the shape of echo soundwaves, in which the portion having single curvature is made of a continue shell, while the double curvature is obtained through a sequence of arches (Figure 1).

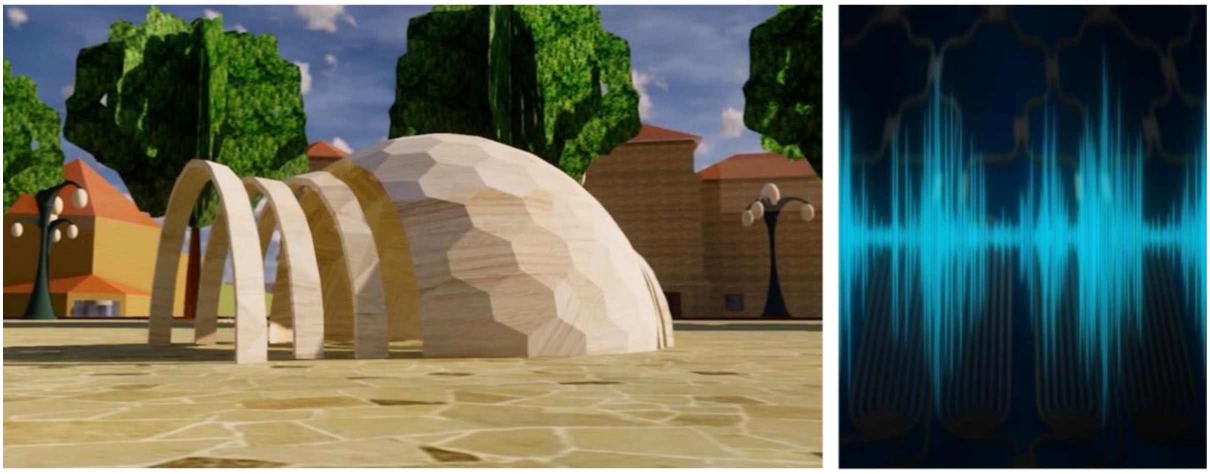


Figure 1: ECHO, 3D generated concept of the shell and an echoing soundwave

Figure 2 shows the basic design process this research follows. The first input in the design process is the initial shape. The required output of this process was a shell, which by definition has one dimension very small compared to the other two dimensions. The initial shape chosen was a three-dimensional surface, with a constant curvature. The surface was created using Rhinoceros® (Figure 3) and referenced into Grasshopper to be used directly in the tessellation process.

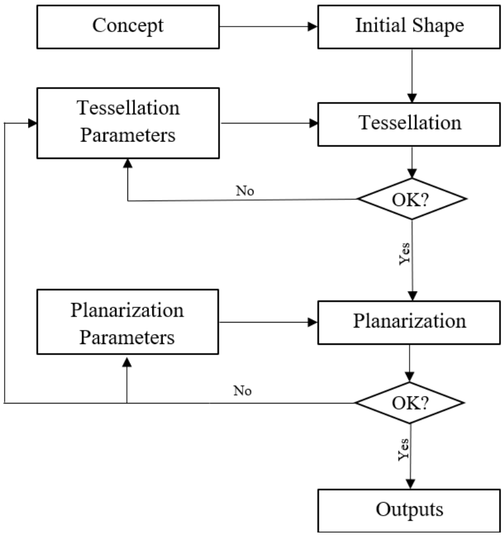


Figure 2: Basic process of a parametric shell design

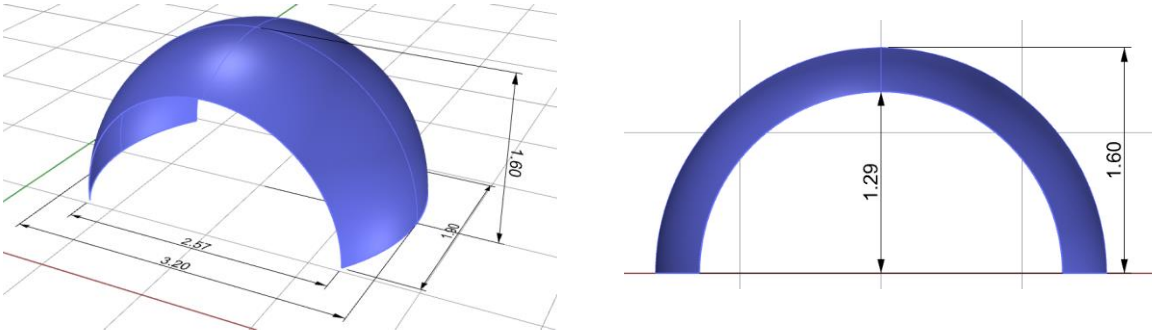


Figure 3: The surface created using Rhinoceros®

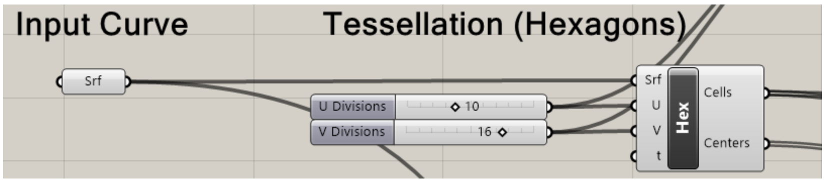
2.1 Parametric Design and Modelling

Parametric design is an algorithm-based process, that uses parameters to define the relationship between a set of inputs to derive a required result. The outputs of this process remain tightly related to these parameters. Changing a parameter at any stage of the process affects the end results directly. However, this effect and its magnitude, depends entirely on the implementation of the parameter in the system being designed. This methodology has been applied to the shell surface created previously to provide the boundary conditions for the planarization process and to form the hexagons in the tessellation process.

2.2 Tessellation of Surfaces

Tessellation is the process of dividing a surface using geometric shapes. The tessellation process has been mainly used for planar surfaces with regular repeating patterns of one or more geometries. This is referred to as tiling. Mathematically, the tiling process can be expanded into tessellation of free-form 3D surfaces. Using different algorithms, this process can be applied to any surface. Computer generated tiles using tessellation algorithms usually result in non-planar tiles that follow the shape of the tessellated surface exactly. This was the case of the ECHO project, for which planarization was then later applied to allow the fabrication by using planar sheets of plywood.

A plugin called LunchBox was used for the tessellation process. LunchBox has different components for different types of tiling. The operation is called "panelling" as it divides the surface into multiple panels of the chosen pattern. A series of different patterns were investigated, and among them hexagonal pattern was chosen because it will minimize the number of connections required between the panels while increasing the possibility of a successful planarization process. Therefore, "Hexagon Cells" or "Hex" component was used (Figure 4). This component requires three inputs and a fourth optional one. The first being the surface, the second and the third are the number of panels in two perpendicular direction U and V which were set to 10 and 16 respectively. The directions U and V are a local coordinates system applied to the surface by the "Hex" component. The fourth input is a parameter that defines the angle of the generated hexagons, which for this application was left at a default value of 0.25. Figure 5 shows the output of the tessellation process.



U Divisions 10

V Divisions 16

Figure 4: Hexagon Panels component of LunchBox plugin

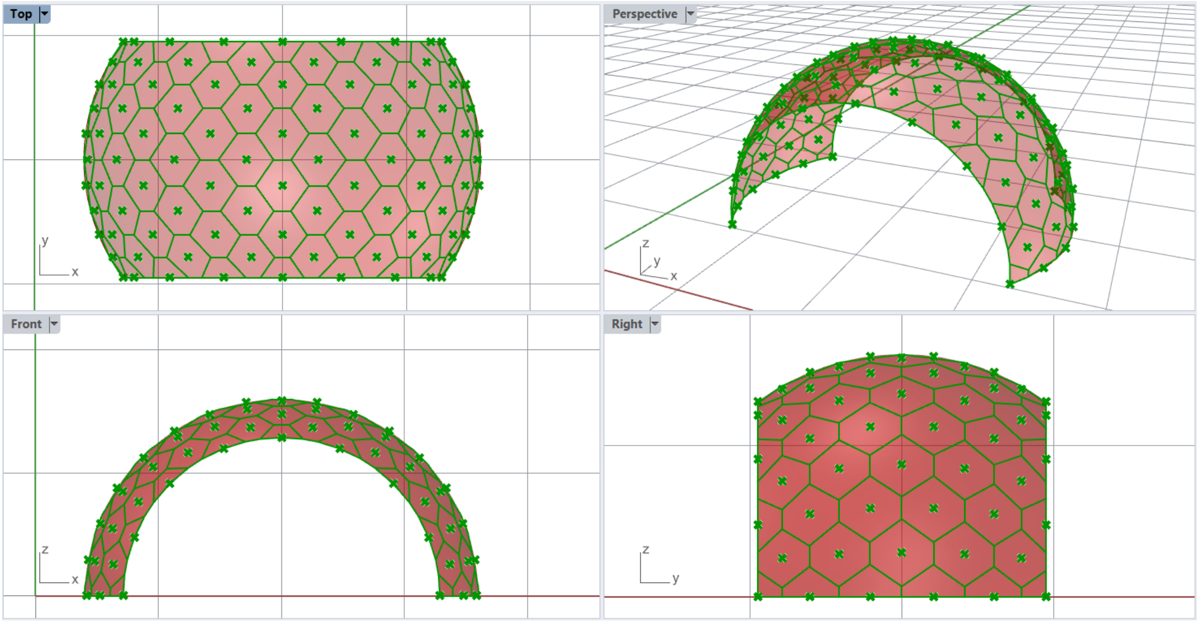


Figure 5: Hexagon panels generated by “Hex” component

2.3 Planarization

The planarization allows to increase the flatness of a surface or make it planar. This process involves applying several forces to different points on the surface to force them into planarity. The plugin Kangaroo2 is a physics engine that uses algorithms and logic to solve the provided inputs [6, 7].

Kangaroo2 provides a large set of constraints and forces that can be applied to points, curves, angles and surfaces. In addition to a set of utilities and physics solvers. The solvers accept curves, points or surfaces as an input. Then it applies the forces and constraints to these inputs. The same process is repeated for several iterations until the solver converges on a solution. The ECHO shell is made of planar plywood sheets. In order to get planar panels that are as much close as possible to the hexagons created by the tessellation, some conditions were applied; a boundary condition, a length constraint on the sides of each hexagon panel to preserve their shape, and planarization forces. The boundary conditions in the required shell is the outer curve of the shell. This is the same as the three curves used to create the shell. The requirement is for any edge vertex of a hexagon that belongs to these boundary curves should be anchored. That is because the outer boundary is the curve that gives the shell its shape. This list of vertices was extracted as shown in (Figure 6) and inserted as input into the Anchor Component of Kangaroo2 (shown in green in Figure 6). This component provides a force that resists the movement of the inputs with a strength that was set to a default high number equal to 10000.

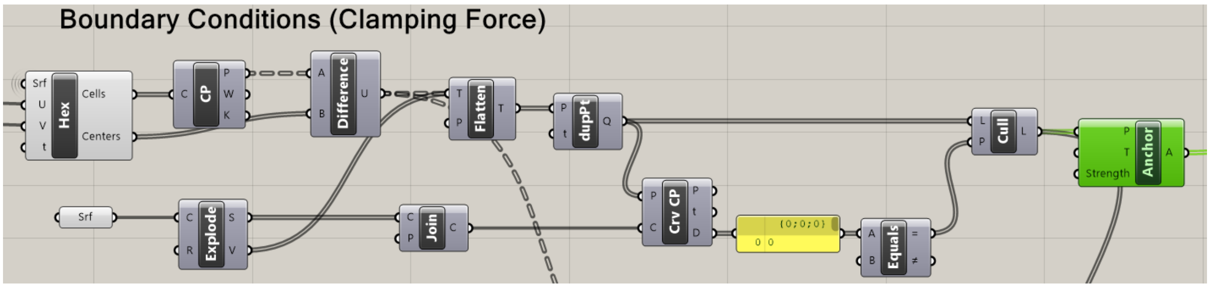


Figure 6: The process of providing boundary conditions as point anchors

The length constraint is a condition that was applied to the hexagons' edges to prevent them from deforming in an undesirable way. The length constrain component receives an input of lines to clamp their length. The lower limit and upper limit are the minimum and maximum lengths for these lines respectively. The input lines are the output of an Explode component applied to the Hex process. The strength of this clamping is a parameter that can be changed at any stage of the design process. Lowering the clamping strength resulted in more deformation in the shape of the hexagons than desirable. After few iterations, the strength was set to 1 (Figure 7).

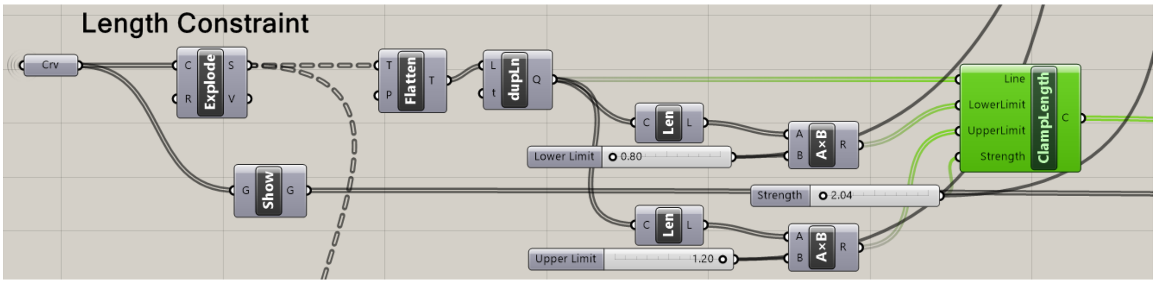


Figure 7: Length Constrain process

In this project, these lines are the edges of dissimilar hexagons. There are no known upper or lower limits. The limits were set as a multiplication of each line length by a number. The lower length for any line was set to its actual length times 0.8. The upper limit was set to the line's actual length multiplied by 1.2. This translates into a clamping force that prevents the lines from deforming by more than 20% in either lengthening or shortening. The planarization forces in Kangaroo2 can be applied to points in order to force them to occupy the same plane. The hexagons that were extracted from the Hex operation were exploded and the control points of the hexagons (edge points) were used as input for the CoPlanar command. It accepts points as input and a strength value that determines the strength of the planarization force. The default for the strength value is 1. However, it was found that a small force can sometimes result in non-planar panels. The reason for this is that the other forces acting on the panels' vertices are high enough for the solver to not converge on an answer. Since the most important goal is for the panels to be planar, this force was set to a strength value of 1000 (Figure 8). Kangaroo2 Bouncy solver is a physics engine solver that uses algorithms to achieve the goals assigned as inputs (Figure 9). The goal objects of the bouncy solver were set to the previously discussed components. The ClmapLength component that includes the hexagons' edges and prevents them from changing in length outside of the set limits, a CoPlanar command that applies a force on the vertices, and an Anchor component that fixes the input points in space.

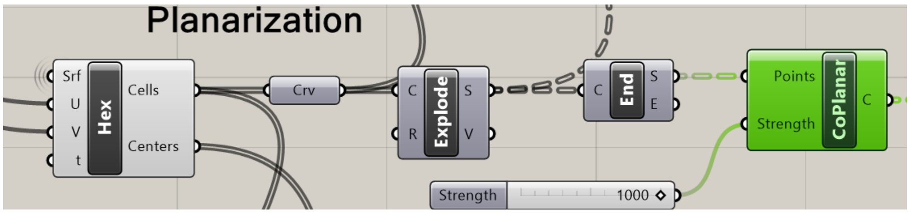


Figure 8: Planarization process and the CoPlanar component

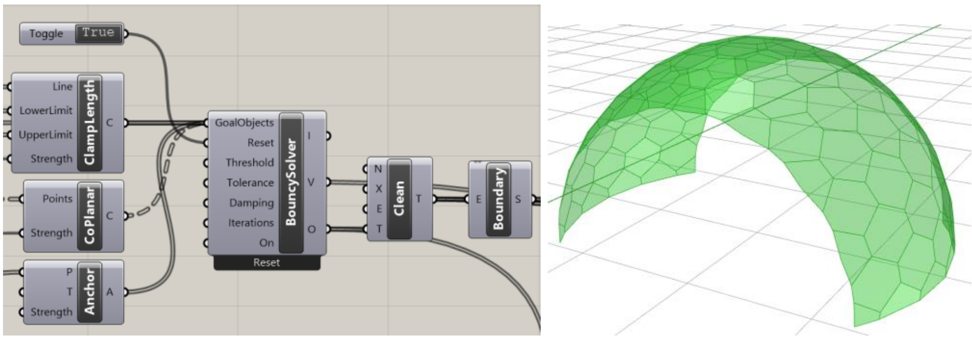


Figure 9: Kangaroo2 Bouncy Solver and the resulting planarized shell

3. Connections

An idealistic shell structure should carry all loads in membrane forces only. This is true only after the shell is completely constructed. Depending on the design, a shell that is still in construction is very unstable. For this reason, any type of connection between tessellated structure cells, should be able to carry a moment for the entire period of construction. This is especially true for shells that are constructed with minimal formwork. ECHO shell connections were designed assuming the formwork will carry most of the load, but the connections will be subjected to a bending moment at the construction stage. The shell consists of thin plywood panels. Since the panels were only 6mm thick, a connection that would interfere with the sheets axially was ruled out.

Multiple connection systems were developed using Autodesk® Fusion360. The final design shown in Figure 10 was 3D printed as 2 parts that will envelope the panels at the connection vertices (where three panels meet). The connection measures 30mm from the centre to the farthest point of the connection and has a thickness of 4mm for each part. The lower part of the connection has three blocks that fit into slots cut into the panels.

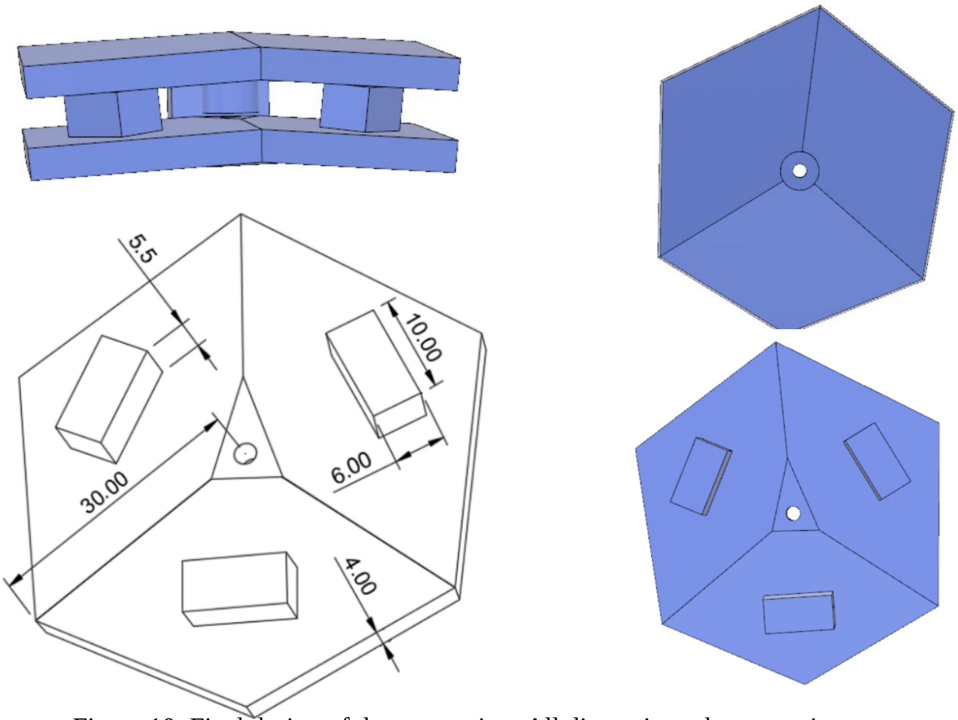


Figure 10: Final design of the connection. All dimensions shown are in mm

This design would depend on friction between the connection's blocks and the panels for stability, and to a lower degree on the clamping force provided between the two parts of the connection. It was possible to add a relief of 0.1-0.3 mm to the interface between the connection and the panels slots and still conserve the rigidity of the connection system. The ECHO shell consists of 94 planar panels connected using 144 connection of this design. Despite the symmetry of the shell, designing a large number of connections individually is time consuming, less efficient and more prone to errors. Developing the connections through parametric design is crucial to avoid these problems.

To create a parametric design of the connections, it is required to pick starting points. These points are already listed as output from the Kangaroo2 Solver. The connection is joining three panels, so three construction planes are needed. The construction planes are created from the surfaces of the panels and they intersect in one point only. This point is always the same as the solver's output. Figure 11 shows the procedure from the starting point to the final connection. Finger joints were added to the panels to provide stability and simplify the assembly. Figure 12 shows the final configuration of connections on the shell.

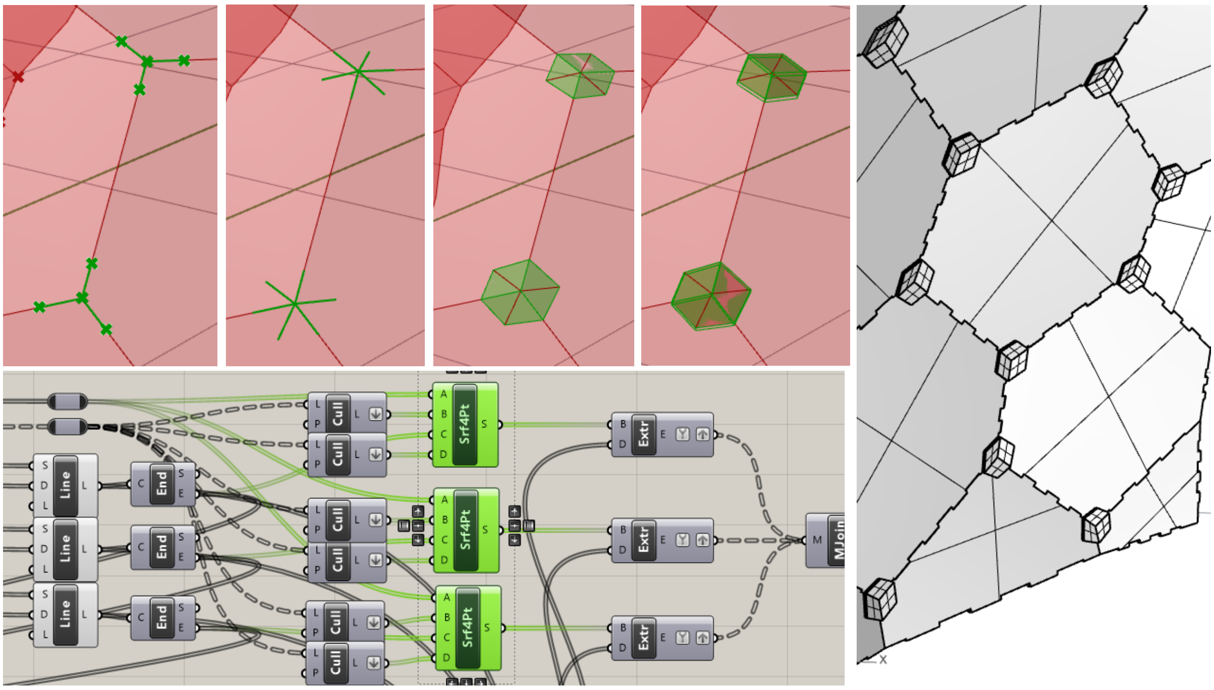


Figure 11: Connection design stages and final result

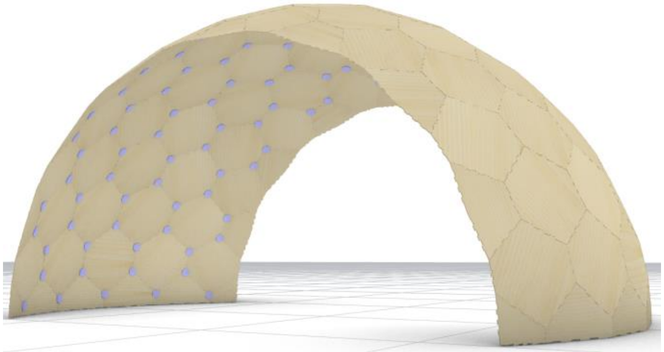


Figure 12: The ECHO Shell showing panels and connections

4. Fabrication

Three panels were fabricated as test by laser cutting 6mm plywood sheets and connected through a 3D printed connection. The connection was designed to retain the panels by friction forces only, without the need for screws or bolts that would have increased the time needed to fabricate an entire shell dramatically. The connections were tested, and proved to be able to hold the panels in place and retain the angle between them to a very good degree of accuracy. Figure 13 shows one connection resisting the bending moment caused by the weight of two panels while being supported at the farthest end of the third panel. The second part of the connection helps in retaining the angle between the panels, and can be joint to the first part by a self-tapping screw or a small metal pin.

Figure 13: Fabricated panels in place with the first connection

5. Conclusion

This paper presents the design of a lightweight wooden shell, that is made of 94 CNC hexagonal panels connected together by ad-hoc 3D printed friction joints. The work focuses on the development of the digital design, explaining tessellation and planarization of the surface, and the conceptual development of the connection system. This last has been designed to allow easy assembly and disassembly. The fabrication of a first portion demonstrates the capacity of the system, and a full prototype will be developed to analyse full feasibility and limitations.

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