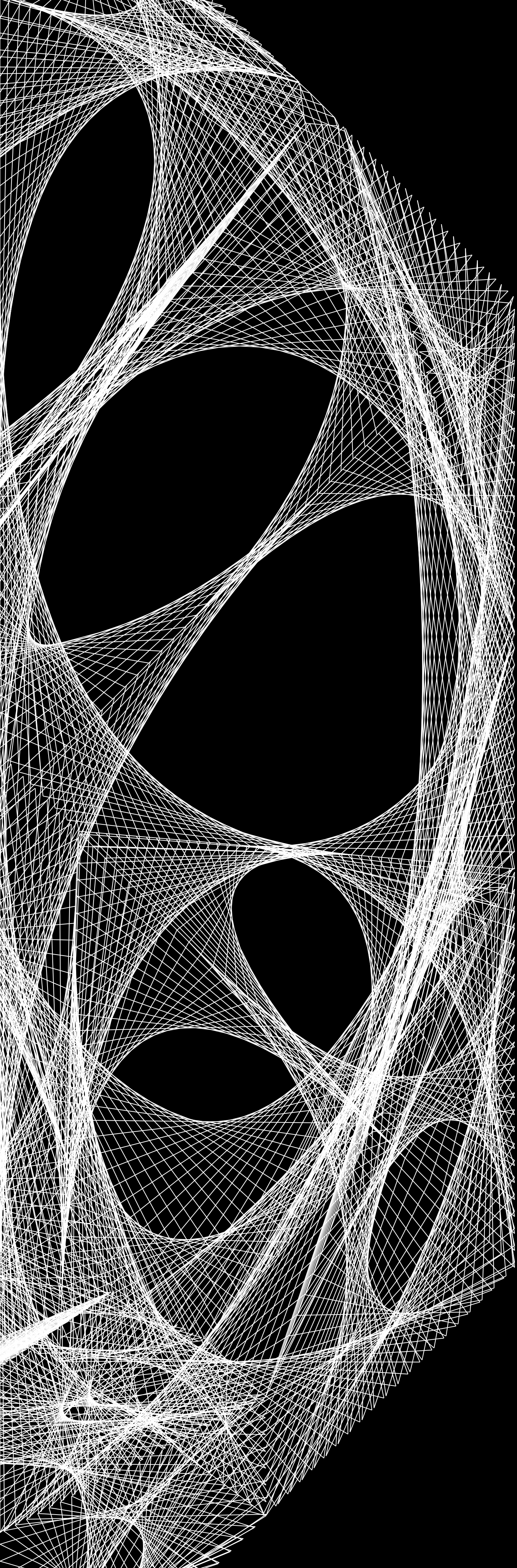

Material exposure

Carbon fiber & epoxy exploration

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Department of Architecture and Civil Engineering

Examiner Daniel Norell
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Chalmers University of Technology
Göteborg, Sweden 2019

2019
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Acknowledgment

I would like to thank my supervisors *Jonas Lundberg* and *Kengo Skorick* for their support throughout this thesis. I would also like to thank my examiner *Daniel Norell* for his helpful advice, *Tabitha Nilsson* and *Peter Lindblom* for helping and allowing me use the workshop extensively. To *John Bogren*, my friend and fellow studio member for spreading his enthusiasm and energy.

I would like to thank my family, my father *Billy Tang* and my mother *Amy Tang* for pushing me towards higher ambitions. To my brother and role model *Christoffer Tang*. To my sisters *Elaine Tang* and *Denise Tang* for their warmth and care during hard times.

And lastly, to dear *Yi Zhang* who put up with me during lowest times.

About the author | Felix Tang

Felix Tang is a 2nd year master degree student in Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden. He began his architectural studies at Chalmers back in 2012 with a specific interest in the digital and technical areas of the subject. Felix's keen eye for details and dexterity that allows him to work with both physical and digital models in a holistic approach.
Born and raised in Sweden, Borlänge with a Chinese background gave him an attitude of hard work ethnic. His keywords to life is adaptability, perseverance and understanding.

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ABSTRACT

How do you build with amorphic material without using a conventional casted mould?

Fiber-composites are one of the highest performing material in terms of its high strength relative to low weight. It's found in major industries such as: auto-, airline-, military-, sailing-, texture industry and even architecture. In architecture, fiber-composites such as glass- and carbon fiber are also considered amorphic, meaning it is lacking shape. The fabrication process uses a large quantity of molds to define the form. This leads to a great deal of waste material.

The fibrous material uses different weaving patterns to determine its structural performance. Density, weaving pattern and materials combined for different purposes. However, this usually ends with the material in factory-weaved sheets for commercial use. Thus already limiting the scope of possible production method and style. The most known twill weave and plain weave is what gives its iconic surface appearance.

This thesis aims to find fabrication methods that can disregard the need for conventional casting molds while working with composite materials. The purpose is to discover more application areas for composite materials in architecture.

This thesis will research and present several alternative algorithmic weaving patterns. The medium will swift between digital and physical form, simulation and execution. The experiments will look into material stability, complexity/simplicity, external and internal influences, aesthetic style and possible large-scale applications.

Keywords: Material experiment, weaving, Manufacturing, Carbon fiber, epoxy, light-weight-structure

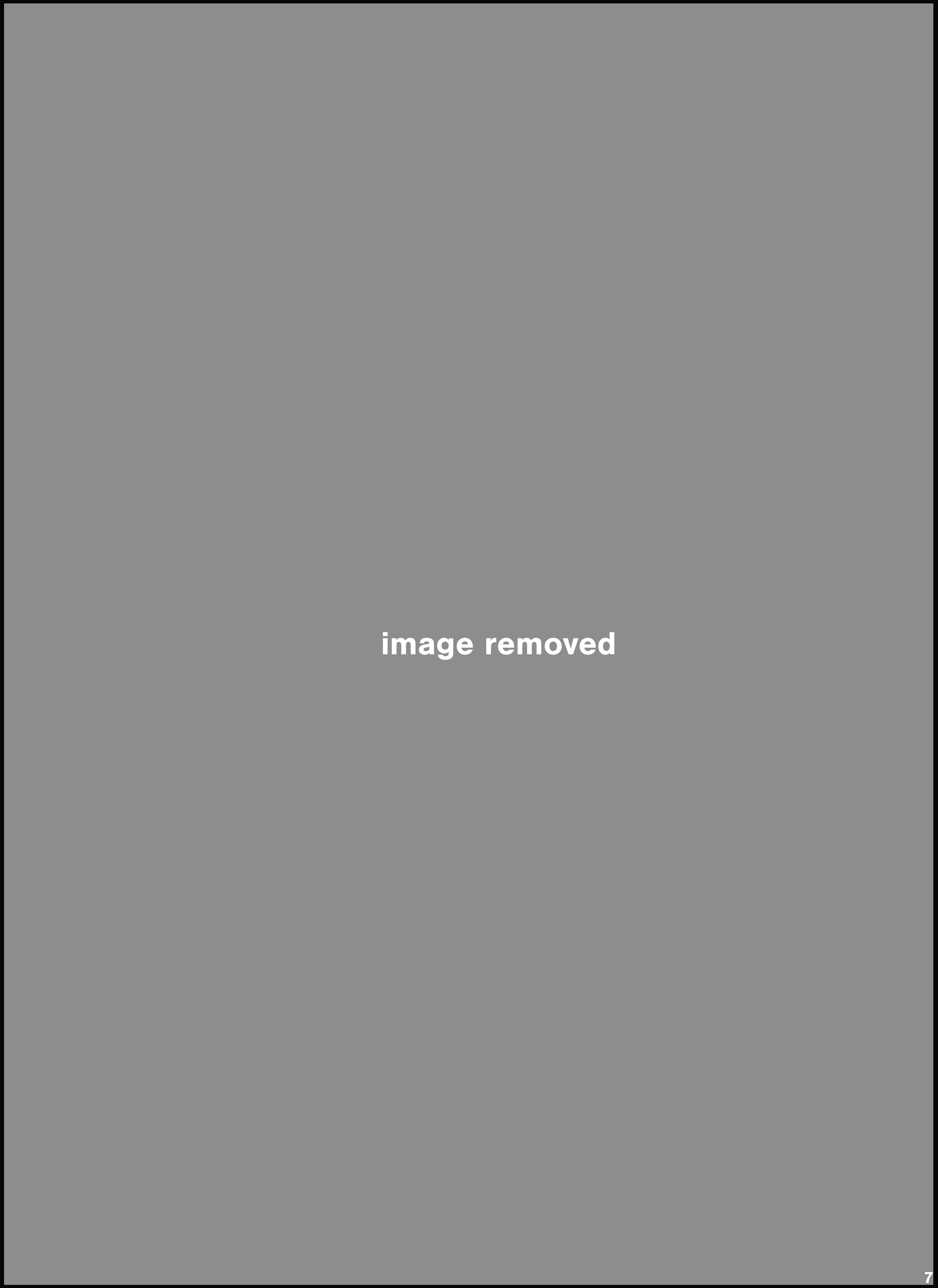


Figure 1. RKP Carbon Fiber Diffuser for 2015 BMW M3 and M4 (European Auto Source, 2015).

What is carbon fiber?

Carbon fiber is a long thin thread of material with the diameter of about 0.0005-0.010 mm. It is almost made of pure bonded carbon atoms aligned parallel to the axis of the fiber.

The process to making carbon fiber is part chemical and part mechanical. The material used in most carbon fiber products is Polyacrylonitrile (PAN) which is an organic polymer. The polymer carbonizes by being drawn and heated through an oven at high temperature. This causes the carbon atoms to shake until the non-carbon atoms are gone. The results is a thin strand of aligned carbon. The fibers are then treated to oxidize on the surface to allow for better adhesion to chemicals such as epoxy.

There are different types of carbon fiber based on their tensile modulus. A tensile modulus is a measurement of the resistance to elastic deformation of a material. Higher tensile modulus require higher stresses to deform a material. “Low modulus” carbon fiber have a tensile modulus below 34.8 million psi. The other varying classes reached up to “Ultra high” with a tensile modulus of 72.5-145.0 million psi. Steel have a tensile modulus of 29 million psi. “...the strongest carbon fibers are ten times stronger than steel and eight times that of aluminium, not to mention much lighter than both materials, 5 and 1.5 times respectively.” (Zoltek, 2019)

Figure 2. The carbon fiber sold in the market is often woven in a power loom into a sheet, usually in twill or plain weave. Twill weave is more popular due to its higher ability to conform to molds better than plain weave. This is a necessity due to the method of working with carbon fiber.

The process of working with carbon fiber sheets is a long process with many details. The trimmed sheets are impregnated with epoxy and layered onto a mold of desired shape. The sheets are then vacuum sealed and packed to remove excess air, epoxy and to further conform to the mold. Without proper vacuum seal the products can end up with undesired deformation in the final results. Excess epoxy also adds weight. The vacuum sealed work piece is then placed in a oven to bake in high temperature until cured. After curing the epoxy can be removed from the mold and finished with clear coat.

The typical process can be tedious, imprecise and mixing epoxy can cause a big mess. Another way is to use “Prepregs” which are sheets of carbon fiber impregnated with epoxy beforehand. The sheets layered with a resin system (epoxy) and ready for lay up once the protective backing layer is peeled off. No extra resin needed. The sheets are placed on the mold, vacuum bagged and baked in oven. The Prepreg can be cut beforehand for minimal weight and layered to increase strength.

The advantage with Prepreg is the ratio between fabric and resin. A 50/50 mix is already difficult to reach from traditional method but Prepreg can reach up to 35% resin. This creates better performance in final product. (Fibregast, 2019)

The disadvantage to Prepreg is the high cost. The less waste material does not out weight the costs to produce and maintain this product. Because of the resin, the prepreg has a shelf life of 6 months and strict storage conditions. The Prepreg is ideally kept cold in refrigerators, otherwise the resin layer will start curing above room temperature. The resin can also not properly cure unless heated above 132 degrees C.

Figure 3. A part of a car made out of carbon fiber sheets. The texture comes from the twill weave pattern of the fabric. The glossy appearance is the result of coating the top layer with lacquer/varnish or clear coat. The auto part itself is not structural but the weight is lower than a glassfiber counterpart. In transportation industry, lowering the weight has many advantages such as lower fuel economy.

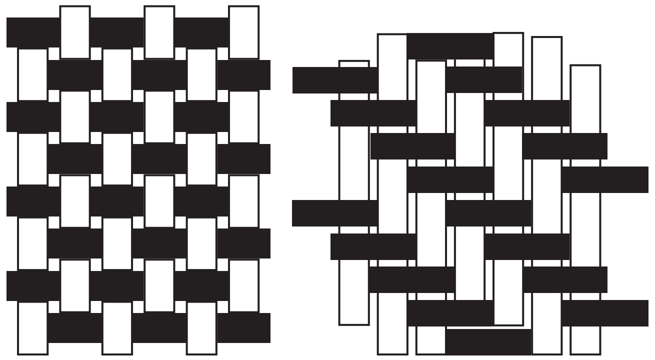


Figure 2. Plain and twill weave pattern. Author’s own copyright.

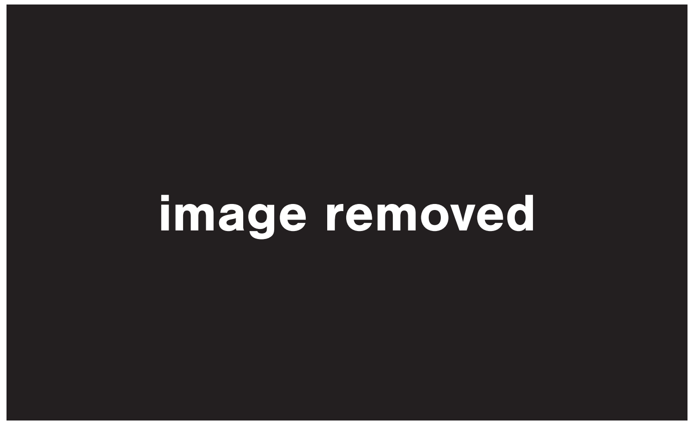


Figure 3. RKP Carbon Fiber Rear Diffuser for 2015 BMW M3 and M4 (European Auto Source, 2015).

Thesis question

How do you build with amorphic material without using a conventional mould?

What future role does Carbon fiber have in architecture and what are the different emerging forms?

Can carbon fiber play a structural and expressive architectural role in a building context?

Method and techniques

The core of this thesis revolves around refining the proficiency and method of working with carbon fiber. To research, learn, interpret, experiment, iterate and evaluate.

First step will be to gather a basic understanding of the material and techniques. To understand the most common fabrication techniques while working with fiber materials. The base serves as a foundation for then to further develop the later techniques aimed for this thesis work.

One topic to research will be about weaving in general. It will look into general patterns used in sold commercially. This is to try and understand the public opinion on what tendencies people have when working with carbon fiber. This part should be in both physical and digital form. There are digital tools with capabilities to interact between both media such as rhino and grasshopper.

The understanding of carbon fiber will come first hand from manual testing. As the project progresses more complexity is added when proficiency allows. There is a significant jump between basic and intermediate understanding of scripting in grasshopper. The parametric scripting will allow for a much higher output of results.

The actually method to working with carbon fiber depends on what direction this thesis leans towards. It depends on if it will focus on the weaving pattern or rather the whole process. A traditional method consists of a mold with desired shape that the sheets conforms to. If the mold is discarded there wont be any support to use vacuum bagging. A way to control the filaments into a frame will be necessary.

Supply of material, glass fiber and carbon fiber threads will be financed personally. Carbon fiber can be purchased online from local suppliers while keeping down the shipping time. Epoxy is sold from same vendors. The quantity of material needed is highly dependent on the scale of the models. Preferably, digital tools can compensate the lack of model scale after the early mandatory material studies.

References

The main reference for this thesis comes from ICD-ITKE Research pavilion 2013-14 & 2016-2017, University of Stuttgart.

The two pavilion are projects made by a team of many disciplinary. It is interesting to see how the fabrication process influenced the design process from the beginning to the final product. The research group managed to blend bio-mimicry, engineering and architecture into a wonderful project. The weaving pattern are results from investigating leaf moths behaviour in spinning silk across distances. This behaviour transferred and replicated to a multi robotic fabrication process to in a pavilion scale.

What I take from these projects is their method using the carbon fiber. The carbon fiber attached to the weaving robots is part of a simple impregnating loop system. The fibers are drawn through a bucket of epoxy and drip edge without twisting by the robot. The resin amount is somewhat controlled by the tension it passes the drip edge. It should be possible to emulate this with manual methods in early stages.

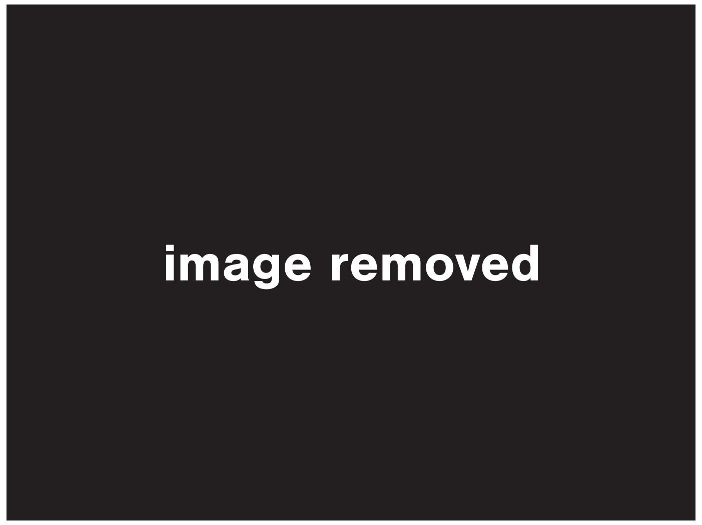


Figure 7. Image #1 ICD/ITKE Research Pavilion 2016-17, Stuttgart. (Halbe, 2016-17).

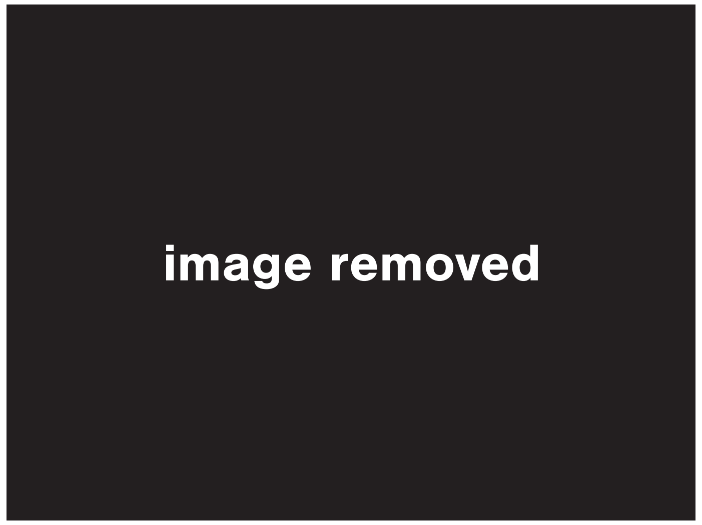


Figure 4. Image #8 ICD/ITKE Research Pavilion 2016-17, Stuttgart. (Halbe, 2016-17).

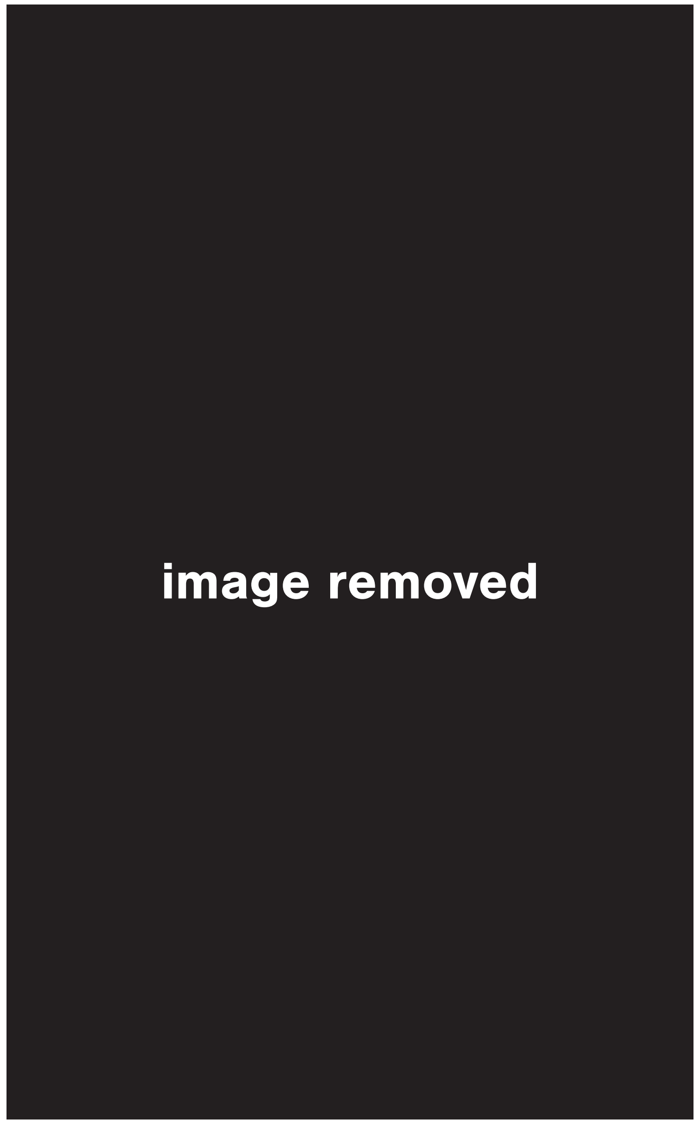


Figure 6. Image #4 ICD/ITKE Research Pavilion 2013-14, Stuttgart. (Halbe, 2016-17).

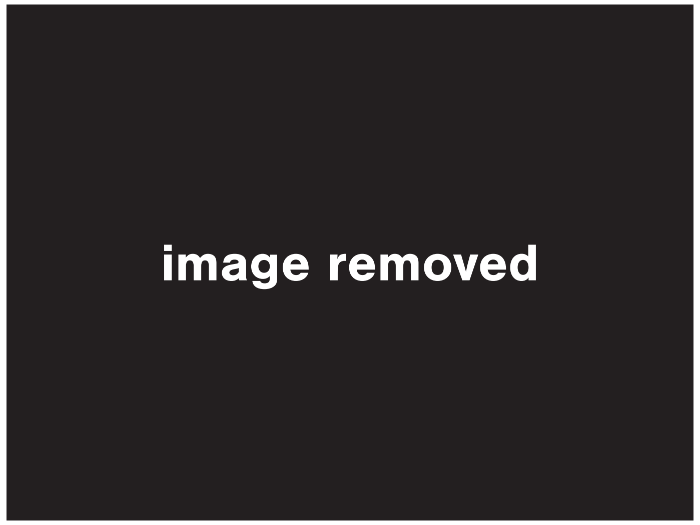


Figure 5. Image #3 ICD/ITKE Research Pavilion 2016-17, Stuttgart. (Halbe, 2016-17).

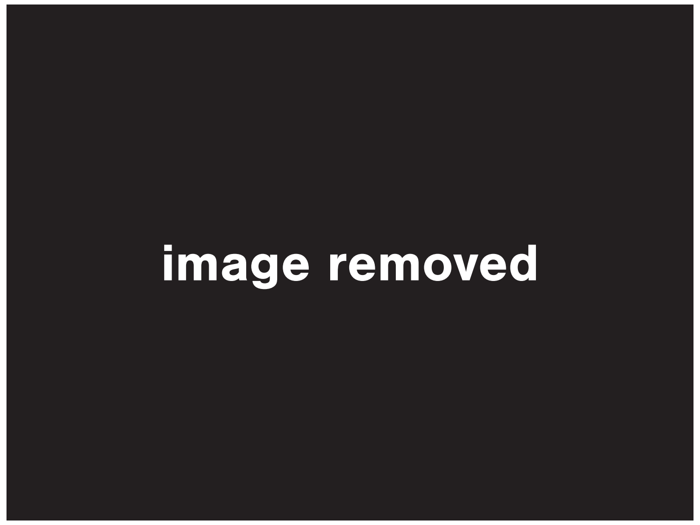


Figure 8. Image #1 ICD/ITKE Research Pavilion 2013-14, Stuttgart. (Halbe, 2016-17).

Physical Exploration
Materiality and method investigation

Figure 9. Cotton thread ball. Author's own copyright.

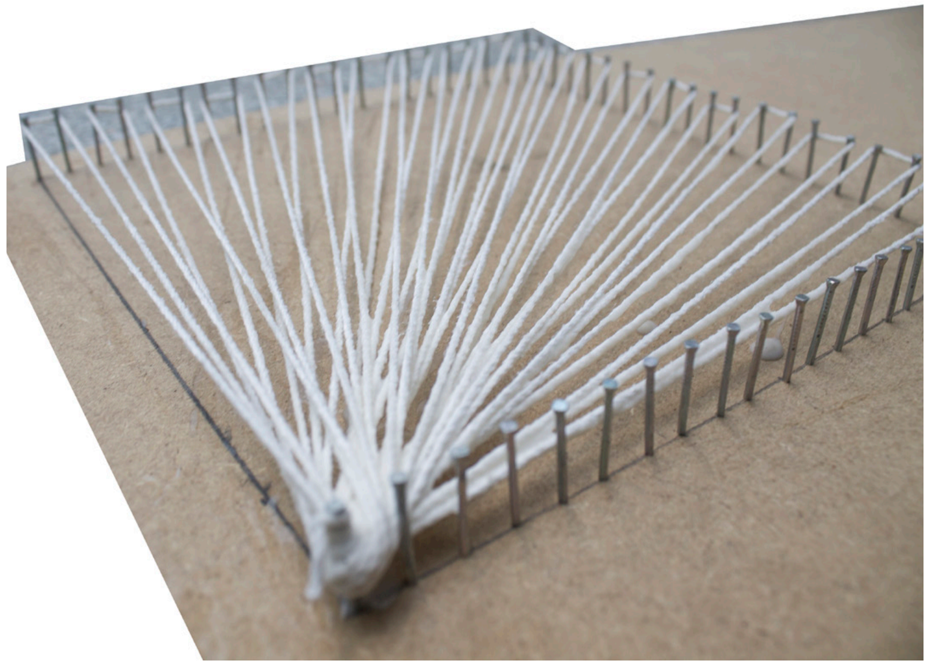


Figure 10. Wool Yarn Pattern 1 Perspective. Author's own copyright.

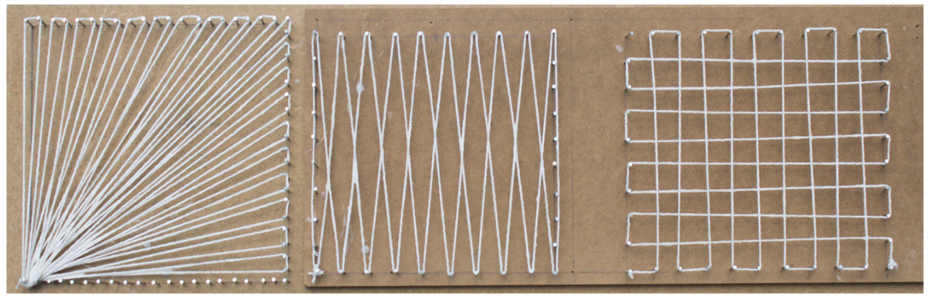


Figure 11. Wool Yarn Pattern 1-3 Top. Author's own copyright.

Experiment 1
Material:
wool yarn with varnish glue as adhesive.

This first experiment was test and get a feel for working in a structured layout formed by nails on the other grid. Each pattern was iterate in a way to gather strings as dense as possible to achieve a little gaps as possible. A denser gathering of strings resulted in stronger properties after cured process.

Figure 12. Cotton Pattern Top. Author's own copyright.

Experiment 2
Material:
Cotton thread and acrylic plastic scaf-folding

In this example the nails are substituted for a laser cut acrylic plastic structure as it allowed for a smaller distances between each gap in each grid. The two pattern show two different approaches to creating a surface with the strings. First pattern is more evenly distributing the strings whilst the upper pattern concentrates a focal middle point with all strings combined.

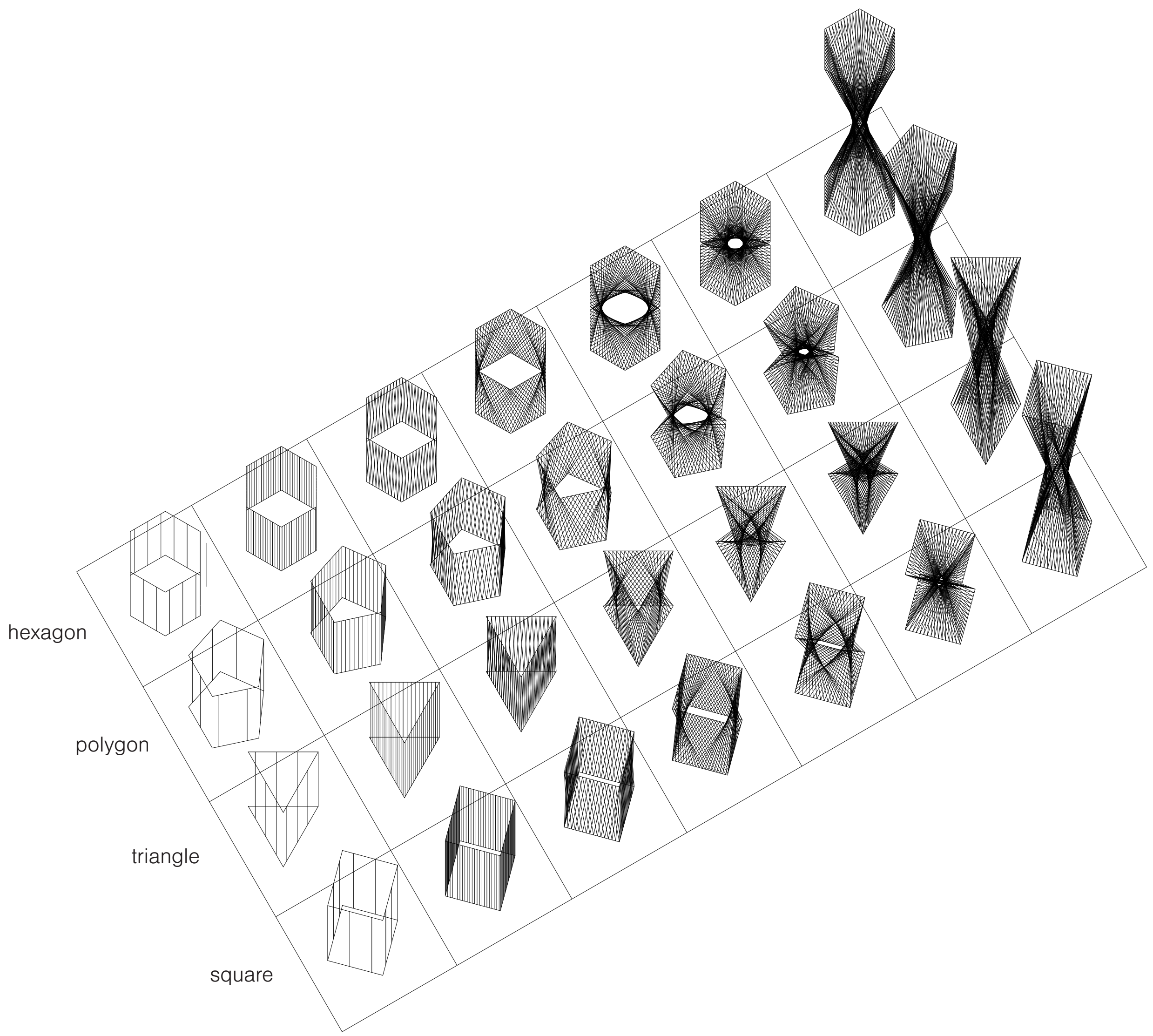


Figure 13. Rhino Grasshopper simulation Axonometric. Author's own copyright.

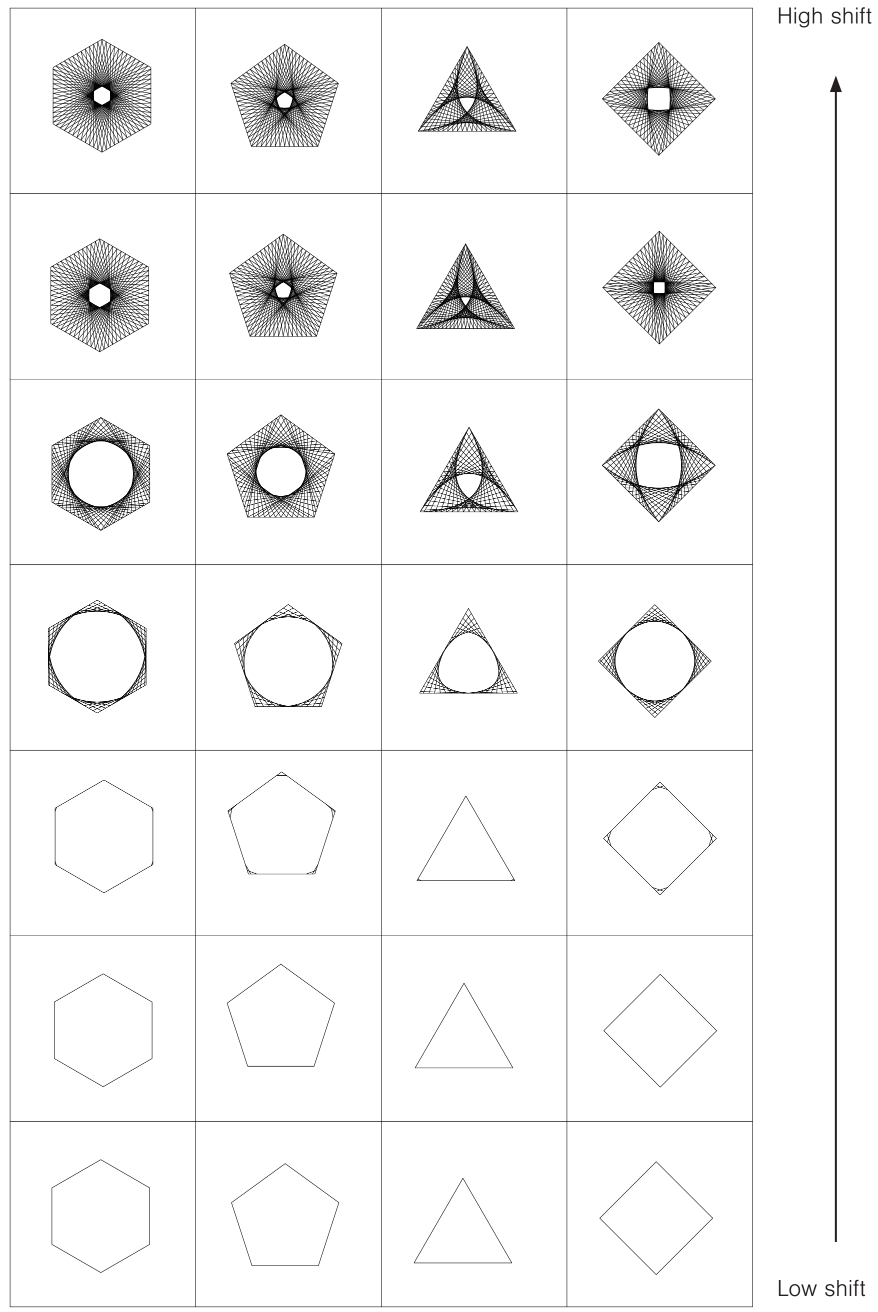


Figure 14. Rhino Grasshopper simulation Top. Author's own copyright.

Experiment 3
Rhino and grass-hopper simulation

Next step was to experiment in a digital environment where the aim was to try weaving patterns applied between two opposing geometric form an thus defining the shape in-between. Each pattern varies in string density from open to closed, and also in shifting which points are connected. By shifting more the shape turns and gets the pronounced slimmer midsection. The last iteration add height.

The shifting of connecting dots is visible from top view as the midsection slims down. The parameter goes from low to higher amount in shifting dots, resulting in sharper angle of diagonal lines and slimmer profile.

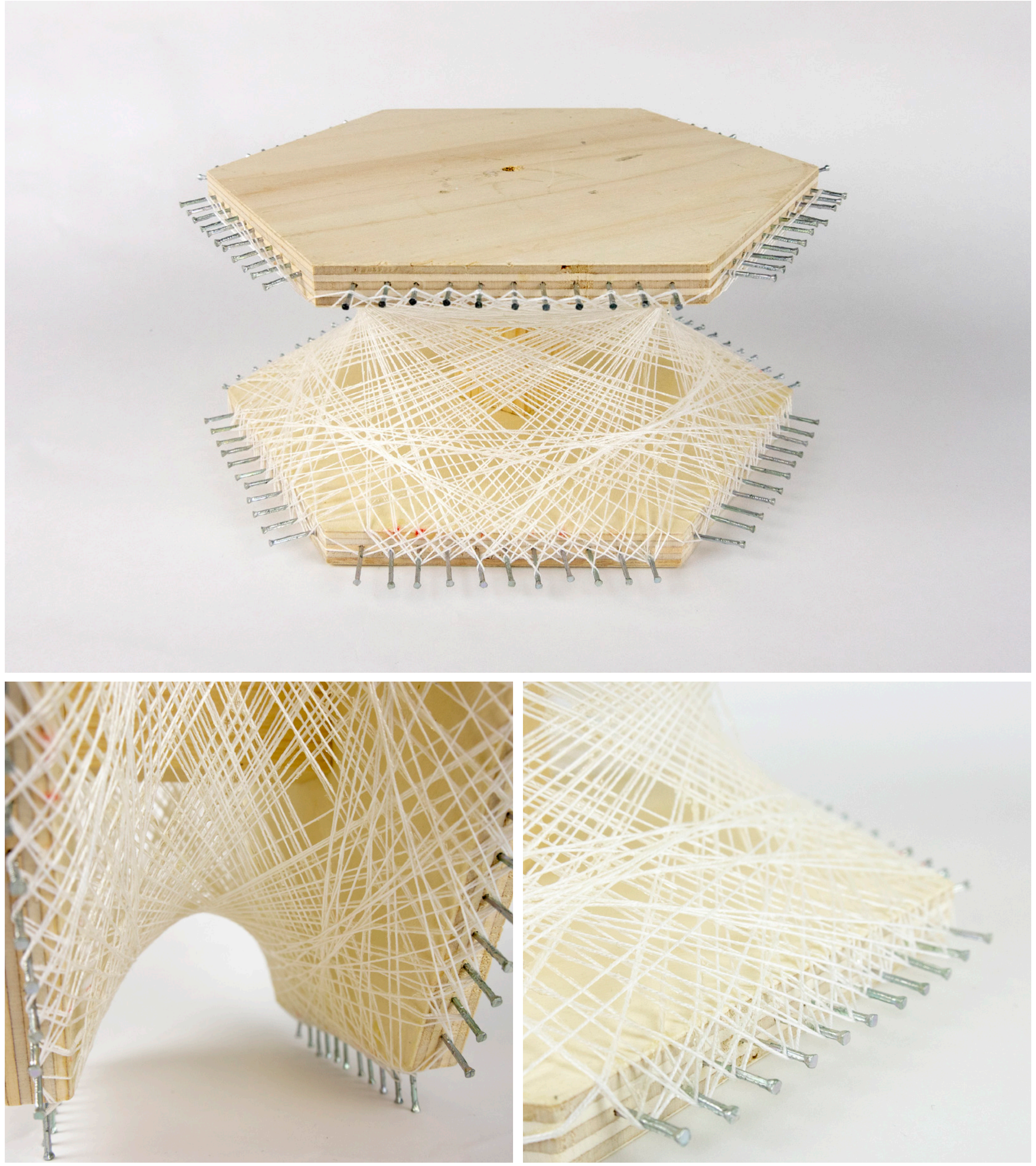


Figure 15. Cotton thread hyperbolic cylinder, 3 angles. Author's own copyright.

Experiment 3
Material: wool yarn, varnish glue, nails and wooden structure.

This is the physical variation of the grasshopper simulation. In this medium the midsection becomes even more pronounced and clear. This model is also referencing ICD/ITKE Stuttgart form that they made. Although they made in a more in quantity and more flexible opposing geometric forms according to their agenda, this model still holds the similar intention.

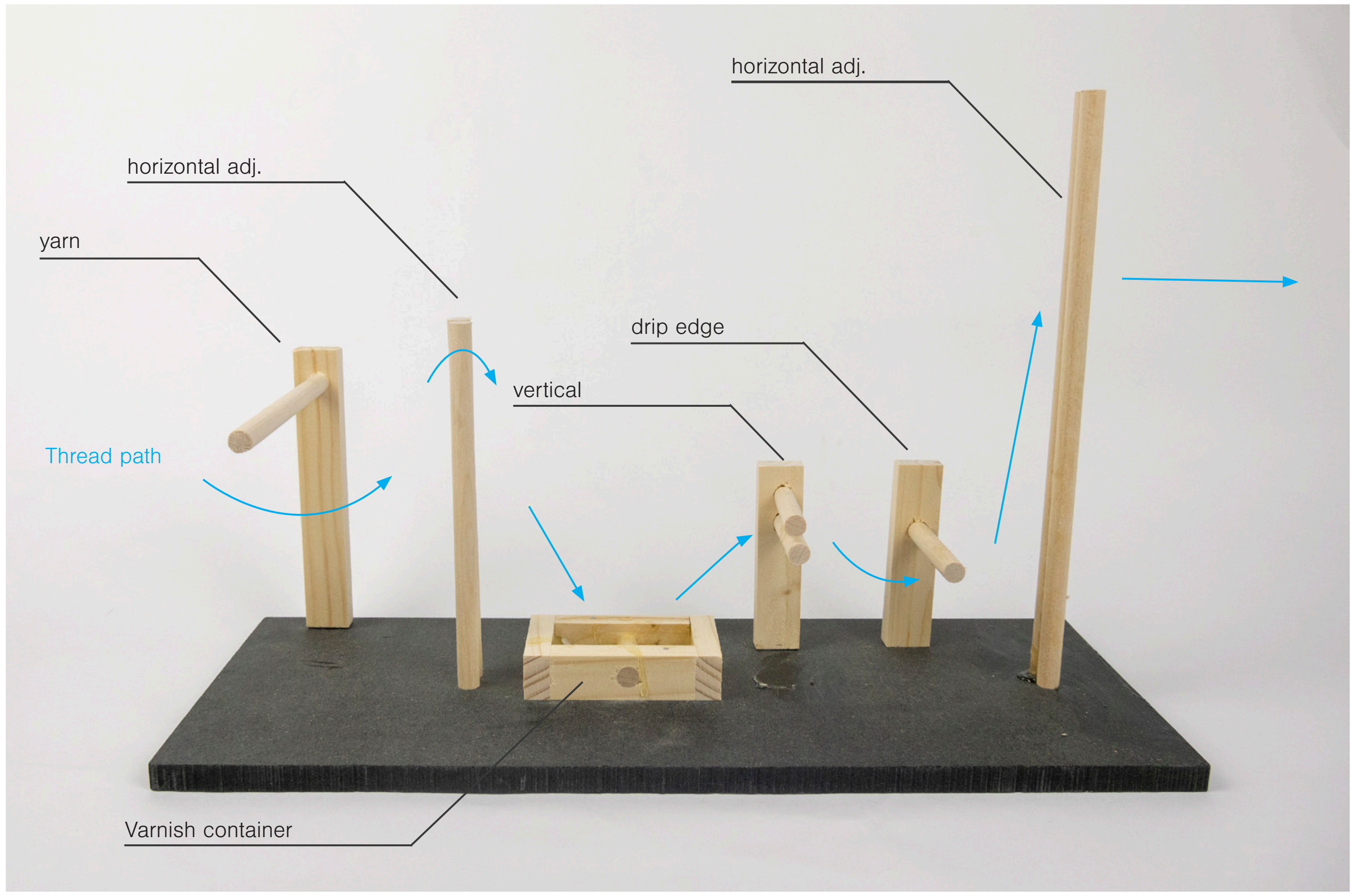


Figure 16. Jig, varnish coater. Author's own copyright.

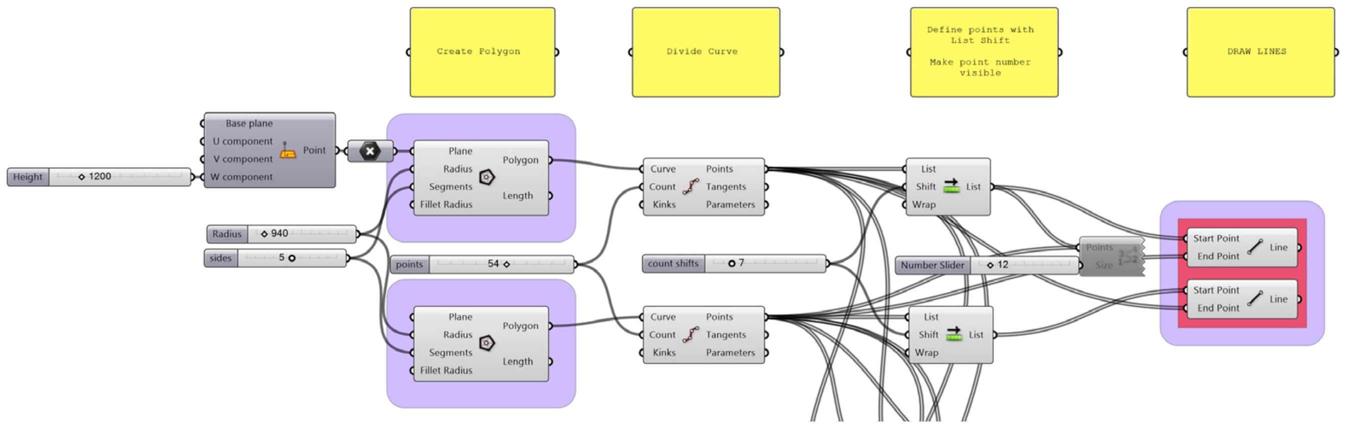


Figure 17. Rhino Grasshopper simulation code, Experiment 3 . Author's own copyright.

The upper image shows the jig that was used to hold the wool yarn and coat it in varnish as it passed through a container in the middle while it was aligned in to right angle and position with the help of the wooden sticks.

The grasshopper script is what generated the models. Starting with deciding number of sides in the polygon forms and its size, density of strings and the connecting dots. The lines are then drawn in both direction to create a closed curve.

Experiment 4
Material: Carbon fiber, epoxy glue acrylic scaffolding

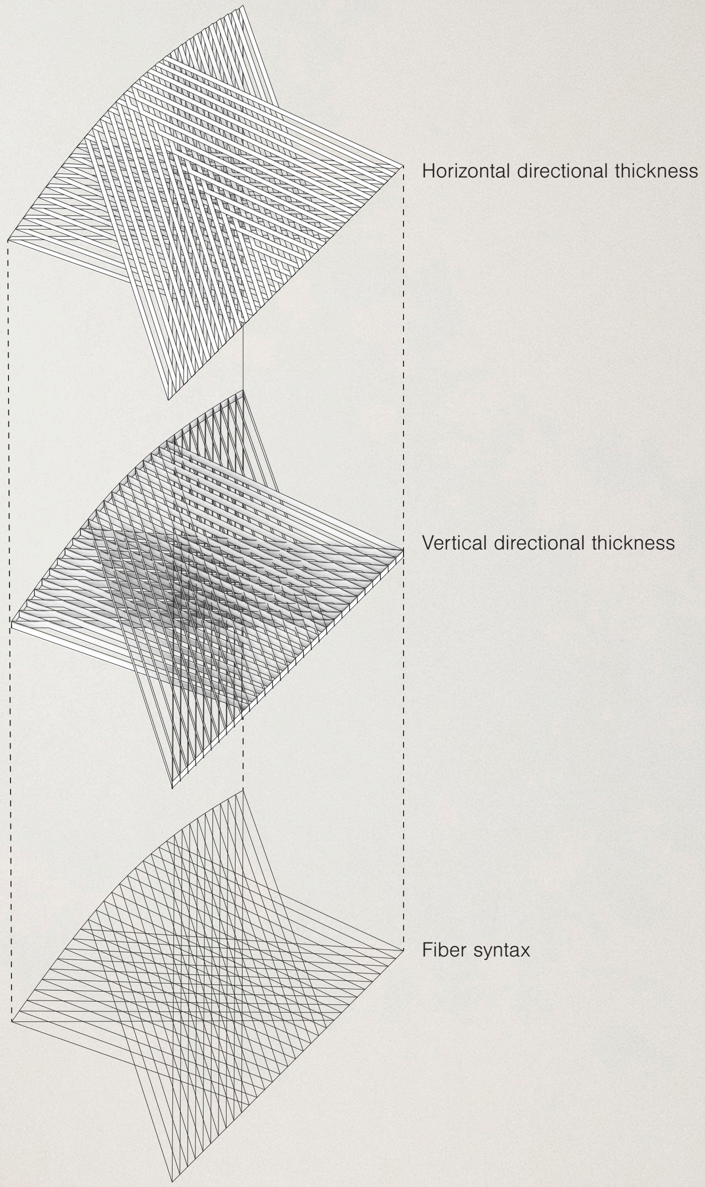
Switching to Carbon Fiber

This experiment analysed the properties of carbon fiber with similar method used in experiment 2. The carbon fiber was dry woven on an acrylic scaffolding without release agent. The aim was to get a understanding of working with carbon fiber for the first time. To see how it would react to the working method. Carbon fiber roving consists of 50 000 strings of filament with the thickness of 7 µm (0.007 millimetres). This makes it ~10 times thinner than human hair which ranges from 60-90 µm.

The safety aspect is very important while working with carbon fiber. The tiny filaments can break and cause skin damage if protective nitrile gloves are not worn. The epoxy releases toxic fumes during the curing process and thus wearing a gas mask is a must. The epoxy can also damage skin so use chemical resistant overalls and eye protection.

Technical data:
Density: 1.8 g/cm³
Tensile strength: 4000 MPa
Tensile modulus: 240 GPa
Elongation at break: 1.7 %
Number of filaments: 50000 = 50k
Filament diameter: 7 µm
Sizing level: 1%
Cross section of single roving: 1.778 mm²

Grasshopper simulated the pattern in advance to control the overlapping layers of fibers. In this pattern there would be 4 areas with 1,2,3 or 4 overlapping layers of fibers. The aim was to find how many layers of fibers creates a desirable strength. This would later serve as a reference point going into further experiments.



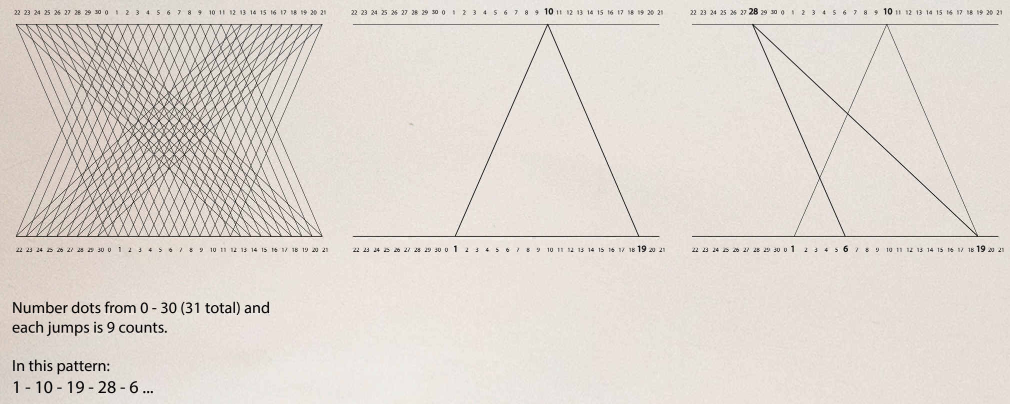


Figure 19. Experiment 4, Weaving Diagram axo. Author's own copyright.

 Figure 18. Roll of Carbon Fiber. Author's own copyright.

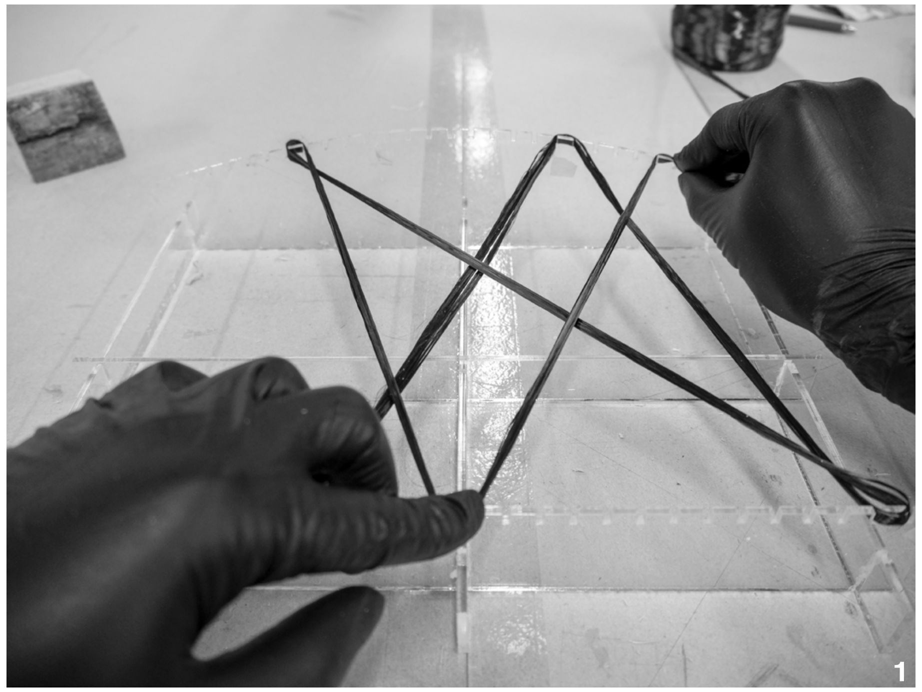


Figure 20. Carbon fiber weaving, Stop Motion Photo 1. Author's own copyright.

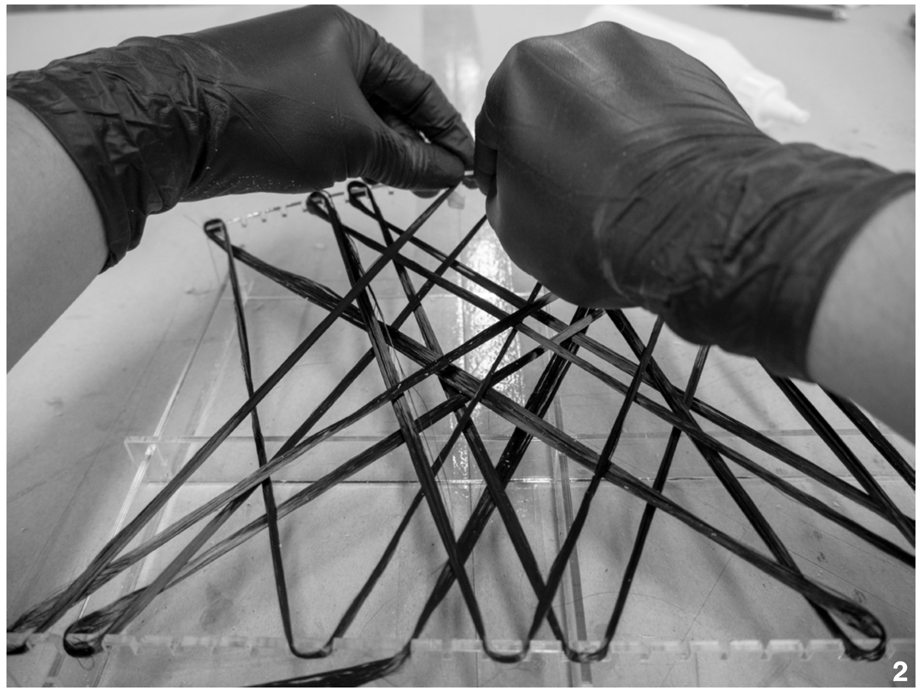


Figure 21. Carbon fiber weaving, Stop Motion Photo 2. Author's own copyright.

Dry weaving process:
The carbon fiber wrapped dry with no epoxy resin applied in this stage. The dry results created a very slick surface with good amount of shine. The 4 different areas are clear and visible. The gaps within the area with 4 overlapping layers were almost completely covered up. 3 and more layers of fiber congested the scaffolding teeth and made it difficult to weave. This caused some fibers on top layer to come off and loosen then initial tension.

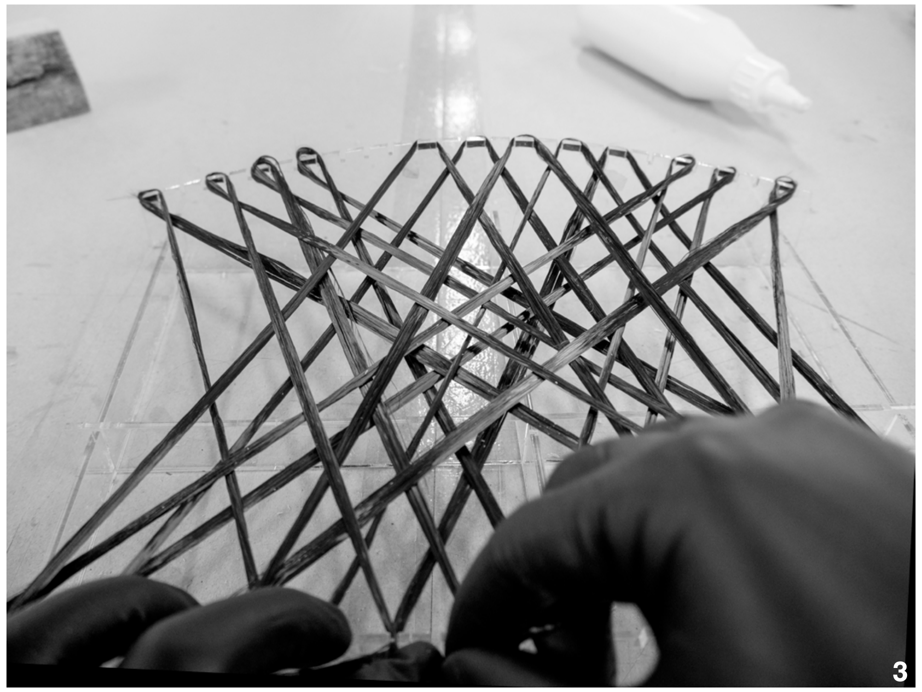


Figure 22. Carbon fiber weaving, Stop Motion Photo 3. Author's own copyright.

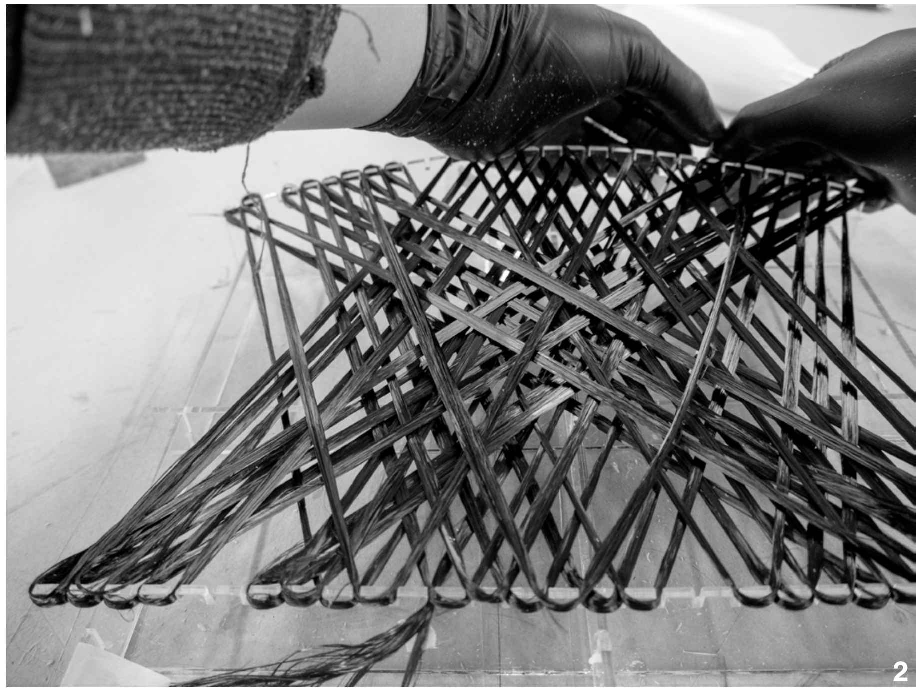


Figure 23. Carbon fiber weaving, Stop Motion Photo 4. Author's own copyright.

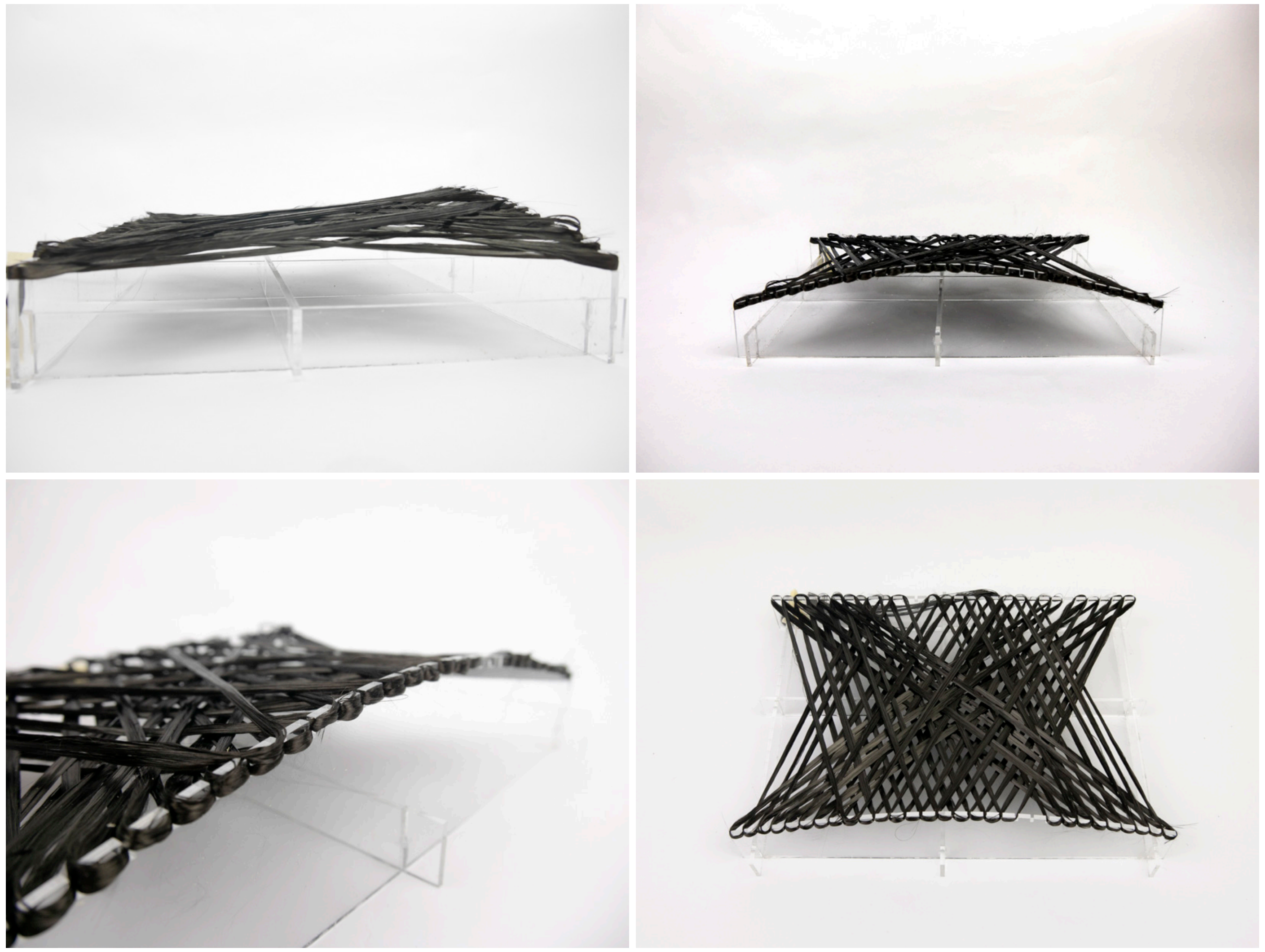


Figure 24. Experiment 4, Pre-epoxy application, 4 Angles. Author's own copyright.

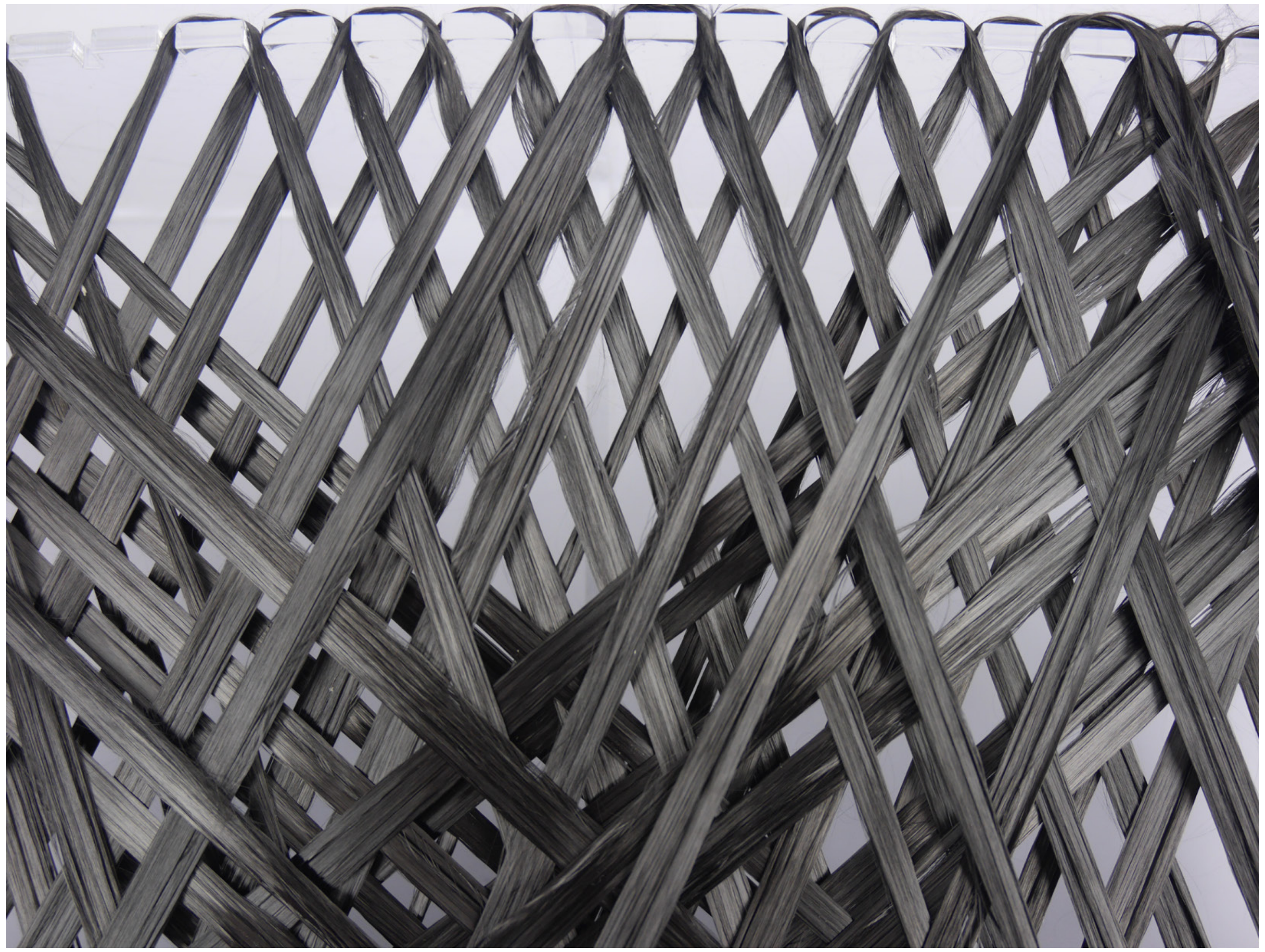


Figure 25. Experiment 4, Pre-epoxy application, Texture. Author's own copyright.

Figure 26. Epoxy application with brush. Author's own copyright.

Figure 27. Mixing Epoxy. Author's own copyright.

Figure 28. Epoxy product. Author's own copyright.

The process to apply epoxy carried out in the following order:
2 part base liquid mixed with 1 part hardener based on weight. 50g base + 25g hardener. The brush applied the epoxy by dripping and stroking it in the fiber direction. If done wrong, the brush could cause damage to the fibers by pulling fibers off from their intended position.

Figure 29. Leftover epoxy resin in paper cup. Author's own copyright.

The remaining epoxy formed a round shape in the bottom of the paper cup after the curing process of 24 hour. The hardened epoxy was yellowish with quite a few small bubble in it.

The curing process generates heat and forms small bubbles.
The bubbles will evaporate itself but if the layered epoxy is too thick it might trap the bubbles. The image above shows this.

If this manifests as a problem, there are few alternatives to solve this. Adding heat with a heat gun or hair dryer during the curing process helps the bubbles to reach the surface and evaporate. Another method is to only use thin layers of epoxy and apply few times.

The actual experiments never used particularly much epoxy and didn't have this problem.

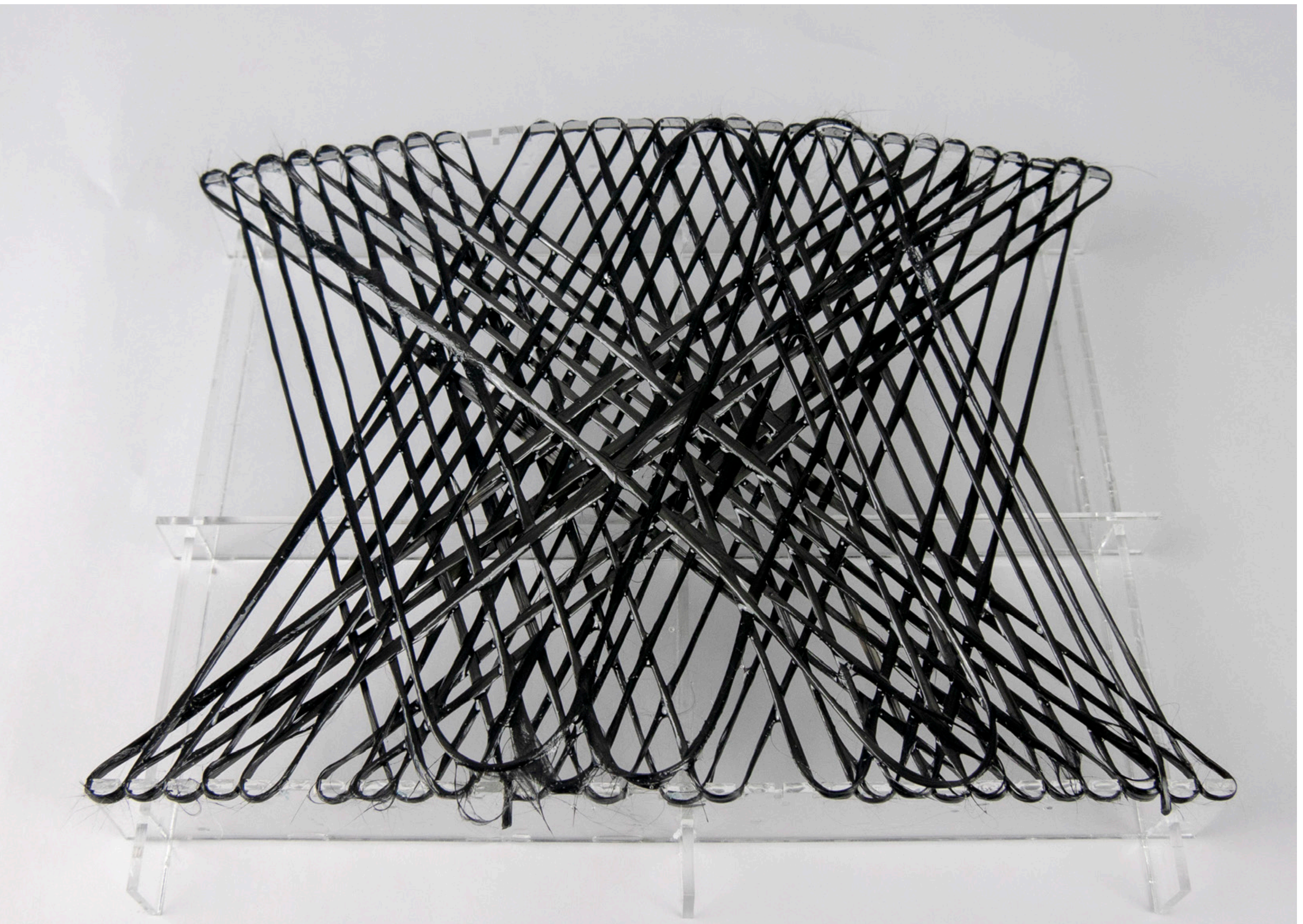


Figure 30. Experiment 4, top. Author's own copyright.

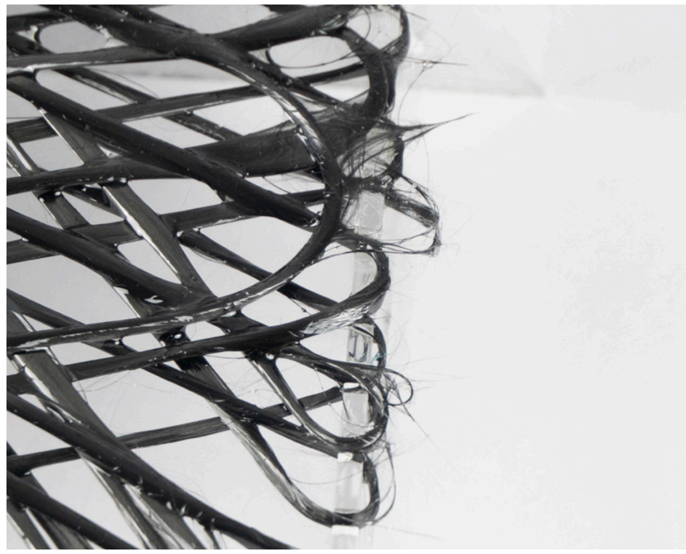


Figure 31. Experiment 4, close up 1. Author's own copyright.

Figure 32. Experiment 4, close up 2. Author's own copyright.

The brush application method showed several weaknesses. Several broken strings of filament gave it a messier appearance and pre-application. The broken filament also dried and became pointy to the point it could cause splinters.

There were areas with too thick layer of epoxy causing the fiber to lose its thin and sleek expression. It now looked more like a singular thick thread. The epoxy caused the fibers to shrink from 10 mm to around 4 mm. There were drips of excessive epoxy running along the scaffolding. The brush also caused more fibers to come off the scaffolding and dried off position.

The epoxy gave the fibers an even shinier "wet-look" after it cured. It gave off the impression of the reflective characteristics of car paint in the automotive industry.

Figure 33. Experiment 4, close up 3. Author's own copyright.

Experiment 5
Material: Carbon fiber, epoxy glue acrylic scaffolding

Experiment 5 focused on overcoming the weaknesses found in the previous experiment.
The brush method didn't work at all and was then changed to using hand and fingers as application tools. Two fingers, coated with epoxy, pinched and dragged along the fiber direction. This made it easier to control the amount of epoxy and kept the thickness very thin. This shortened the working time by combining both the weaving and coating process to a single process.

The plastic scaffolding was also changed from 2 grids to 3 grids with the one in middle adding height. It gave the form a more expressive complexity than before. The shape now resembles a tent with an entrance and a clear difference between the bottom and top, front and back.

The scaffolding unfortunately broke down mid-process when weaving. The added tension from the fibers stressed the middle grid and cause it to sag. The fibers became loose and the top edges became rounder in the final cured form.

The changed pattern allowed more fiber-to-fiber contact by moving the scaffolding teeth tighter. The layers packed denser with two layers of fibers overlapping. Each pass crossed over multiple layers, binding them all together.

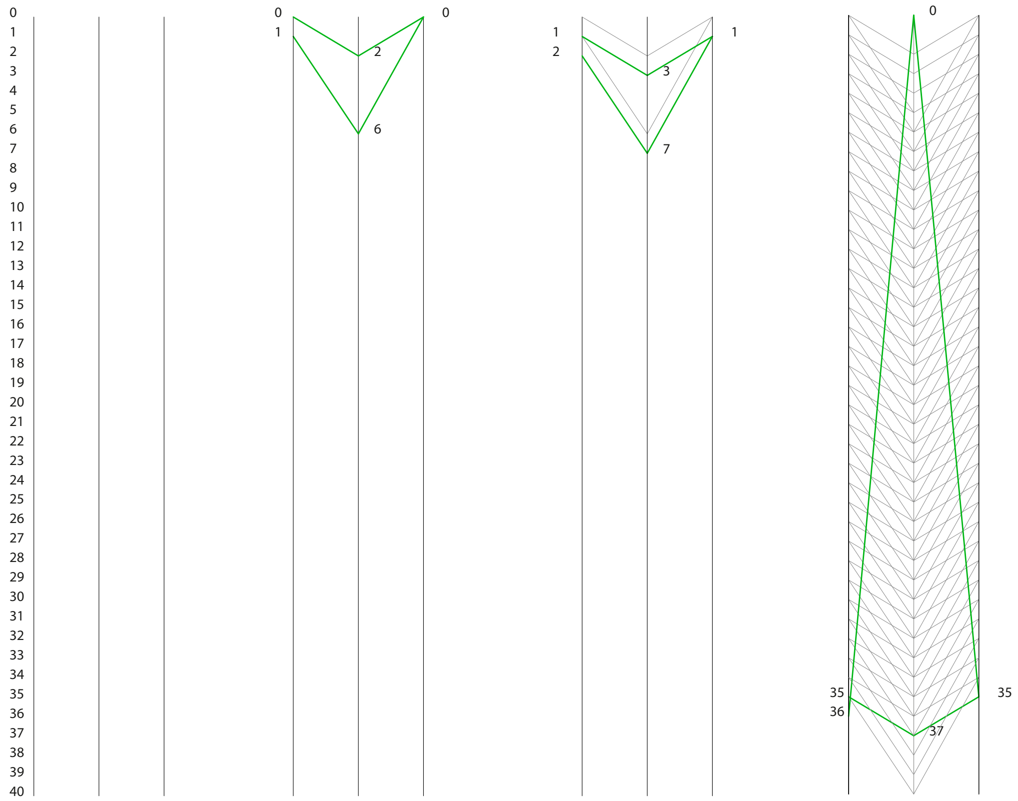


Figure 34. Experiment 5, Weaving pattern diagram. Author's own copyright.

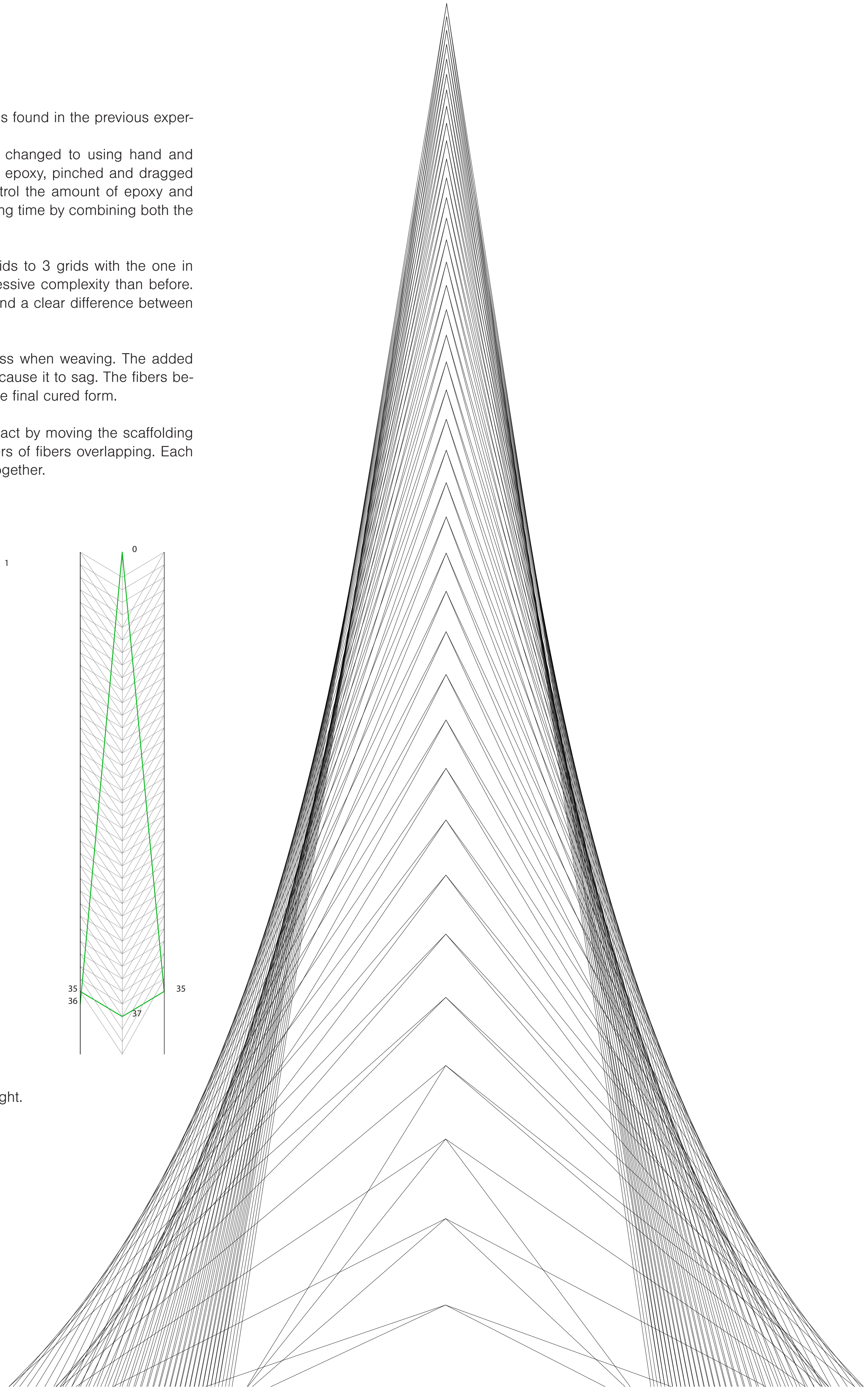


Figure 35. Experiment 5, Weaving syntax front. Author's own copyright.

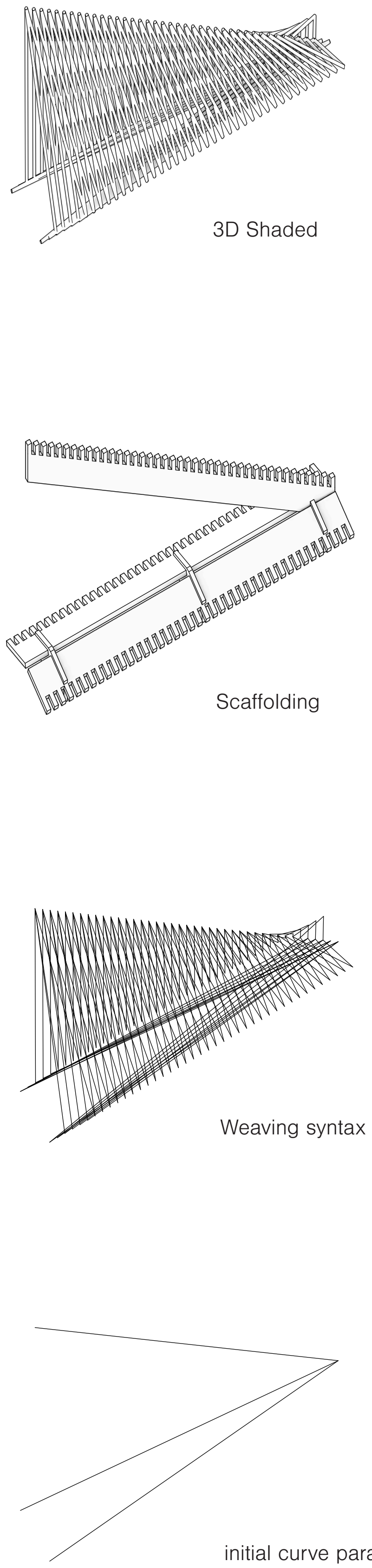


Figure 36. Experiment 5, Weaving Diagrams axo. Author's own copyright.

Figure 37. Experiment 5, applying release agent. Author's own copyright.

The acrylic scaffolding were first coated with a release agent to later help the removal process once the epoxy had cured. The spray created a thin film on the acrylic surface which resembled like "frosted glass". The release agent is a solvent base, silicone-free liquid suited for working with epoxy resin in both hot and cold environment . Multiple passes insured proper coverage and for best effect.

Another common technique is polishing and waxing the mould beforehand. This 2-step process generally gives a higher quality surface finish on contact areas between mould and cast object. The spray was preferable as it is easier to cover crucial and small areas like between the teeth. It is a faster application time and the contact areas weren't visible anyway.

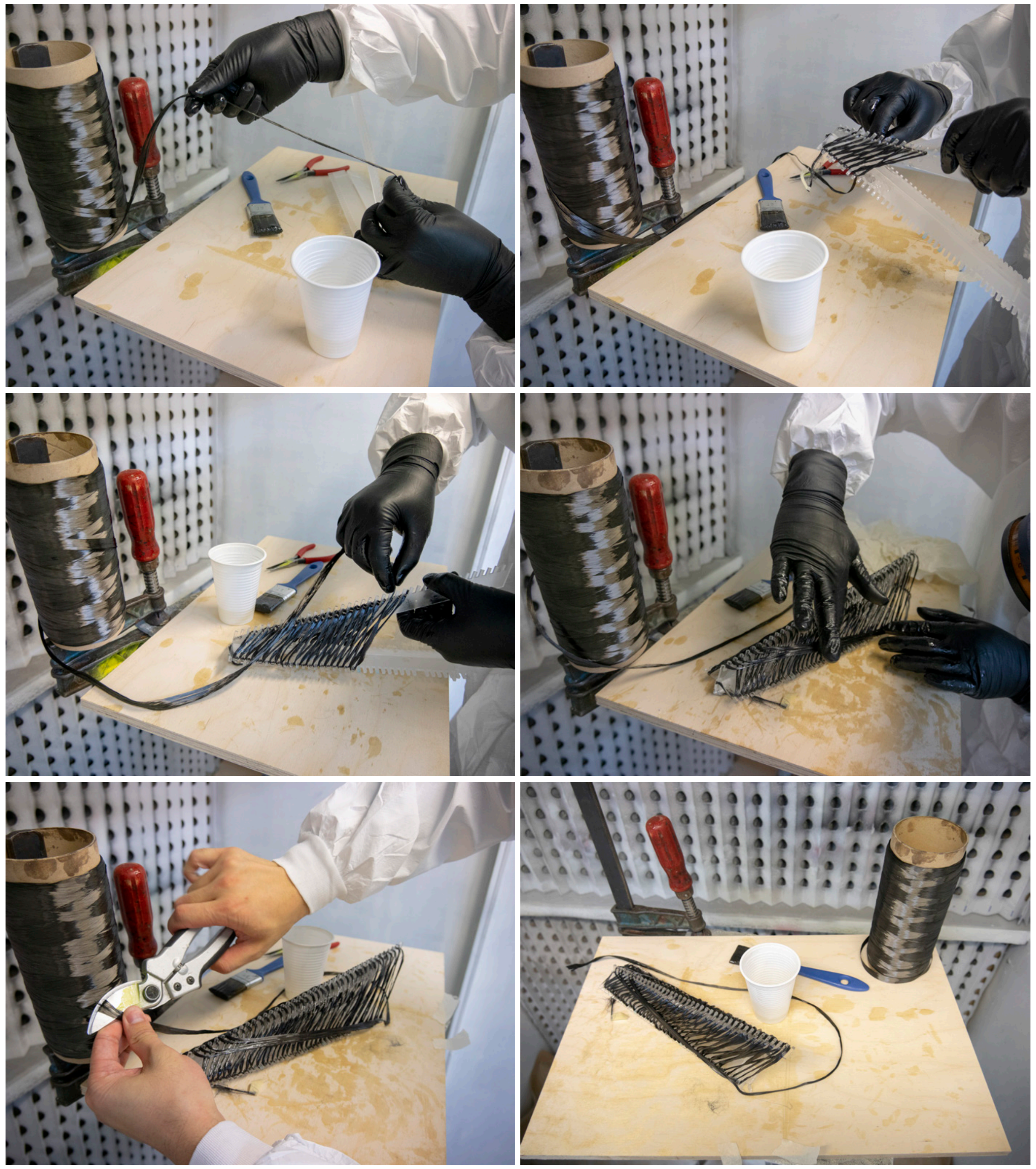


Figure 38. Experiment 5, Weaving process1-6. Author's own copyright.

The fingers impregnated the fibers by pinching and dragging along the fiber direction. The finger dexterity in the pinching motion gave a finer control of the amount of applied epoxy.

The method created a bigger mess with excessive epoxy dripping from the hand compared to using the brush. However, the impregnated fibers were little heavier and easier to weave with compared to them dry.
The added tension from the fibers broke the scaffolding mid-process and the form started to sag. The sagging happened between the 3rd and 4th picture in *figure 28*.

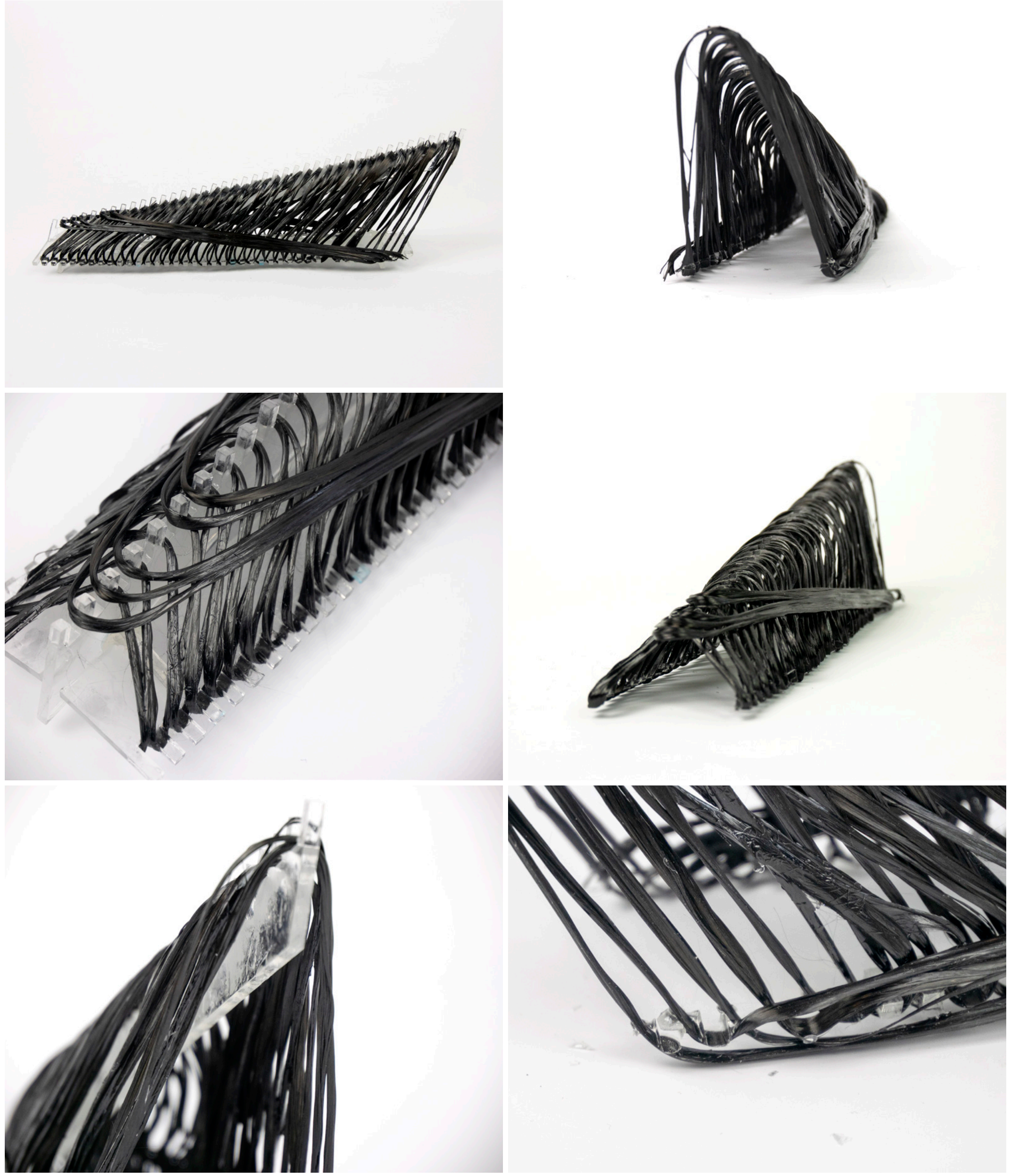


Figure 39. Experiment 5, cured 6 angles. Author's own copyright.

With scaffolding:
Before the separation of the scaffolding and the cured form.

Without scaffolding:
The cured epoxy formed square hollow shells after acrylic scaffolding. Some of it stayed after removing the scaffolding.
The scaffolding broke and discarded after separation.

Up-close photo. The sagging and bending fibers caused by the broken scaffolding is clearly visible. The hand application of epoxy resin gave the fibers a more dry and less saturated look with the filaments more pronounced.

Figure 40. Experiment 5, Close up 1. Author's own copyright.

Up-close photo. Despite the sagging, the last few fibers that came on top of the other ones kept it's sharper angle. This was quite interesting and it gave it a very angular and particular expression. This became the corner stone for next experiment to try out.

Figure 41. Experiment 5, Close up 2. Author's own copyright.

Experiment 6
Material: Carbon fiber, epoxy glue acrylic scaffolding

Experiment 6 followed up from the previous experiment.
The strengthened the scaffolding prevented the weaving from breaking it. The stronger and more rigid scaffolding gave it stability to withstand the accumulated tension from the fibers.

The weaving pattern is the same as in experiment 5 but the middle grid is re-positioned. The middle grid shifted from being parallel to the outer grids to more forefront. This created a sharper angle of the woven fibers, going from 8°s to 60°. The sharper angle packed the fiber denser into a thick and even surface. The there were no space for gaps between the fibers anymore.

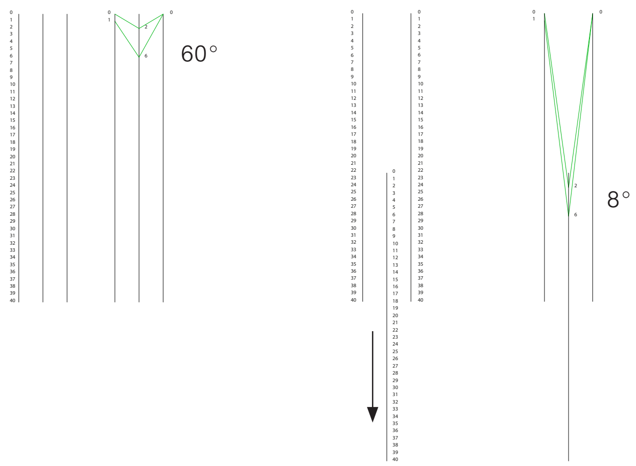


Figure 43. Comparing pattern 5 & 6. Author's own copyright.

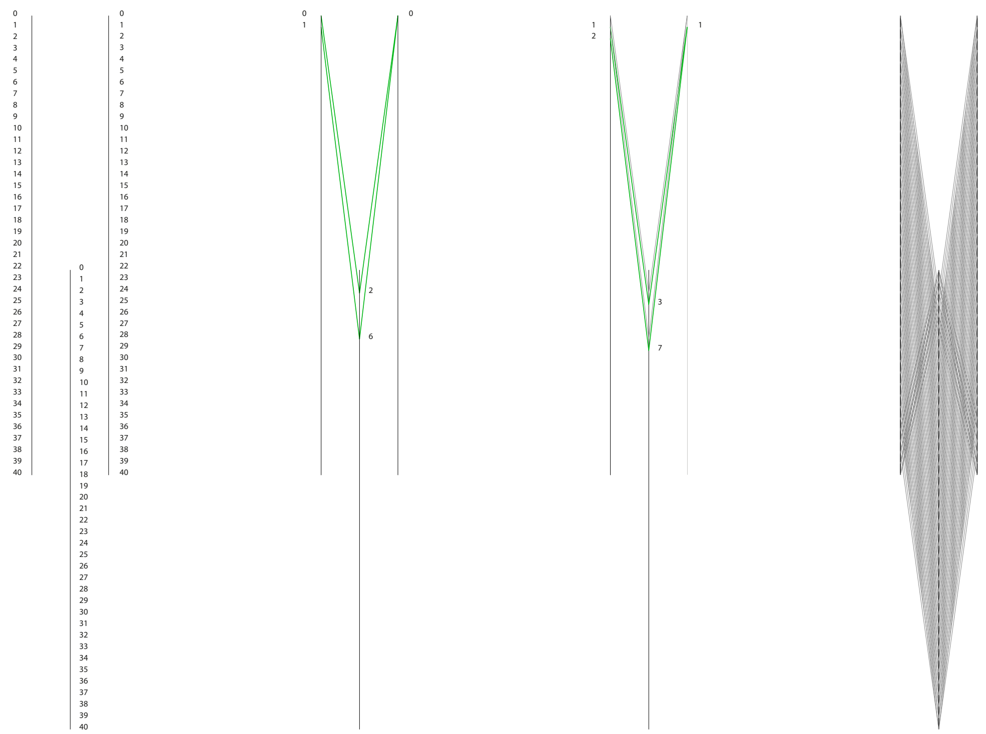


Figure 42. Experiment 6, Weaving pattern. Author's own copyright.

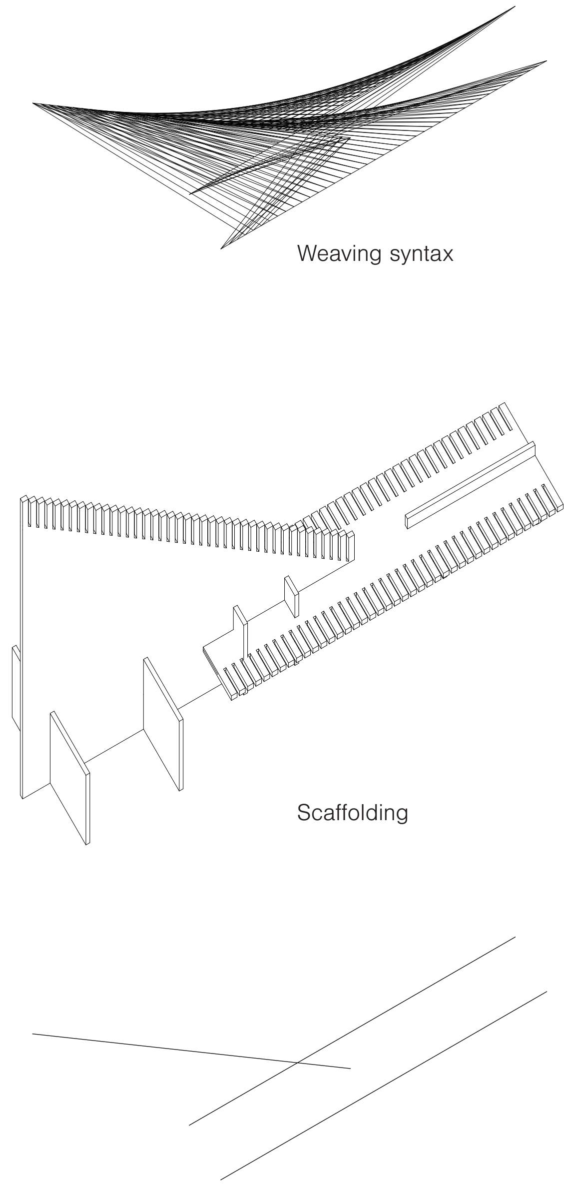
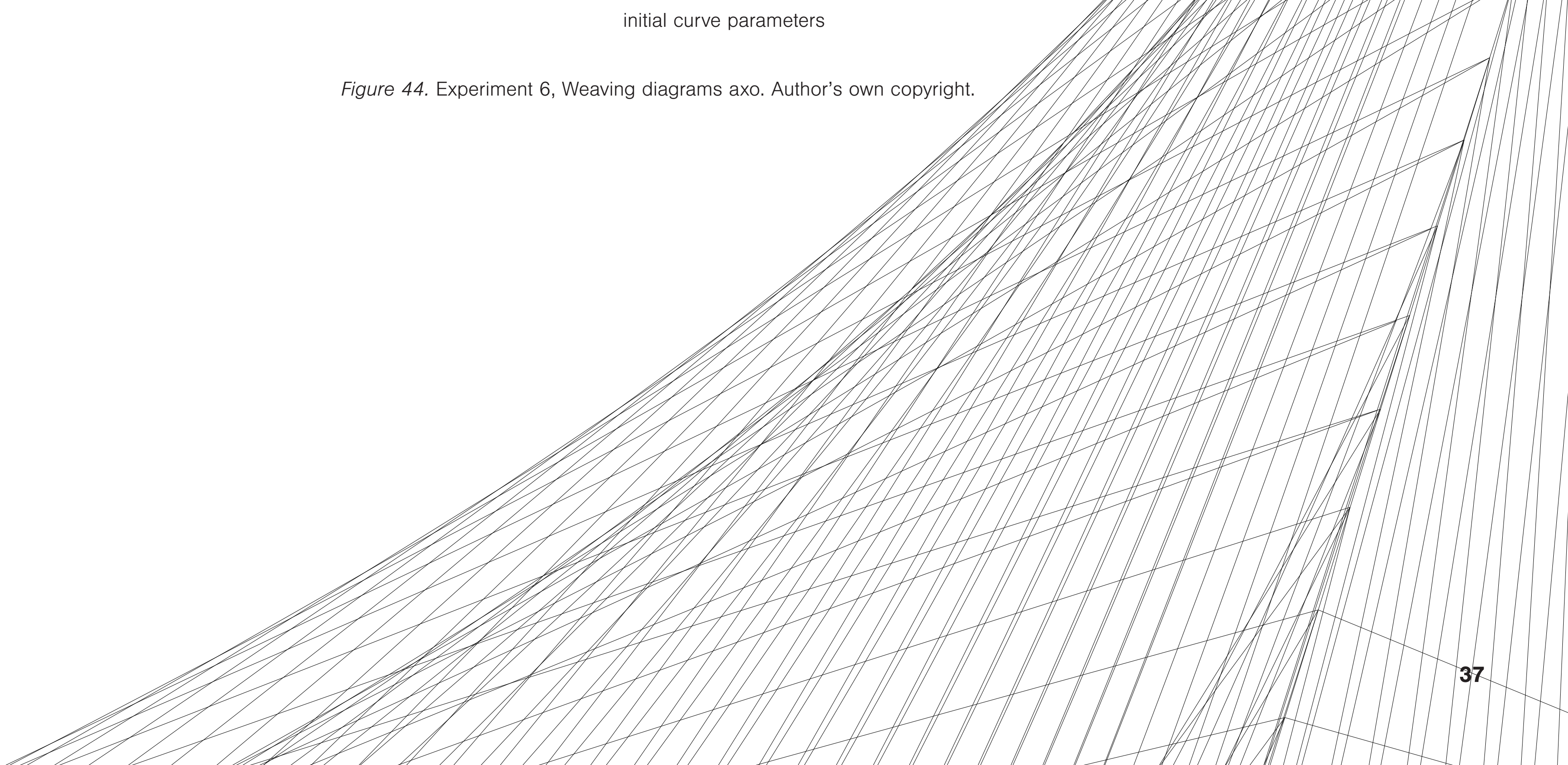


Figure 44. Experiment 6, Weaving diagrams axo. Author's own copyright.



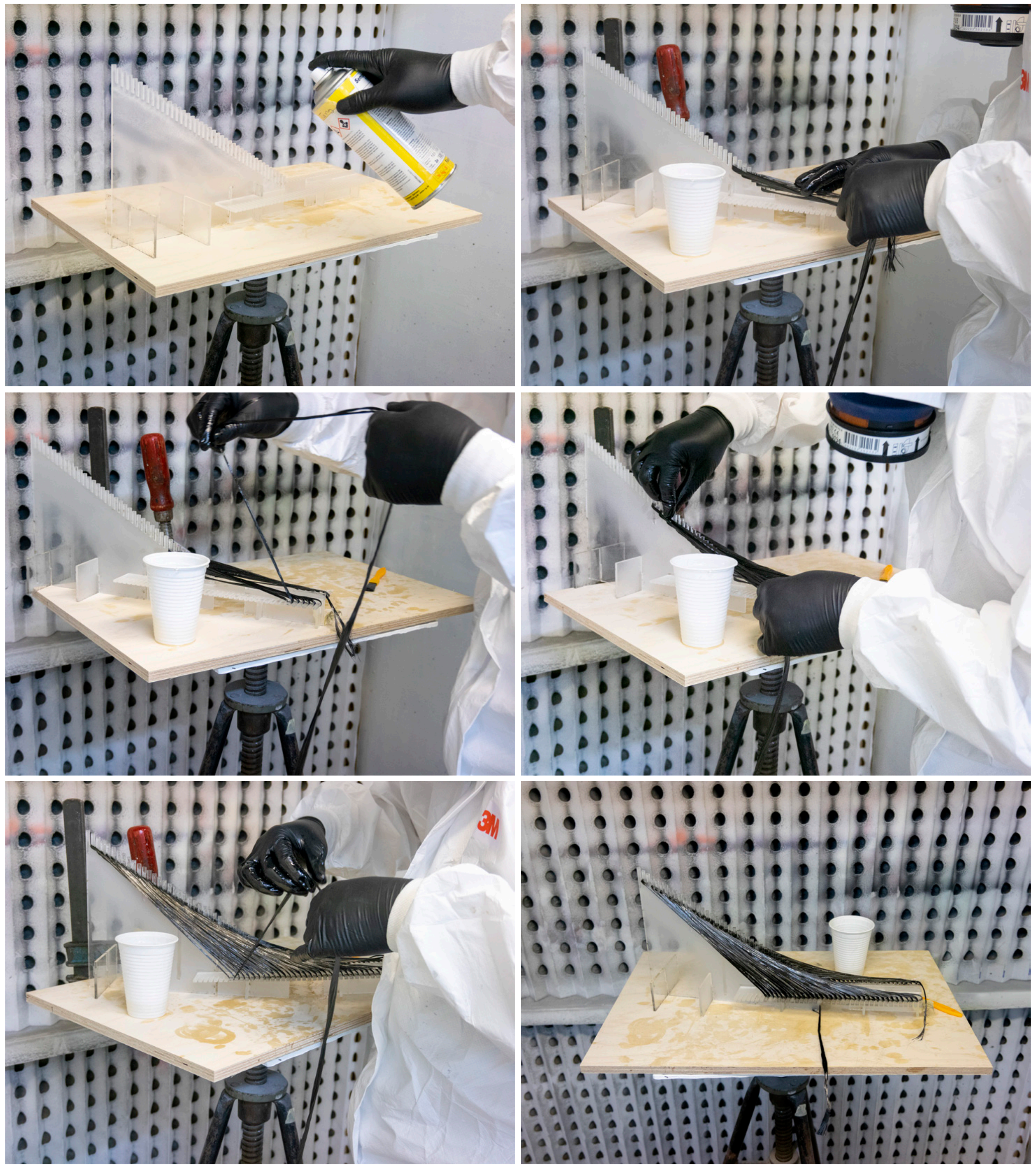


Figure 45. Experiment 6, Weaving process 1-6. Author's own copyright.

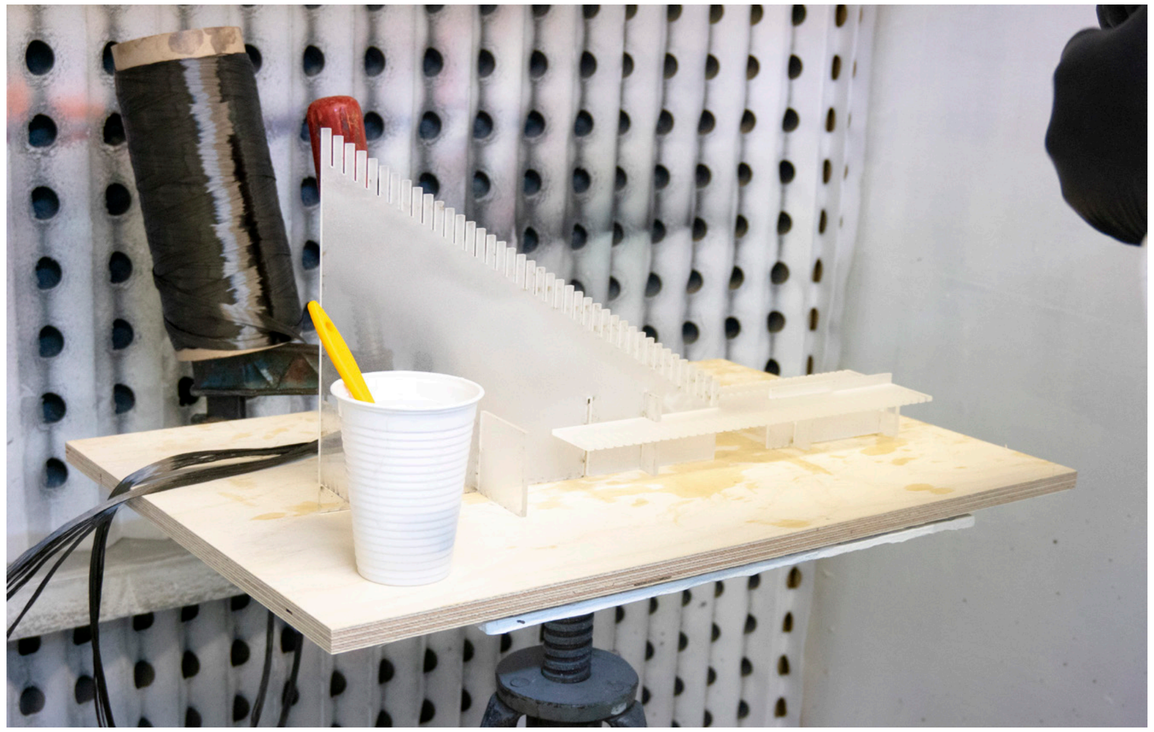


Figure 46. Experiment 6, Prepped Scaffolding. Author's own copyright.

Figure 47. Experiment 6, Weaving process curing. Author's own copyright.

Figure 48. Exp. 6. with scaffolding 1. Author's own copyright.

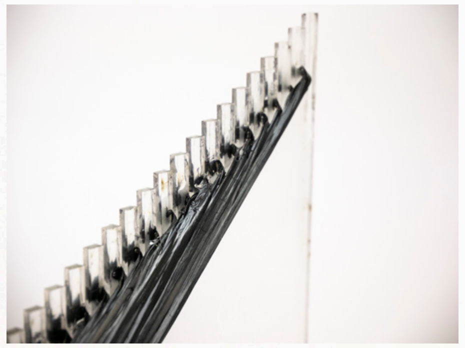


Figure 49. Exp. 6. with scaffolding 2. Author's own copyright.

Figure 50. Exp. 6. with scaffolding 3. Author's own copyright.

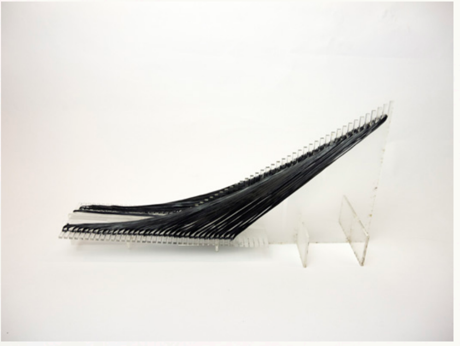


Figure 51. Exp. 6. with scaffolding 4. Author's own copyright.

Figure 52. Exp. 6. with scaffolding 5. Author's own copyright.

With scaffolding:
Figure 50. The scaffolding held up very good with a few exception of a slight vertical bending in the mid section with highest tension. No twisting or horizontal bending found. Strengthening of scaffolding proved effective.

Figure 53. Exp. 6. breaking scaffolding. Author's own copyright.

Breaking the scaffolding:
Figure 52. Breaking off the acrylic teeth were the easiest and fastest way to remove the scaffolding. The teeth broke off when pressed down onto the table. The release agent made the separation easy by preventing the epoxy to adhere to the acrylic.

Figure 54. Exp. 6. Results 1. Author's own copyright.

Without scaffolding:
Removing the scaffolding left several circular holes on lower part. These unavoidable holes could be used for future application. Joining similar pieces together could work.

Figure 55. Exp. 6. Results 2. Author's own copyright.

Without scaffolding:
The fiber maintained a stretched and organised shape during throughout curing time. The results are striking.

Figure 56. Experiment 6 Results 3. Author's own copyright.

Digital Exploration
Large Scale Parametric Concepting

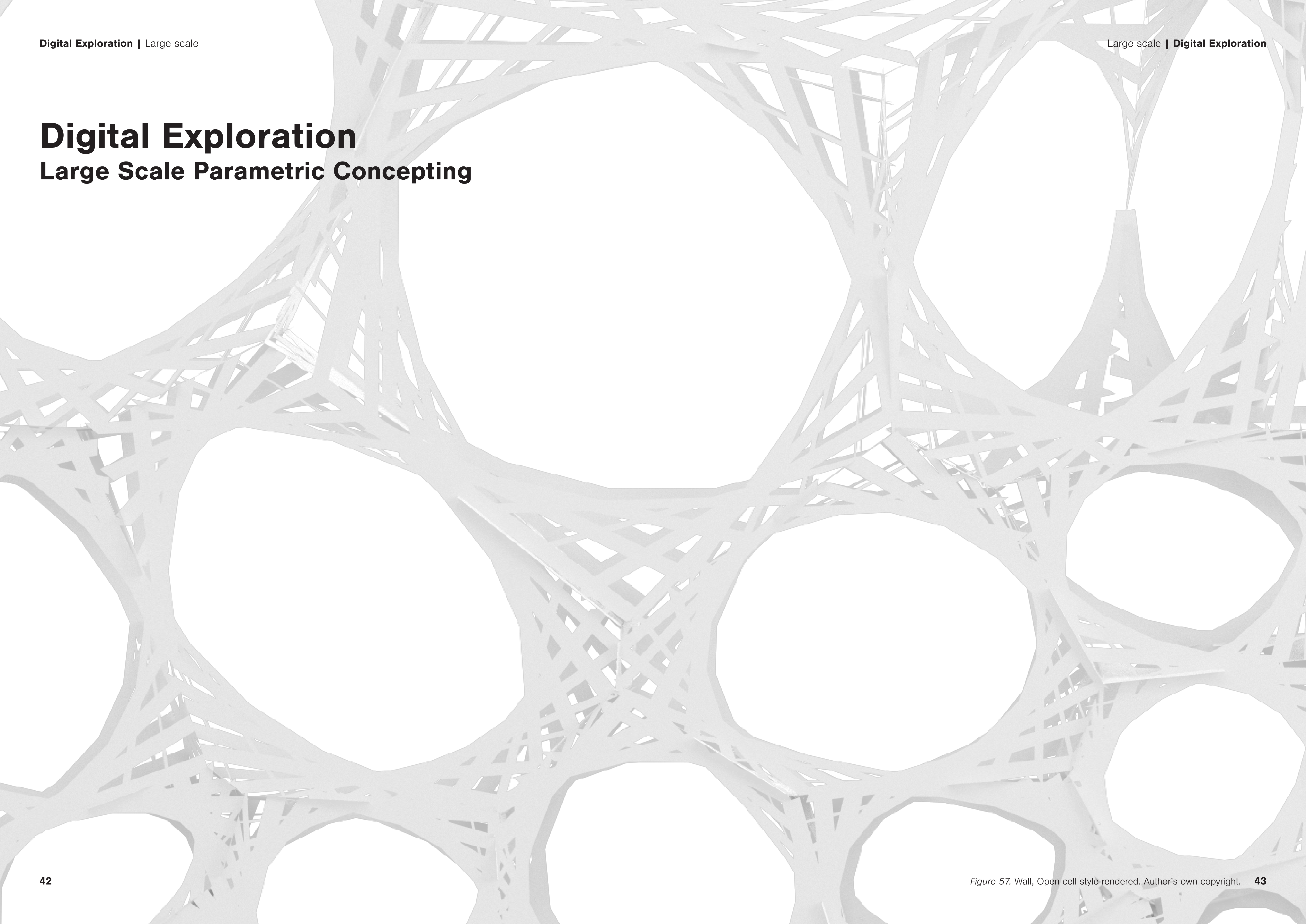


Figure 57. Wall, Open cell style rendered. Author's own copyright.

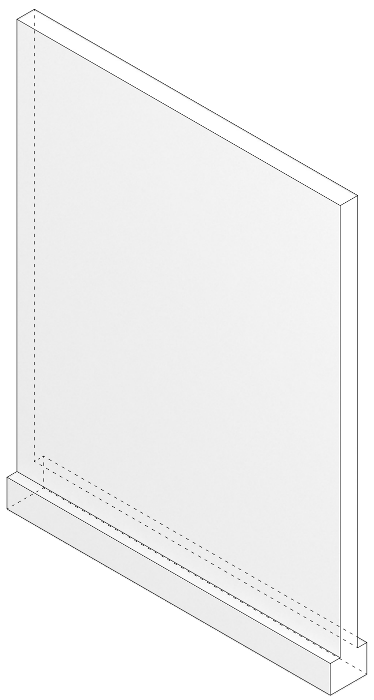


Figure 58. Digital process 1. Original wall Author's own copyright.

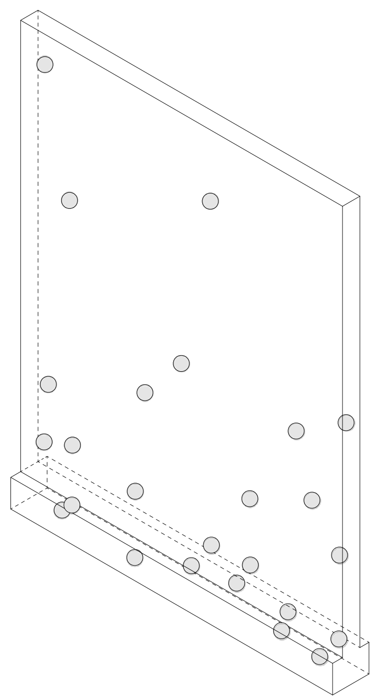


Figure 59. Digital process 2. Point cloud as center of cells. Author's own copyright.

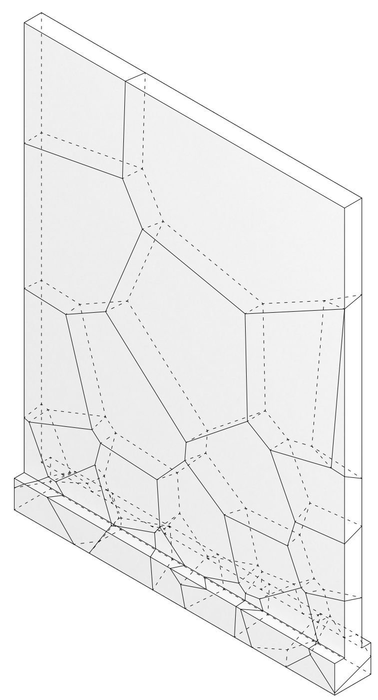


Figure 60. Digital process 3. De-constructed wall into cells. Author's own copyright.

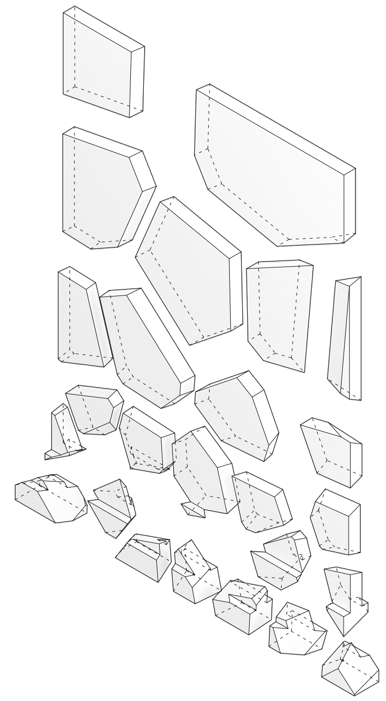


Figure 61. Digital process 4. Exploded wall. Author's own copyright.

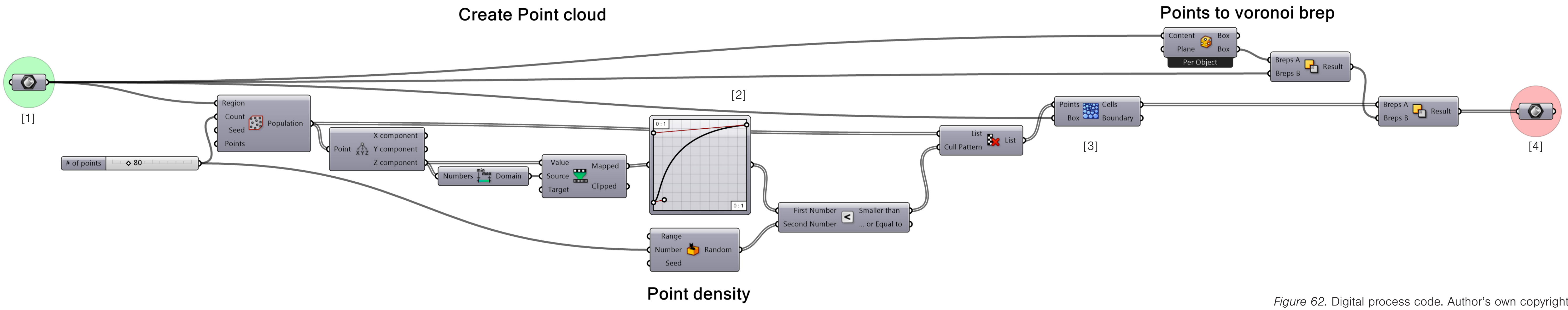


Figure 62. Digital process code. Author's own copyright.

Digital process and code explanation

Figure 62. This code from grasshopper shows the work-flow of de-constructing objects into smaller components.

[1]. The process begins from a simple solid brep representing any building elements, in this case a wall.
[2]. The wall is first populated with points. The curve graph controls the density, number and distribution of the points.
The curve in the example allocated more points in the lower parts of the wall than the in the top.

[3]. Each point represents the way the wall will de-construct into cells. Each point is the center of a cell and the distance between points defines the size of the cells. Smaller cells in a denser distribution means more material. More material results in higher load capacity. Placing smaller cells in anticipated load-distribution areas can lead to better use of material.

[4].The code gathers and individualises every generated cell.

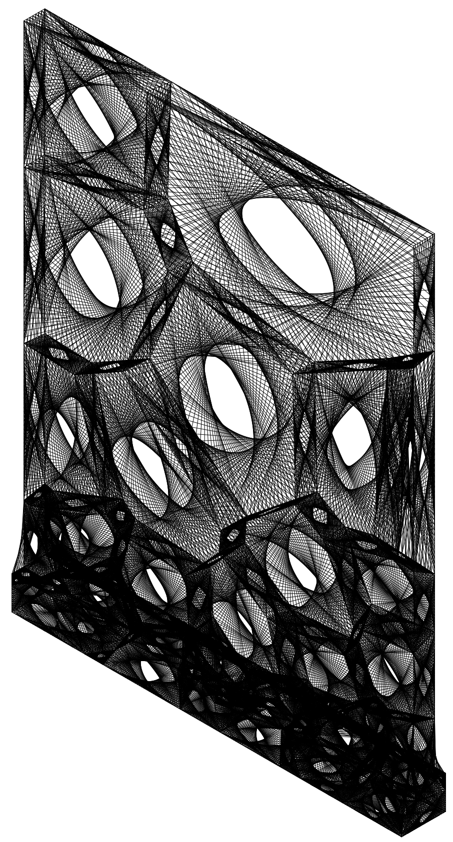


Figure 63. Digital process 5. Fiber wall, Full wall Syntax. Author's own copyright.

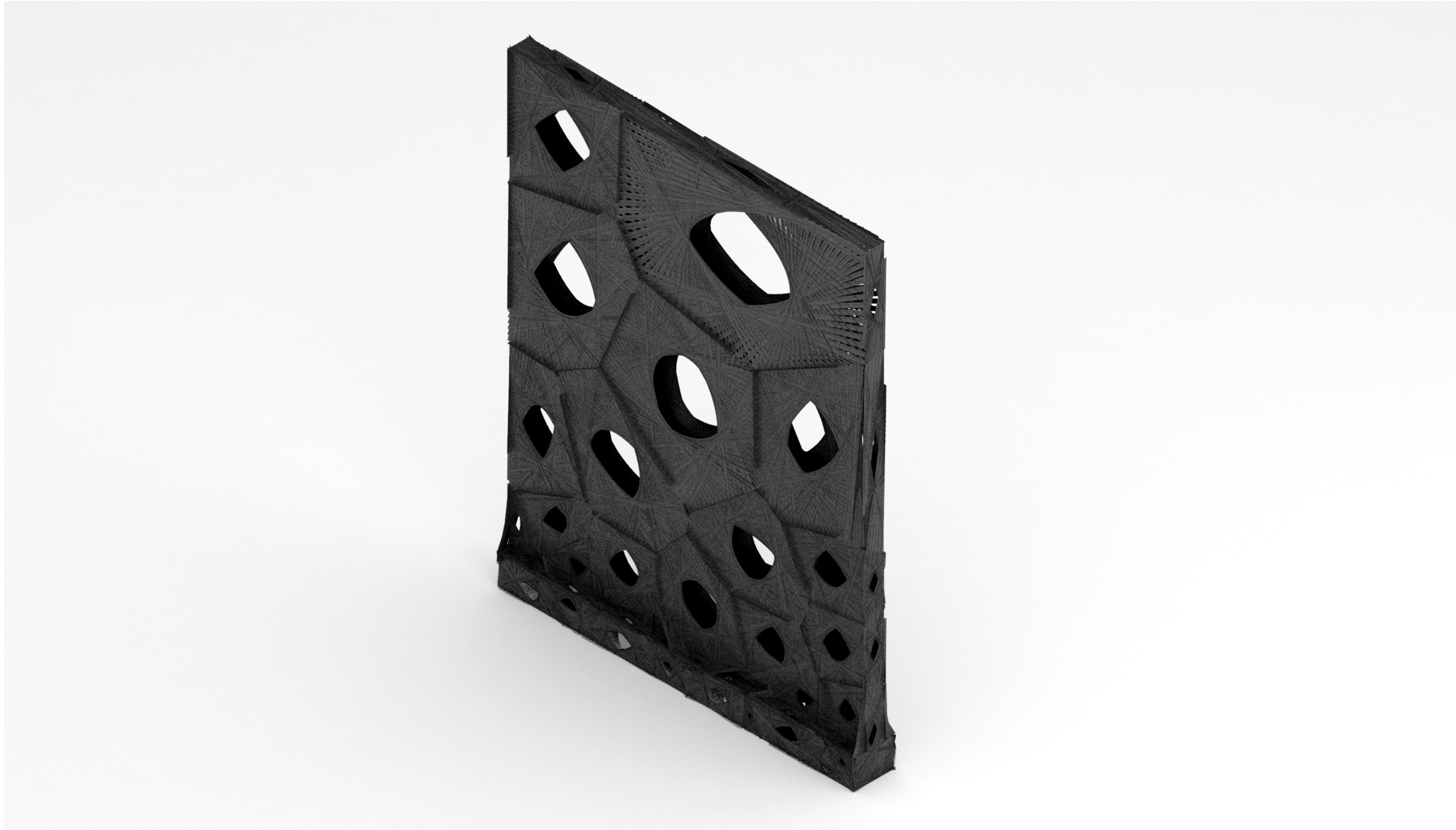


Figure 64. Digital process 5. 3D rendered wall. Author's own copyright.

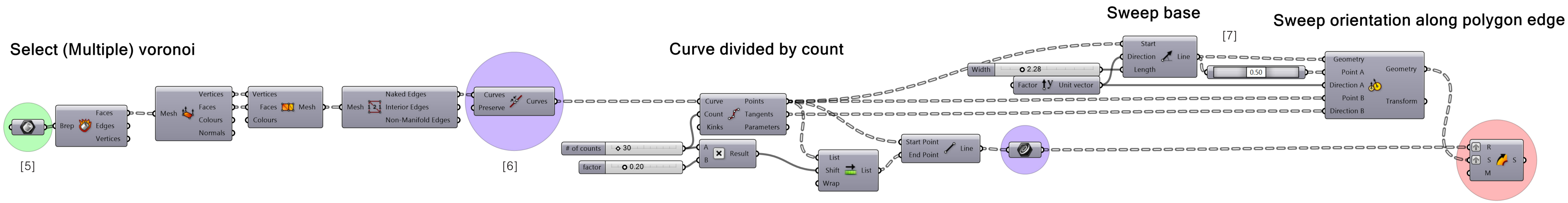


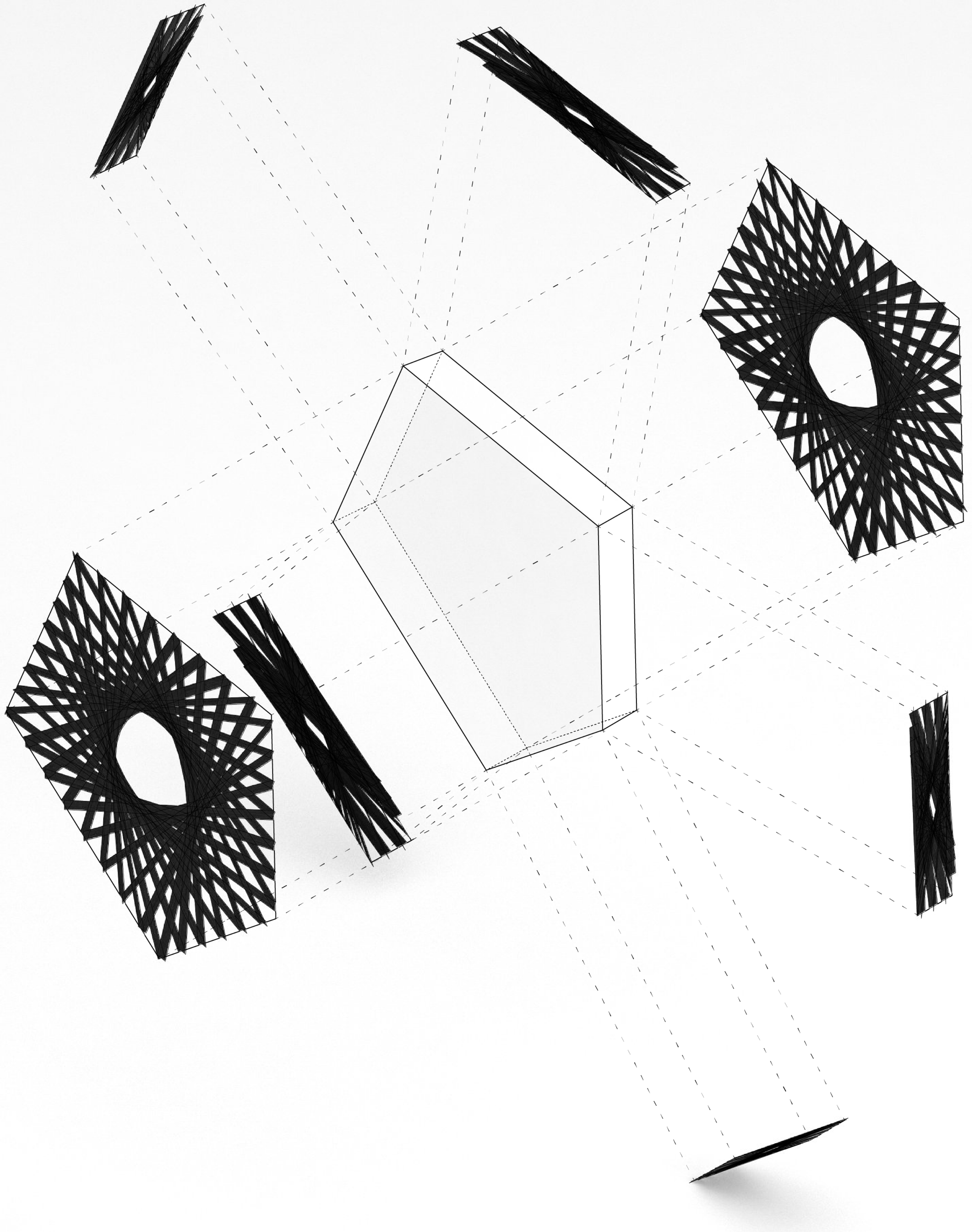
Figure 65. Digital process 2. Author's own copyright.

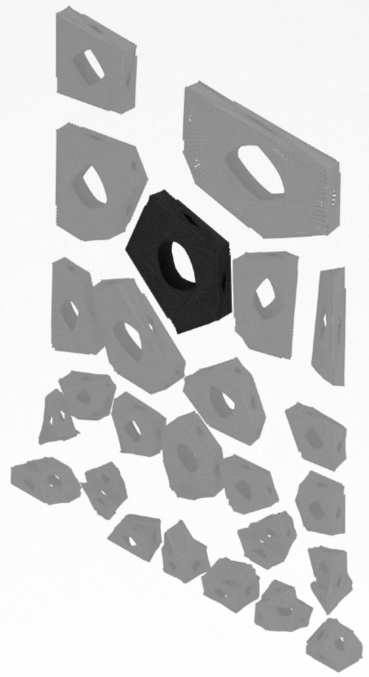
Figure 65. [5]. All the cells made in the previous code are first selected.

[6]. The boundary edges of the cells divides into several points. The points becomes the position of the teeth in the scaffolding.

In this example the curves divides by count, a chosen number of points. This would later caused a variety of problems in manufacturing. The fixed number of points on varying sized edges would cause inconsistency between the points. The distance between the points would became too large or too small. The points would miss-align and assembling cells wouldn't be possible.
Thankfully, the rendering highlighted this problem early and then adjusted before finalizing. In the later revision parameter changed from "count" to "distance".

[7]. The code drew new curves between the points to represent the carbon fiber syntax. Thickening the curves allows the program to create a rendering.





Exploded view of an individual cell

Figure 66. This drawing shows the syntax and complexity of what would be necessary to create a cell. The woven carbon fibers between the defined points makes up the walls of the cell.

Figure 66. Digital process, individual cell, exploded. Author's own copyright.

Exploration of cell styles

Figure 67. The appearance of the cells changes depending on how the fiber syntax is woven. The cells can be more opened or closed depending on the number of counts between connecting dots. The factor is the division of the total number of points.

A lower factor, lower number of counts, makes the cell more "open".
A higher factor, higher number of counts, makes the cell more "closed".

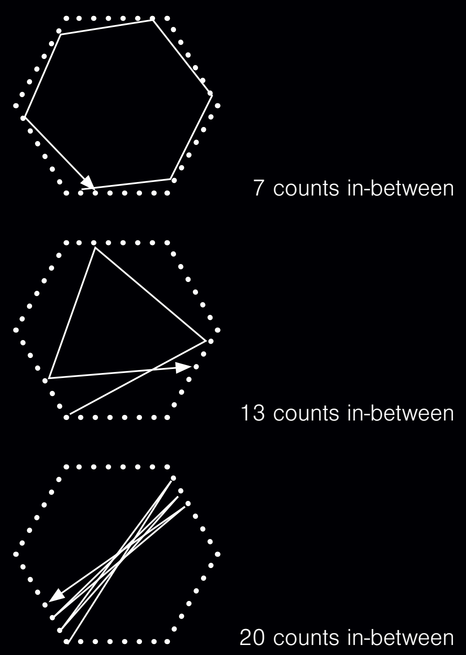
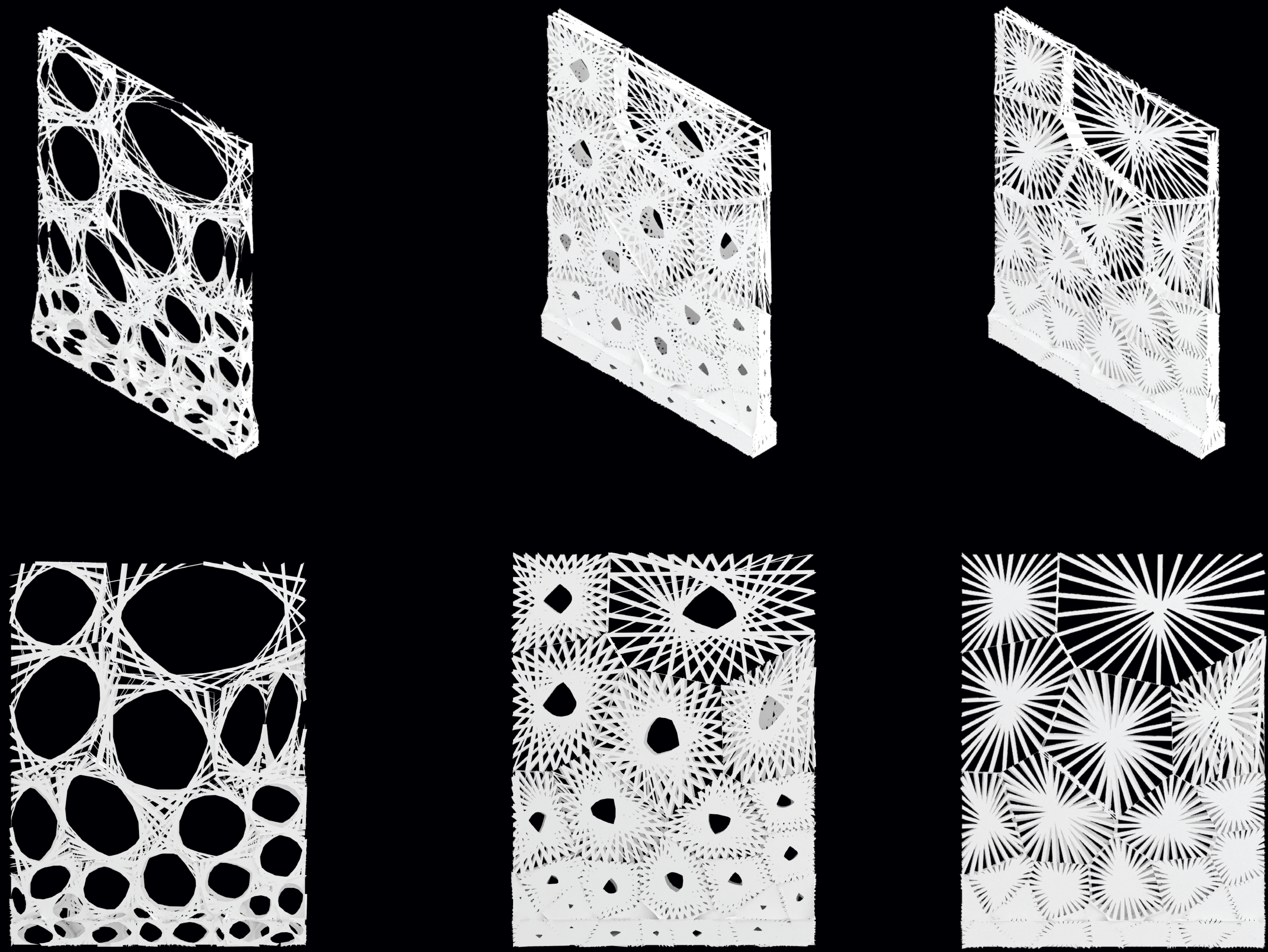


Figure 67. Cell styles, diagram.. Author's own copyright.



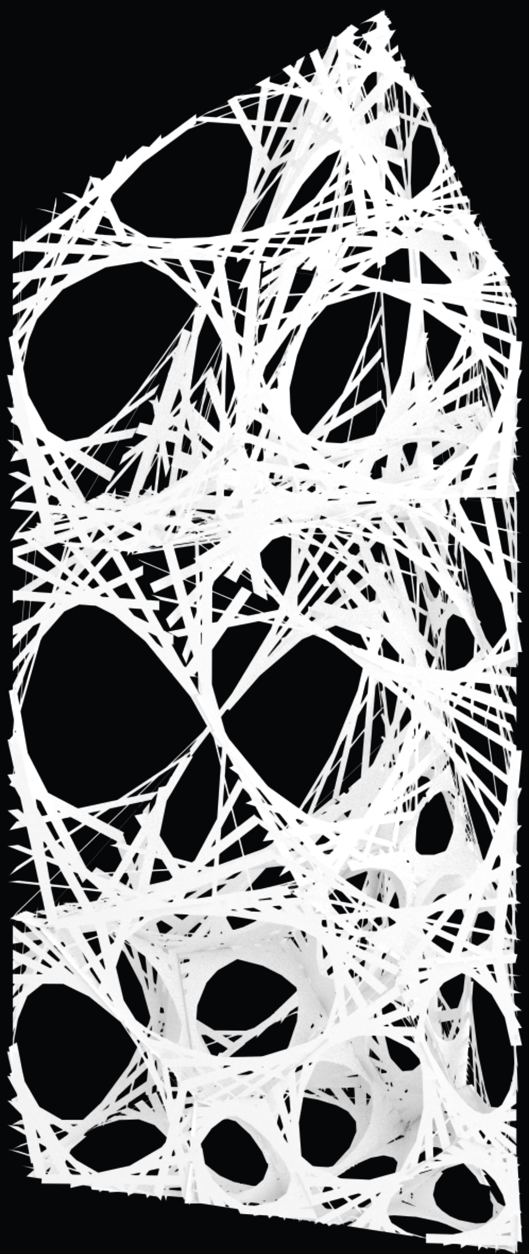
Wall 1
Cell style: Open
Factor: 0.2

Wall 2
Cell style: semi open
Factor: 0.4

Wall 3
Cell style: Closed
Factor: 0.5

Figure 68. Cell styles 1,2 & 3, Front & Axo. Author's own copyright.

Exploration of Base form
The object form changed from a wall to a pillar. This was to see if the code would work on an another type of structural building element. The code well on different polygonal pillars, showing pleasing results. The ambition is to have the means to use organic and free-flowing forms and finally allow unrestricted freedom in creation. The different pillar types also use different cell types with varying degree of openness.



Triangular pillar

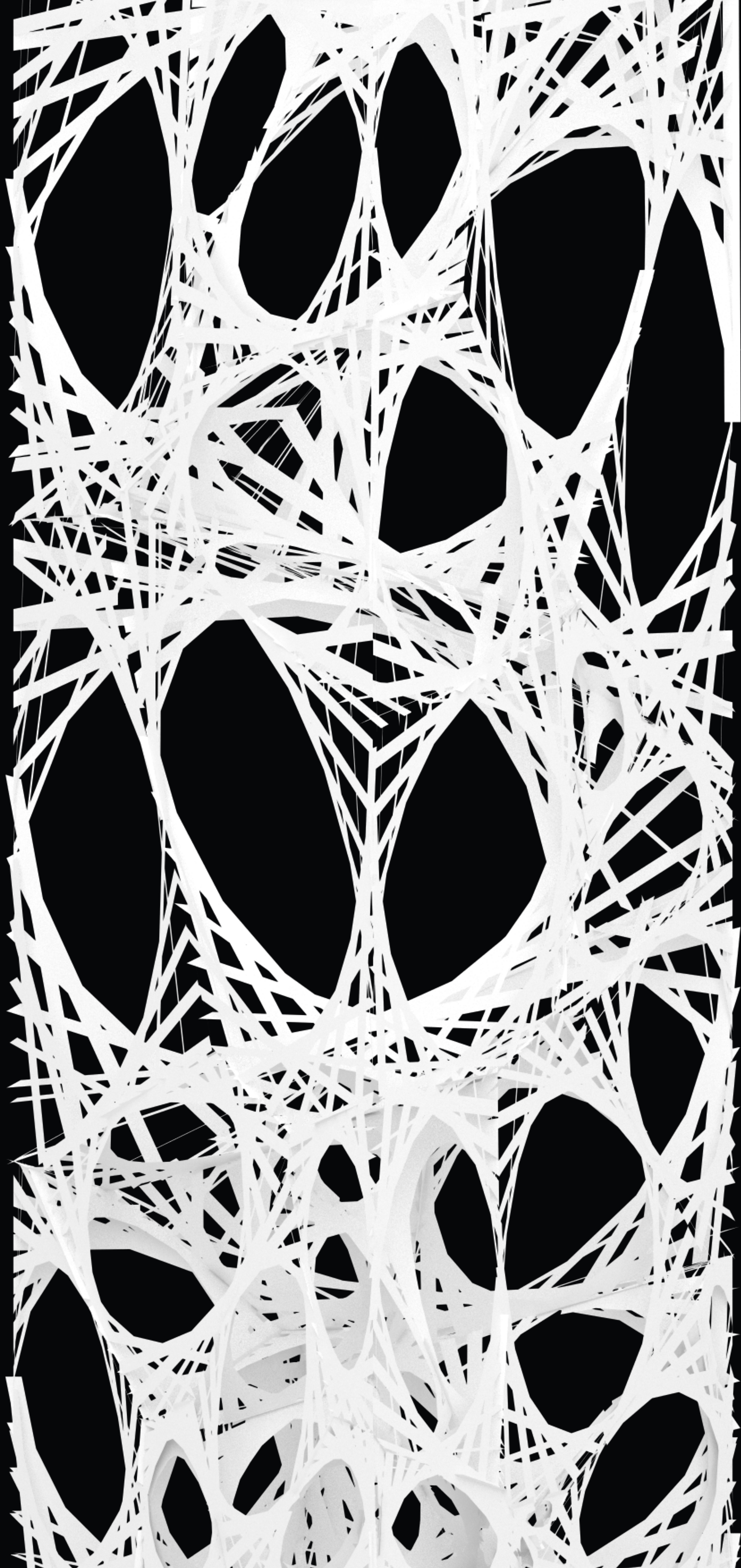
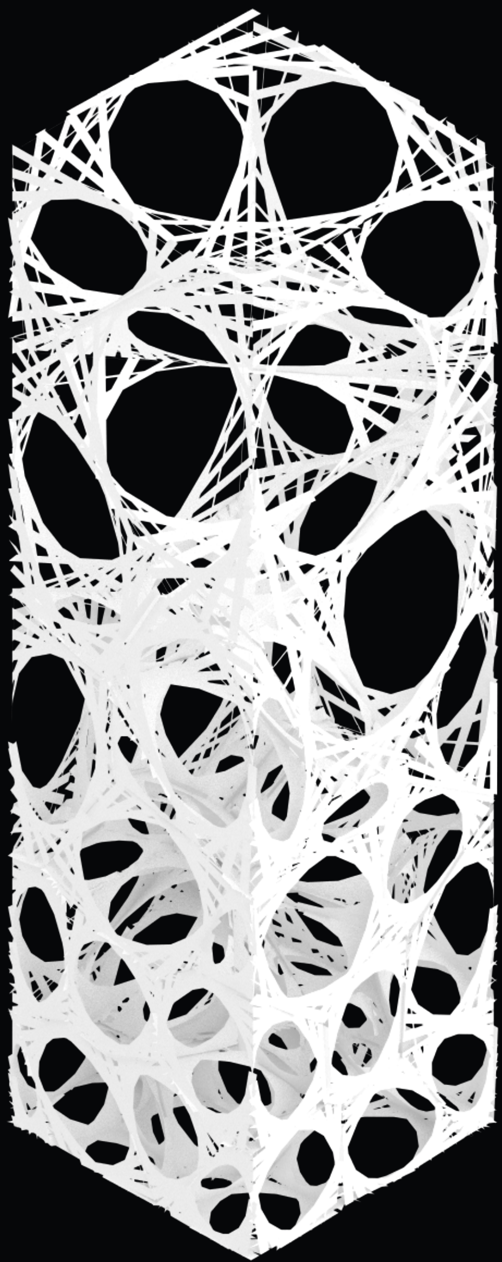


 Figure 69. Pillar types, Triangular. Author's own copyright.



Rectangular pillar

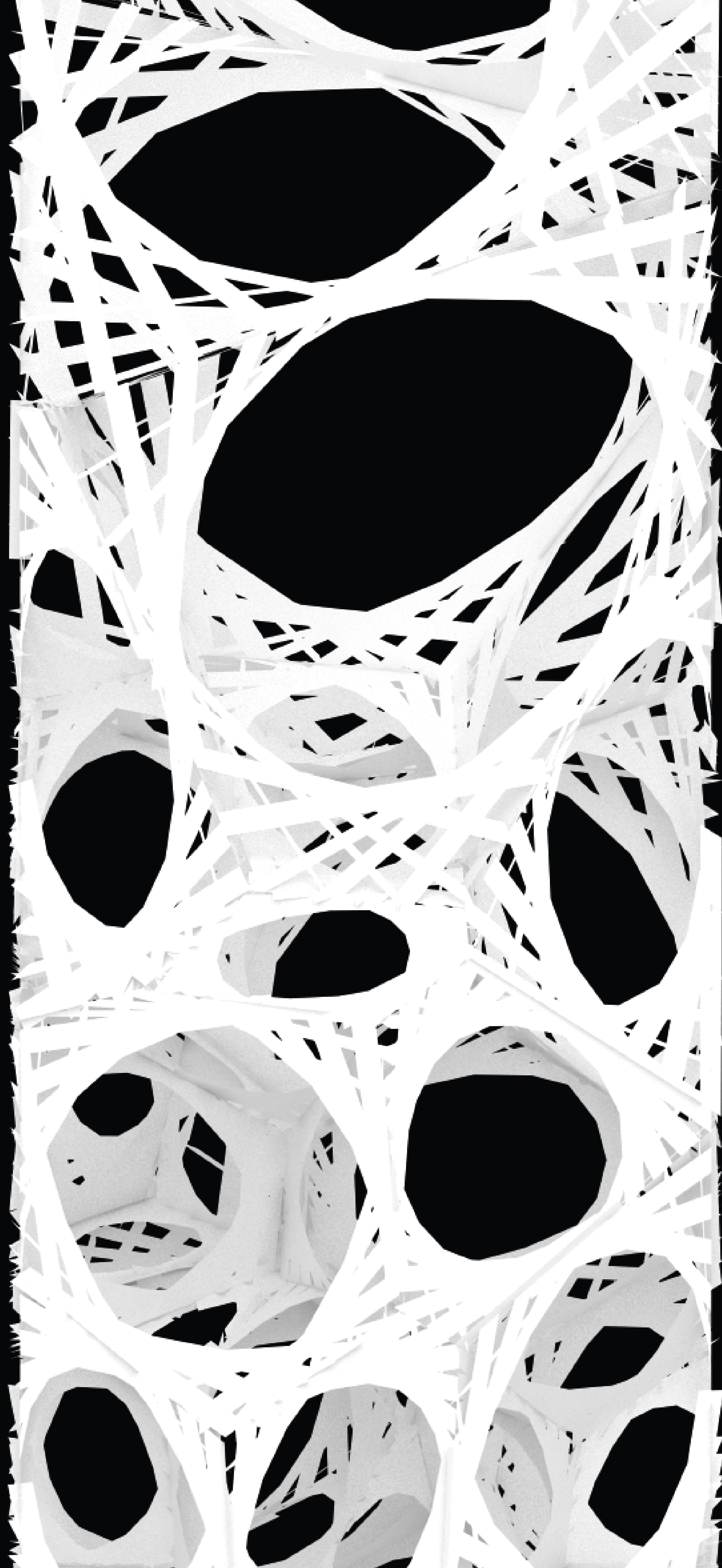
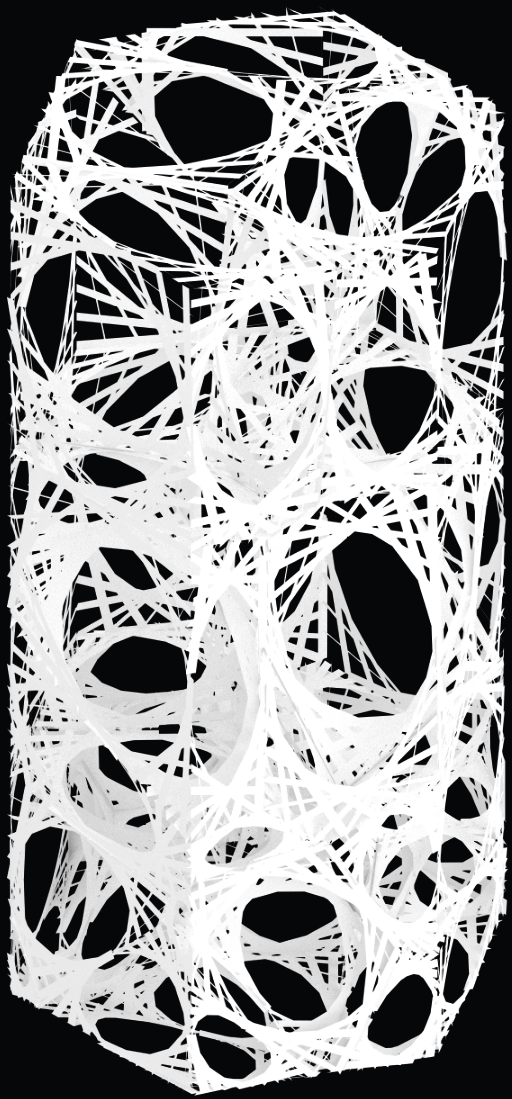


 Figure 70. Pillar types, rectangular. Author's own copyright.



Hexagonal pillar

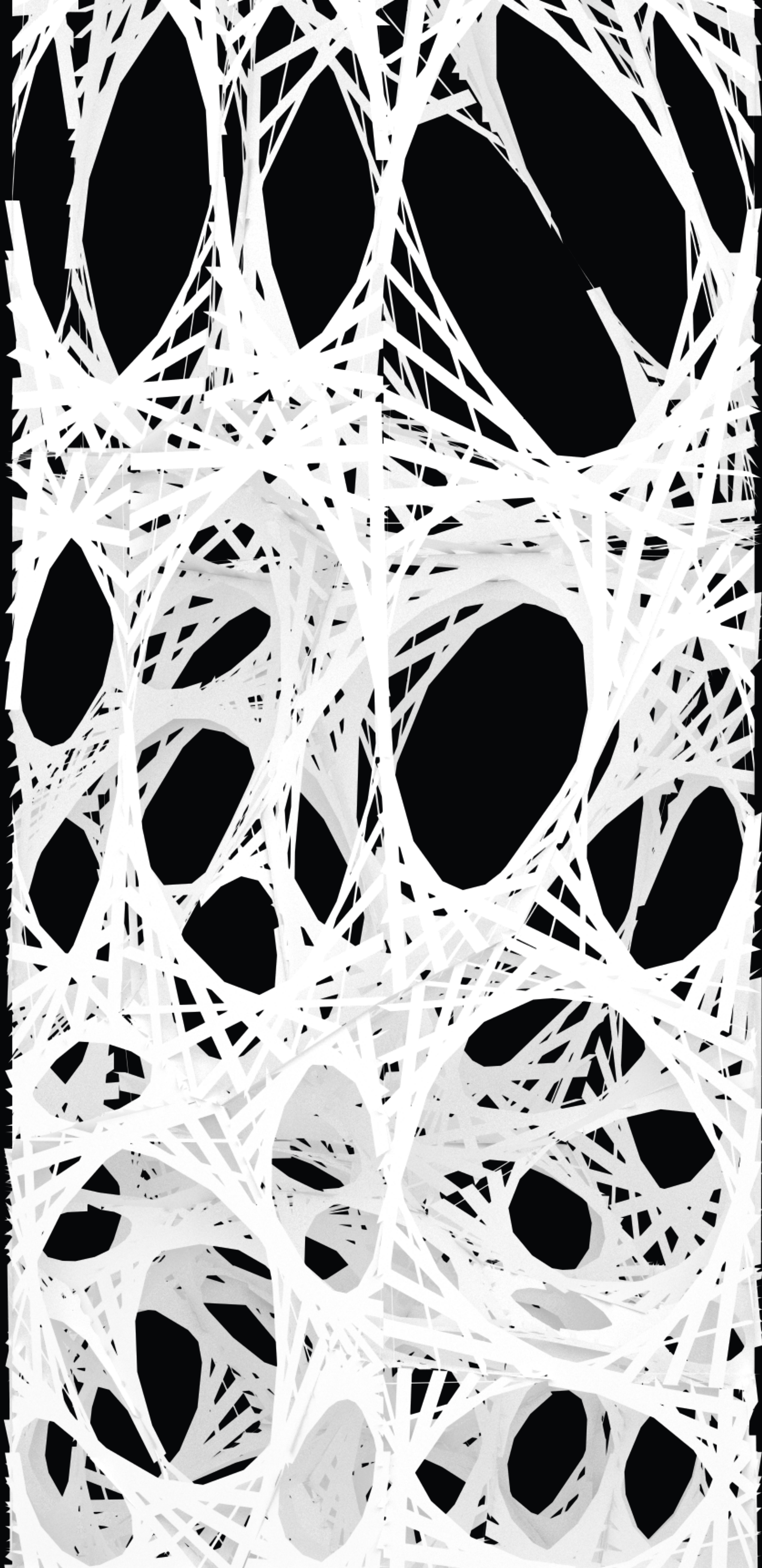


Figure 71. Pillar types, hexagonal. Author's own copyright.

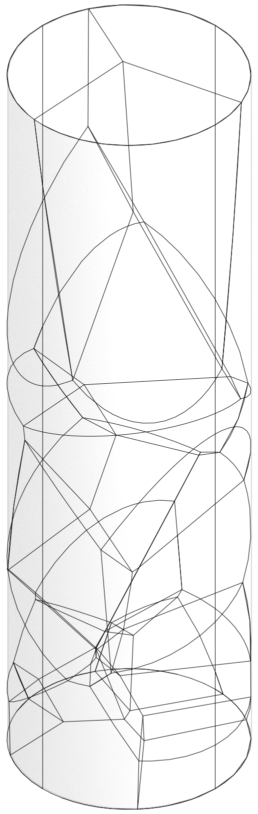


Figure 72. Pillar types, Round De-constructed. Author's own copyright.

Figure 73. Pillar types, Round rendered. Author's own copyright.

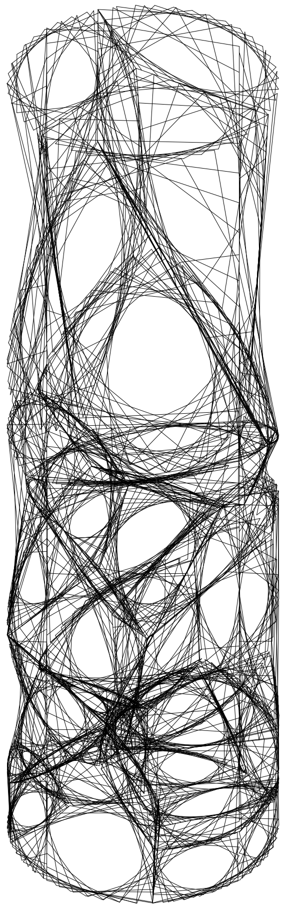


Figure 74. Pillar types, Round Axo. Author's own copyright.

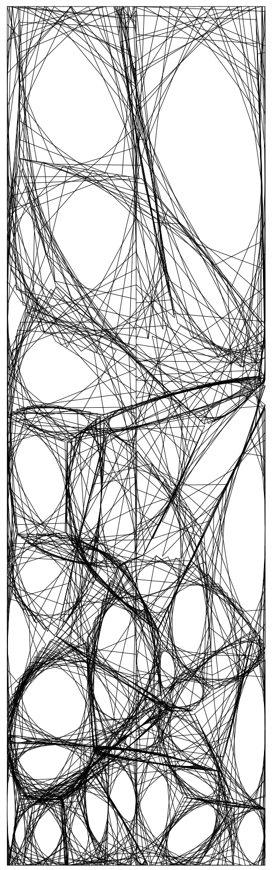


Figure 75. Pillar types, Round front. Author's own copyright.

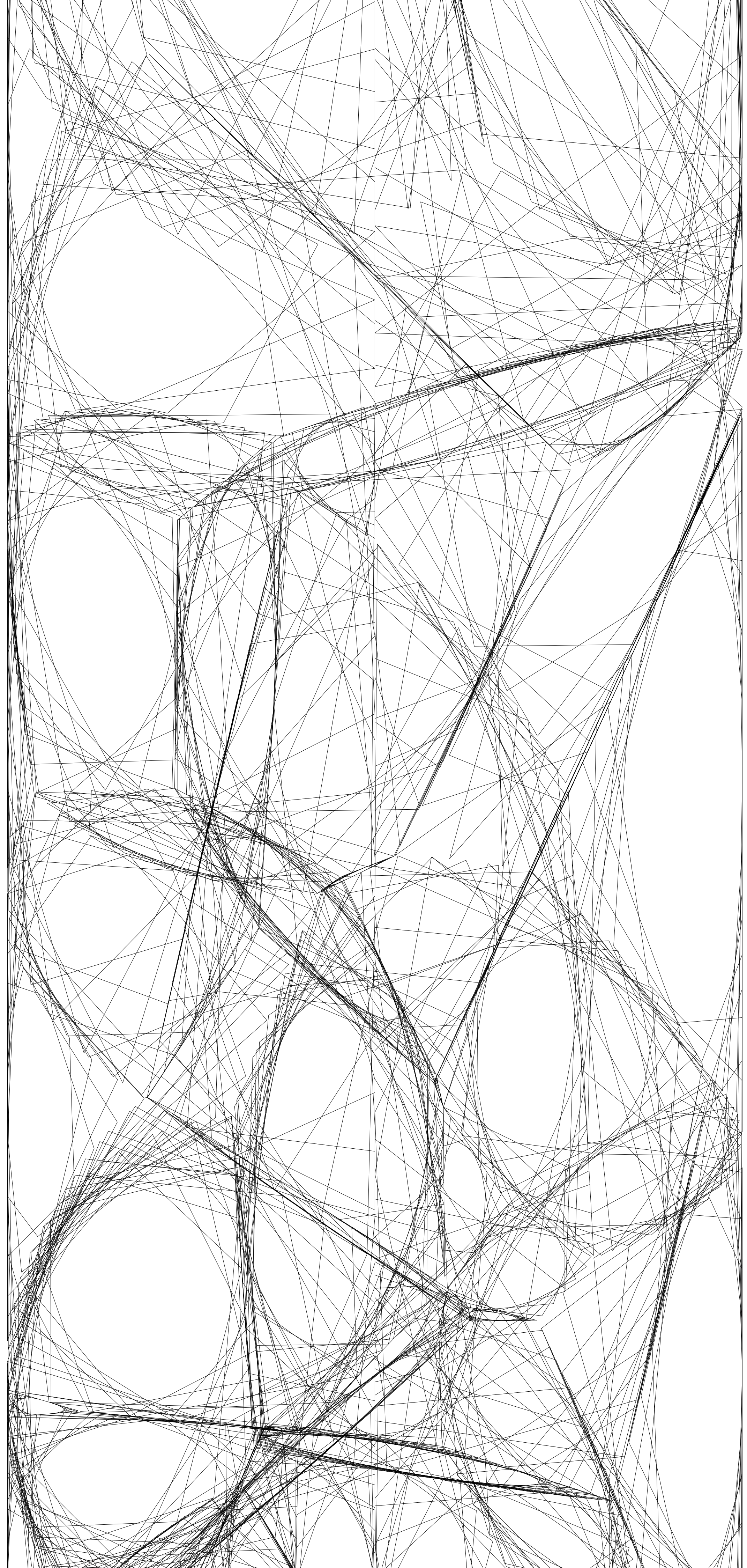


Figure 76. Pillar types, Round Rendered Axo. Author's own copyright.

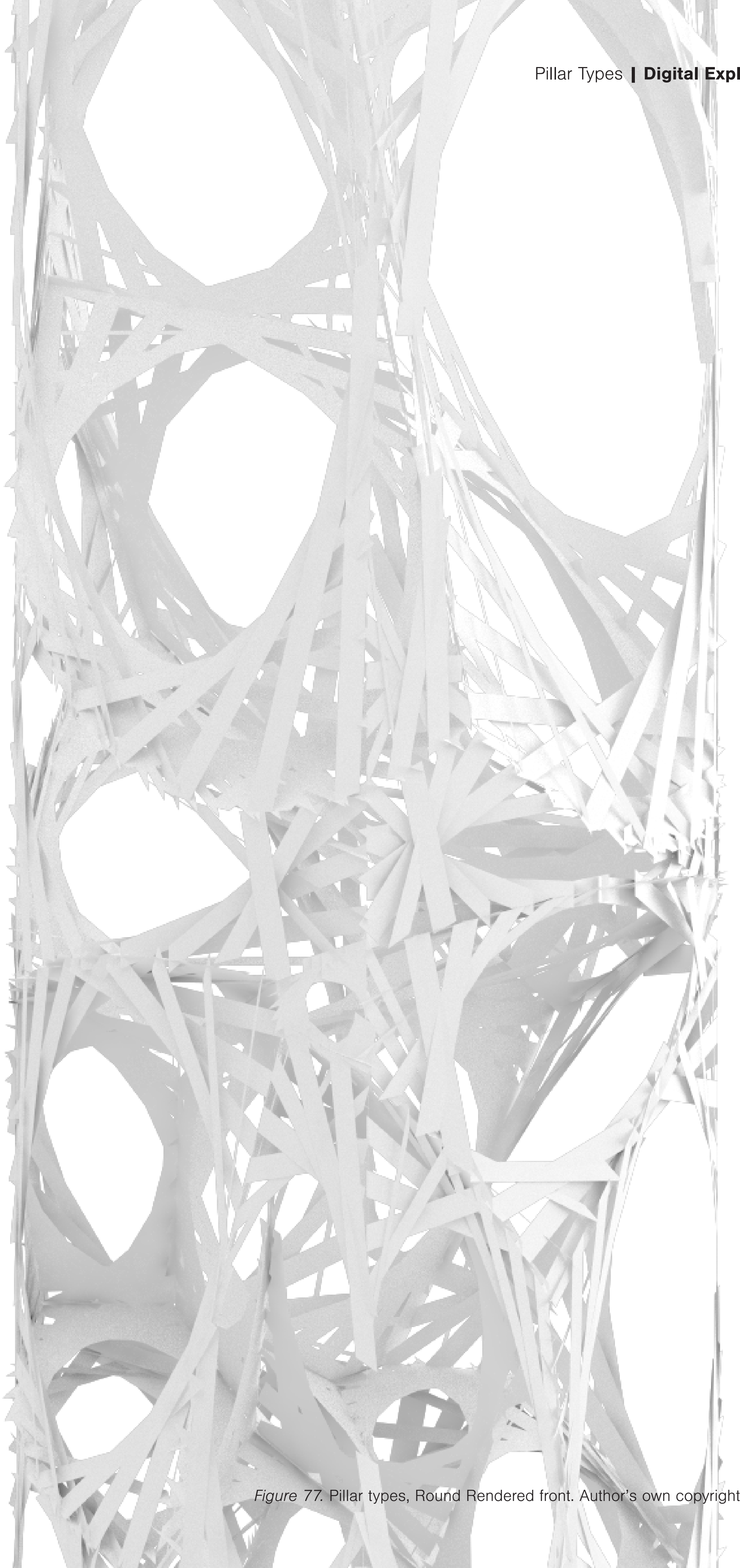
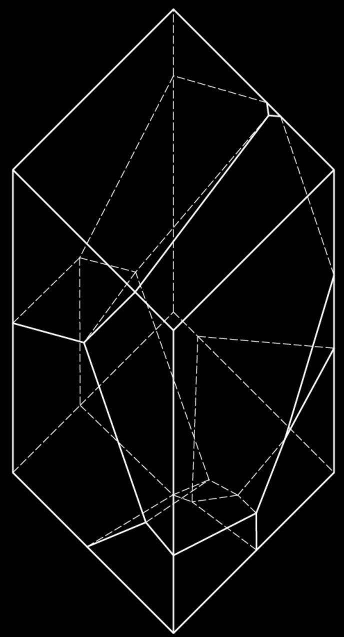
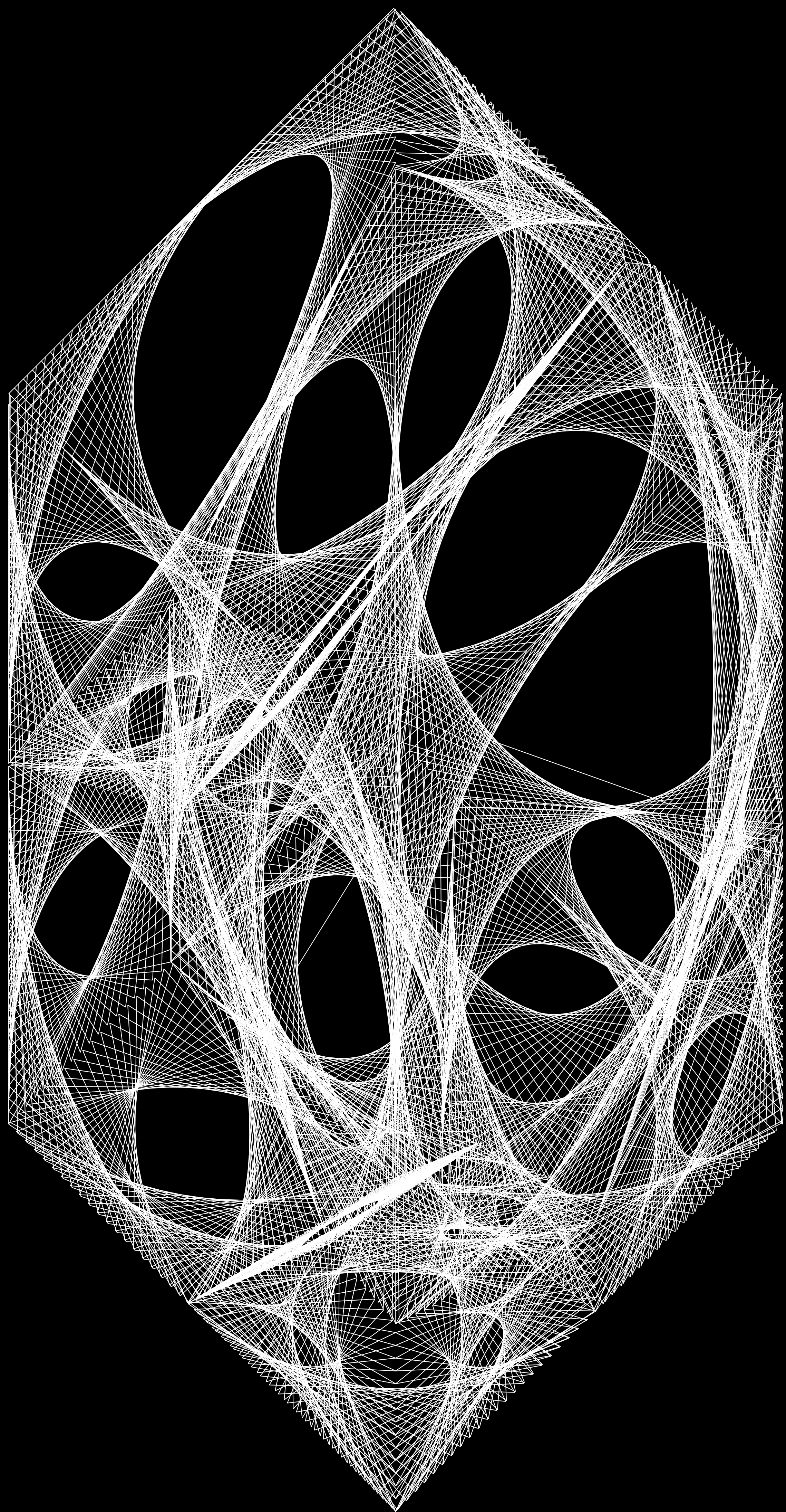


Figure 77. Pillar types, Round Rendered front. Author's own copyright.

Physical Proposal
1:1 Final model





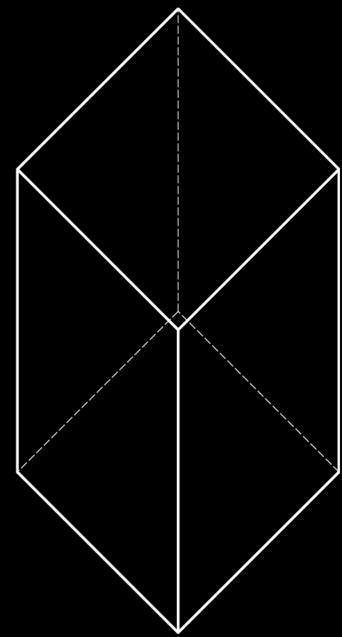


Figure 78. Final model Axo. Author's own copyright.

The Final model, made in 1:1 scale, represents a small rectangular stool. Sized 300x300x600 (Width*Length*Height). The aim with the physical proposal is to put the digital process into practical use. To try and reproduce the digital model into a physical model as accurate as possible.

The basis of a stool is almost identical to a pillar. Both have a similar design and loaded with structural forces from above. The stool is first de-constructed into 6 smaller cells. Each cell is then fabricated to become independent from the other. The idea is to symbolize the flexibility of the process to create a larger object with smaller ones. The process becomes less restricted by the final objects actual scale.

The work went generally smooth with a few set backs. This is a given considering the major jump in production volume. Majority of expected problem areas were simulated and checked beforehand with grasshopper. The vast amount of control and information provided through parametric design is unrivalled. The one of the biggest set back came actually from running out of carbon fiber during the weaving. More fiber had to bought and this delayed the process with many of days.

Dealing with the joinery of all the pieces caused the most thinking and many ideas went back and forth. One ideas was to use a screw and nut on the hole left after removing the scaffolding. This didn't work when three or more cells met at one area. Three edges could line up for a basic screw to run through. There would also be the problem of a foreign material in a structural detail area. Would this compromise the carbon fiber performance?

At the end only carbon fiber was used in the joints. Like the weaving process, the fiber was sewn into the seams in a cross hatch manner while coated in epoxy. The stitching cured to the final model and united all the pieces.

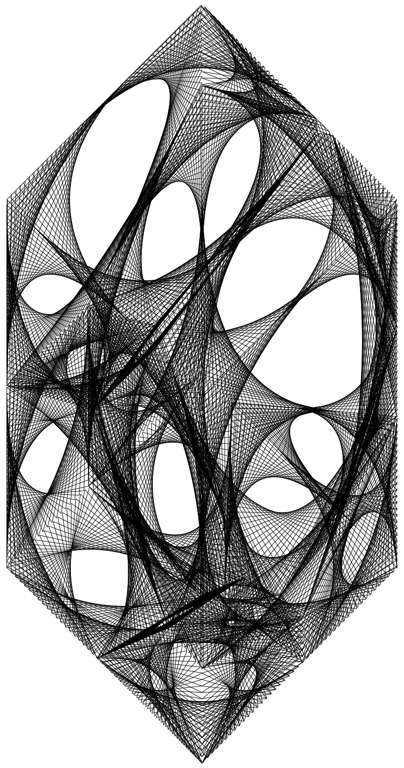


Figure 79. Final model Exploded axonometric. Author's own copyright.

Physical stool
Size: 300x300x400 mm³
Total fiber length: 614.5m

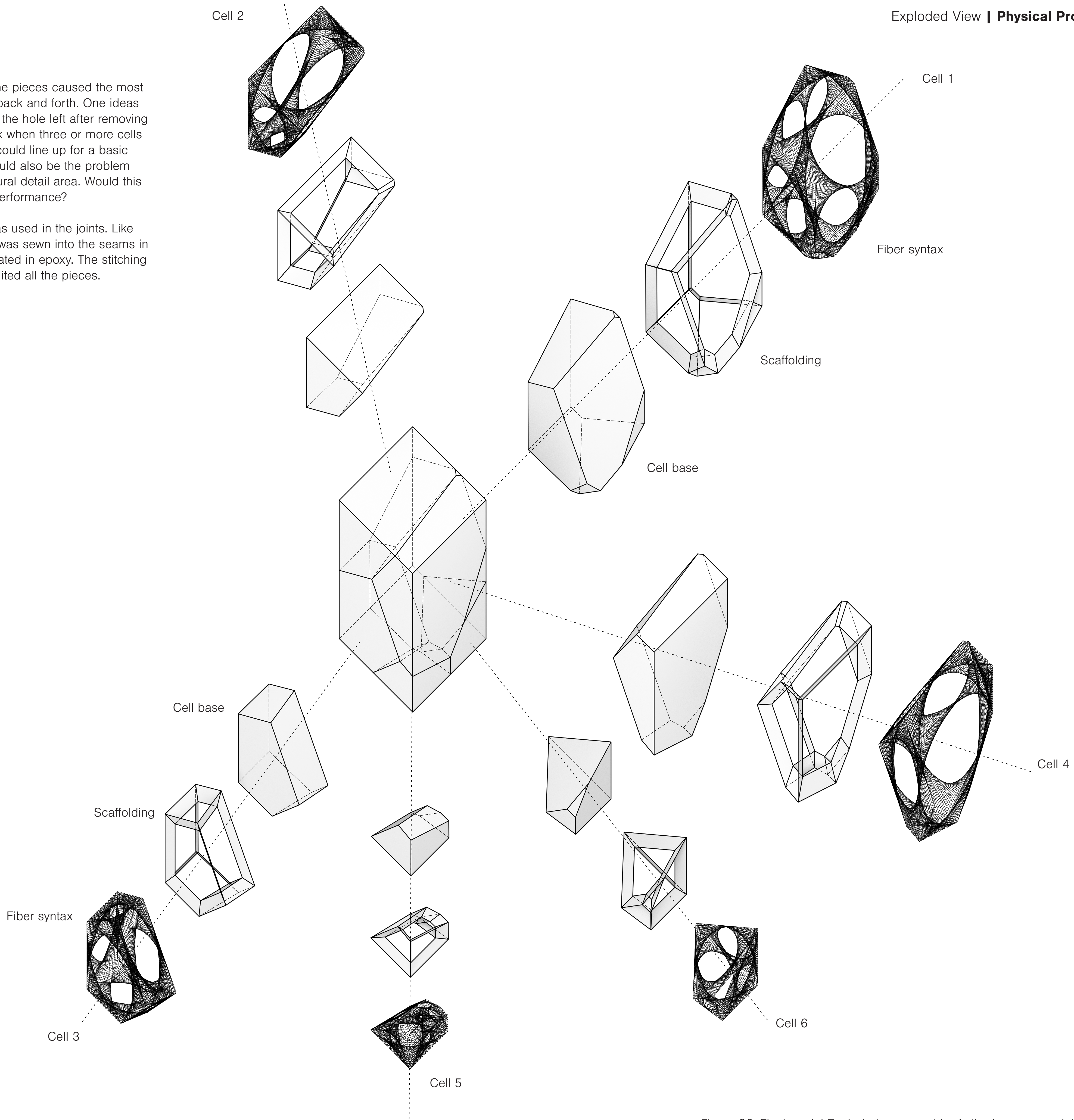
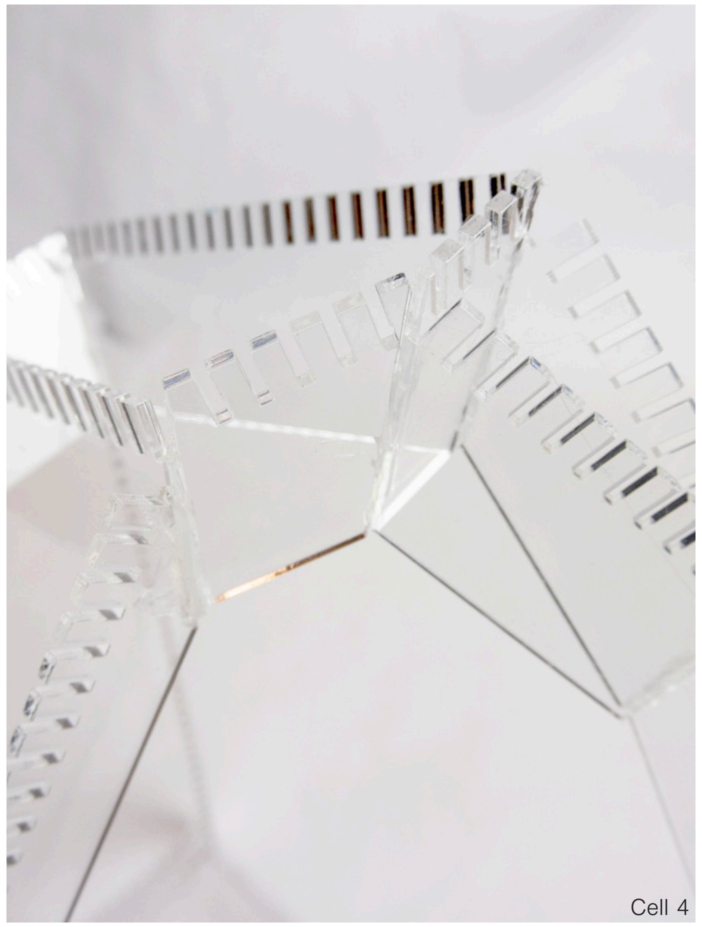


Figure 80. Final model Exploded axonometric. Author's own copyright.



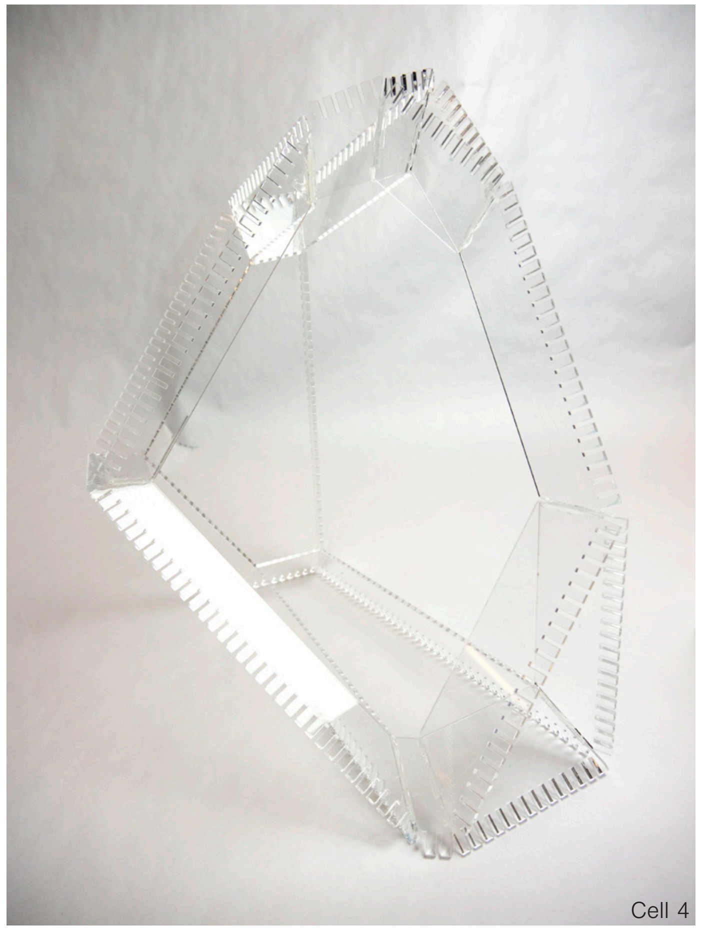


 Figure 81. Final model, Acrylic scaffolding, Full. Author's own copyright.

Figure 82. Final model, Acrylic scaffolding, Close up. Author's own copyright.

Figure 83. Final model, cell 6. Author's own copyright.

Figure 84. Final model, cell 4. Author's own copyright.

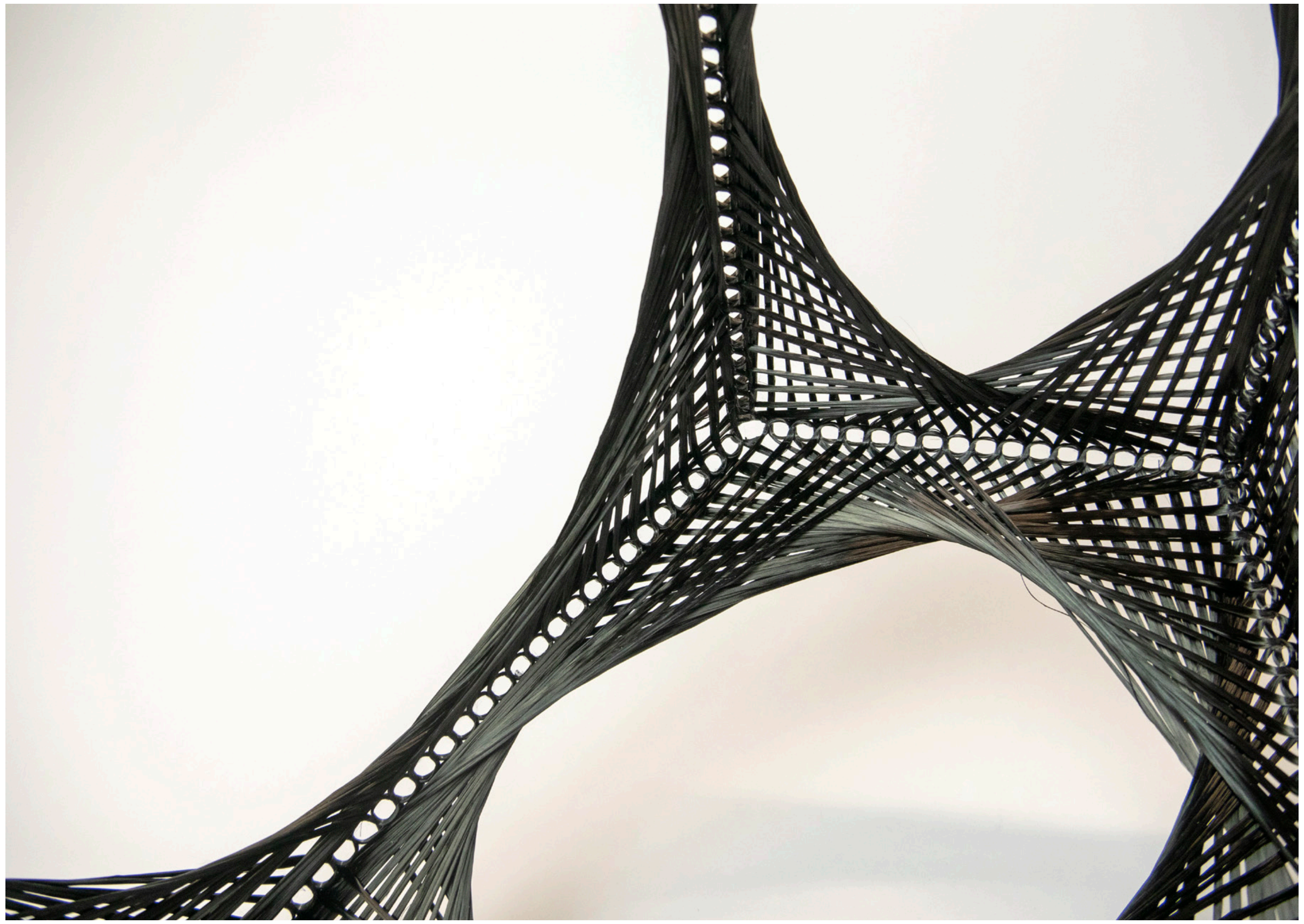


Figure 85. Final model, cell 4, close up. Author's own copyright.

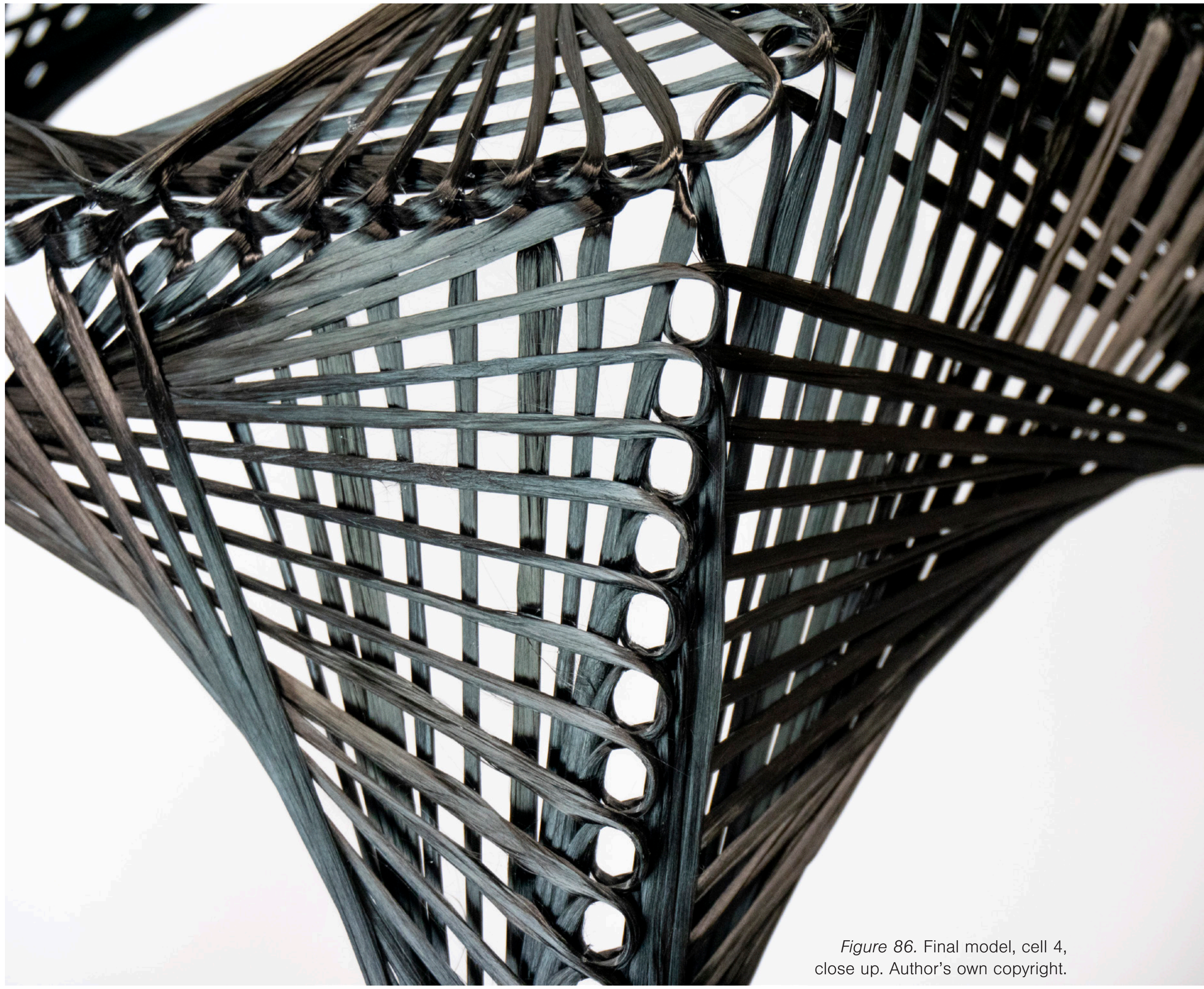


Figure 86. Final model, cell 4, close up. Author's own copyright.

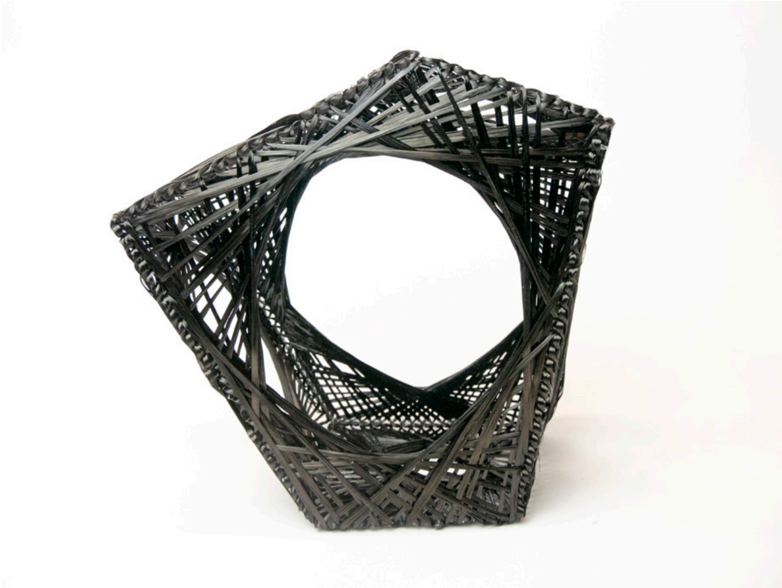


Figure 87. Final model, cell 3. Author's own copyright.

Figure 88. Final model, cell 5. Author's own copyright.

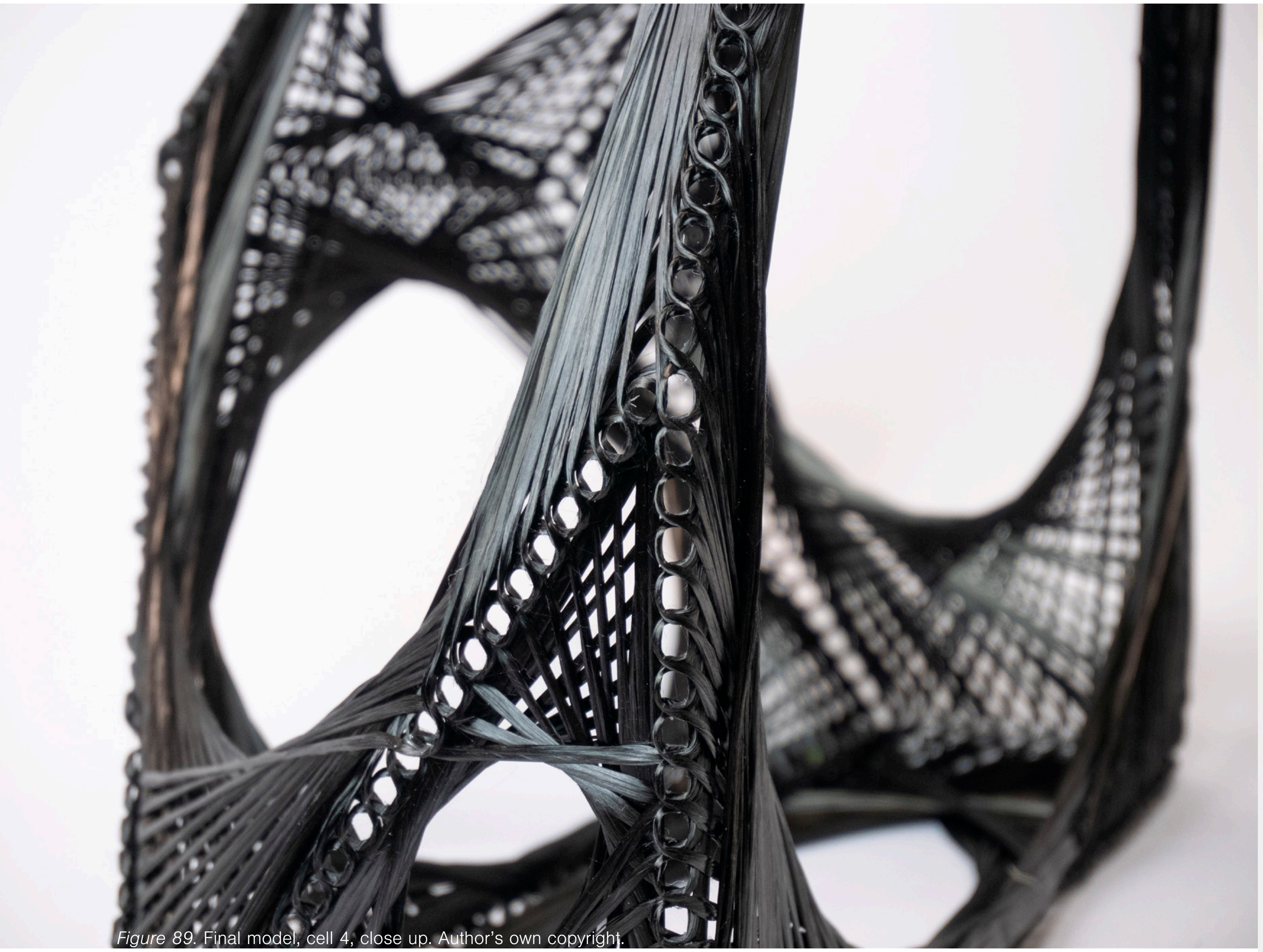


Figure 89. Final model, cell 4, close up. Author's own copyright.

Figure 90. Final model, cell 3, close up. Author's own copyright.

Figure 91. Final model, cell 5, close up. Author's own copyright.

Figure 92. Final model, cell 2. Author's own copyright.

Figure 93. Final model, Joining cells 1. Author's own copyright.

Figure 94. Final model, Joining cells 2. Author's own copyright.

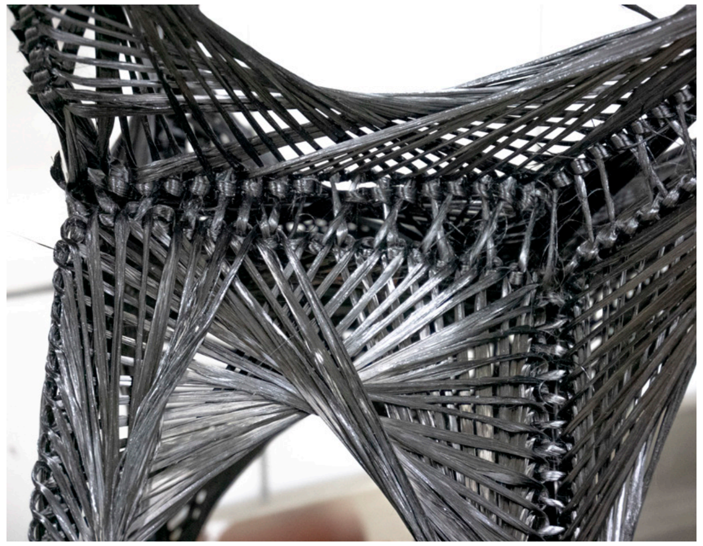


Figure 95. Final model, Joining cells 3. Author's own copyright.

Figure 93. Cells stitched together with carbon fiber and needle. The simple needle made of bendable iron thread. This allows for fine adjustment in shape when needed during tight areas. The needle also bent into a hook sometimes.

Figure 96. Stitching done in a cross-hatch pattern, overlapping and looping each hole left by scaffolding. Cross hatching created a tight fit and kept the tension well without coming loose.

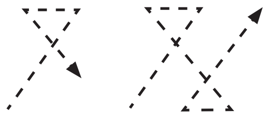


Figure 96. Final model, stitching pattern. Author's own copyright.

Figure 97. Final model. Two cells joined. Author's own copyright.

Figure 98. Final model. Four cells joined. Author's own copyright.

Figure 99. Final model, 60kg test load. Author's own copyright.

Figure 100. Final model on pedestal. Author's own copyright.

Figure 101. Final model. Author's own copyright.

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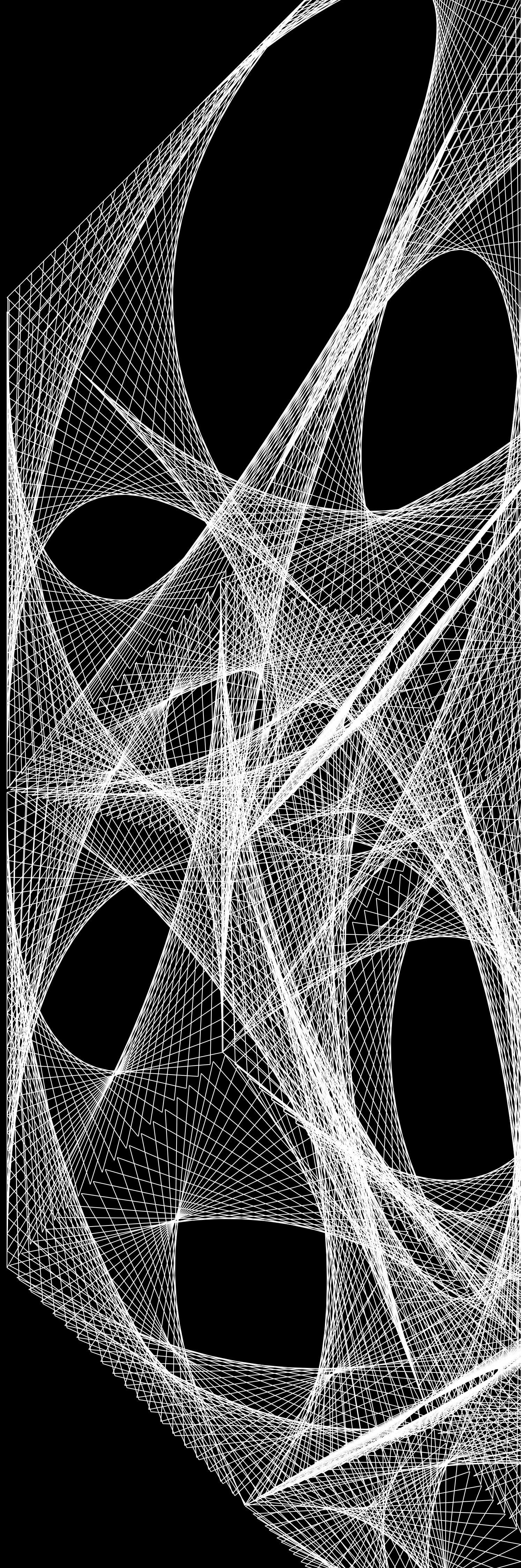

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