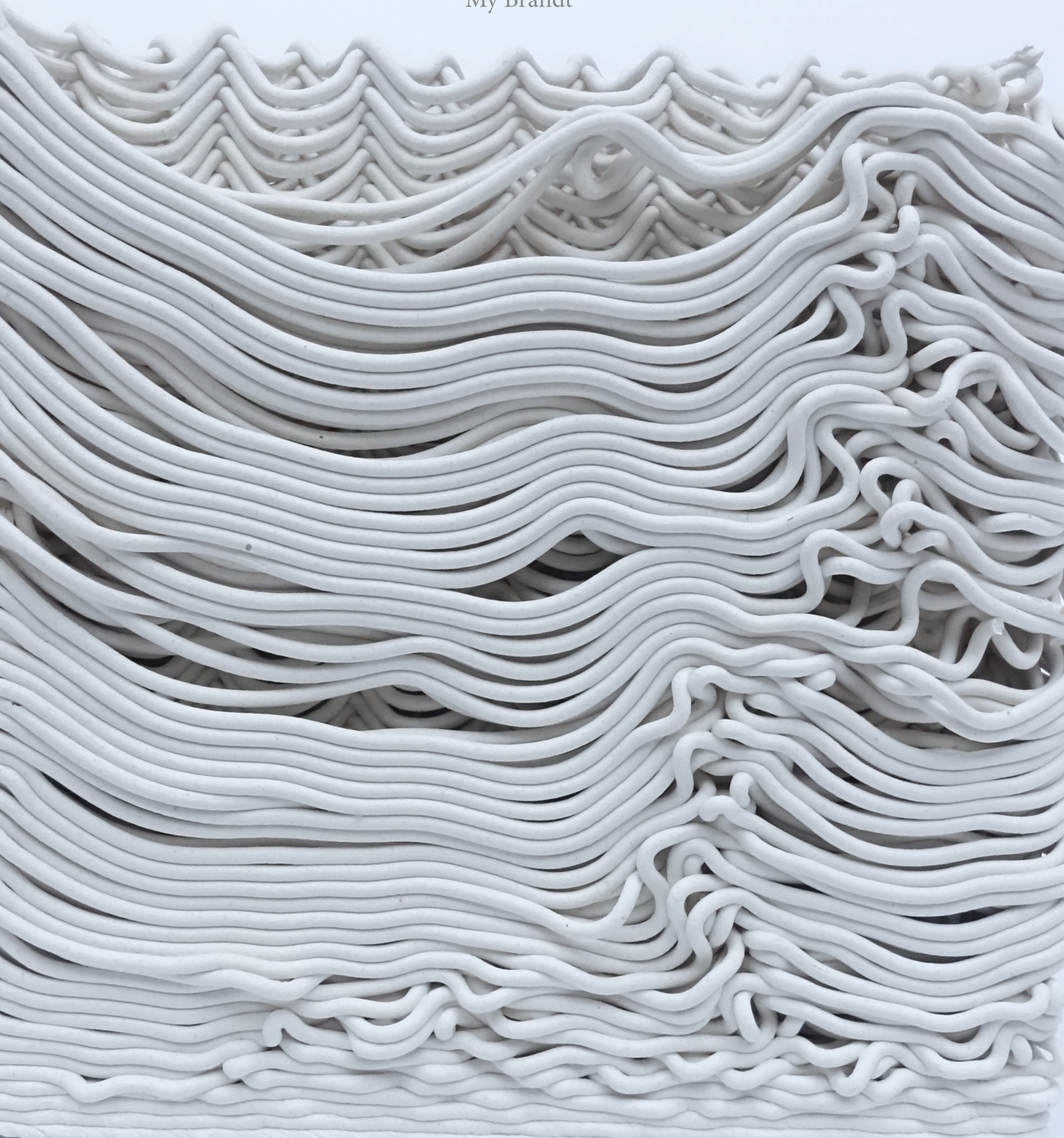
CONSISTENCY

My Brandt



Consistency

Masters Thesis in Architecture
Lund School of Architecture

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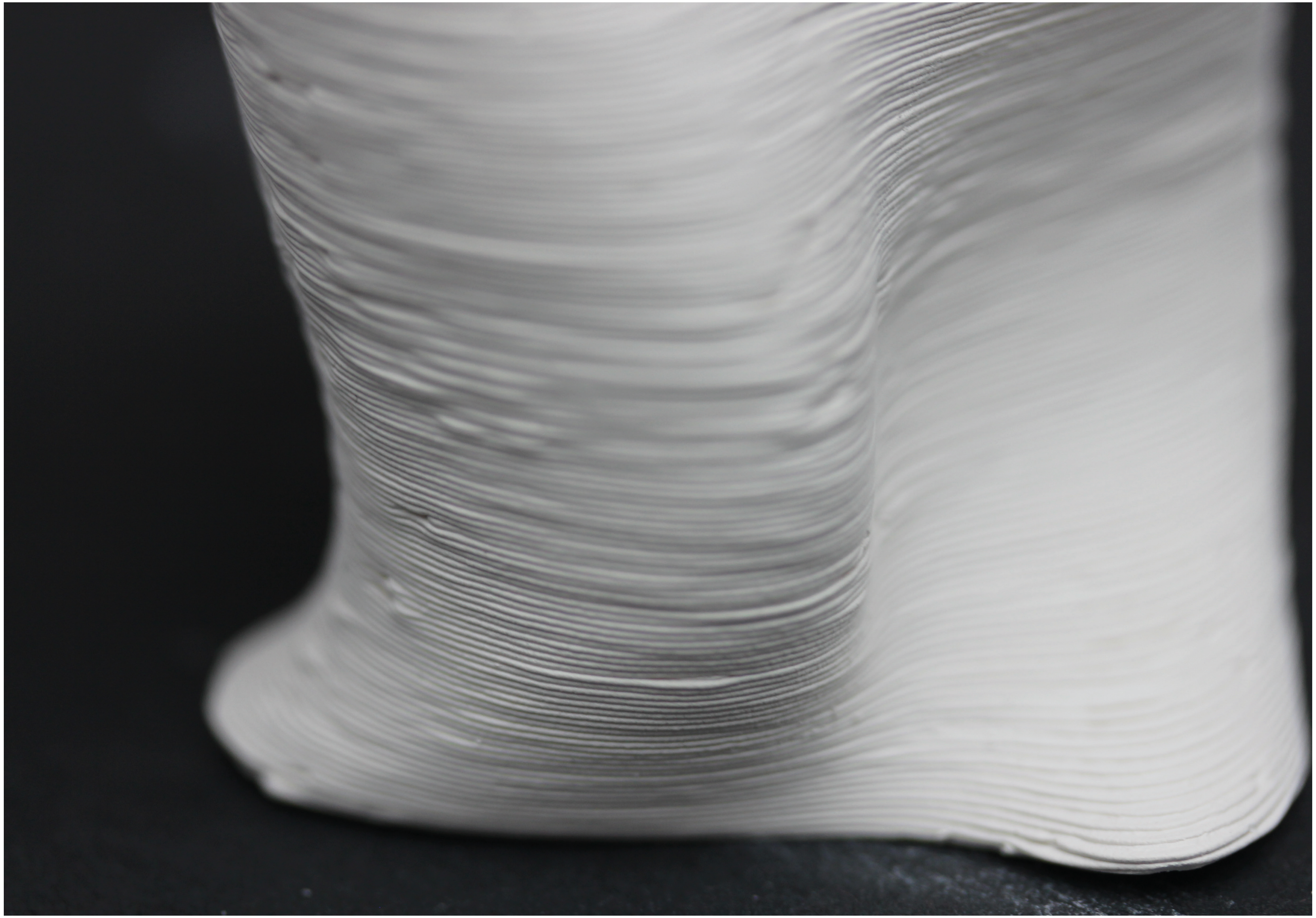
Abstract

No site, no client and no program, instead digitally fabricated physical models were the driver of this project. The method of research-driven design liberated the project from functional and performative demands and opened up for other questions to be raised. The two things that informed the design were the construction process and the material. The material used is clay. With its liquid form, plasticity and ever changing nature it introduces the coincidental in even the most planned objects. The uncontrolled clay meets the absolute control of a 3D printer. In the combination of the two something interesting happens. The robotic machine is used to create something otherwise unimaginable with that material, using only the material and its inherent properties but in a new way. The print is not a replica of a computer model, it is a new object with new properties and advantages. The construction method is thus used to further develop the model. The models can have a range of benefits from aesthetic to performative. They can be developed in accordance with the construction process or by intentionally going against it, using the machine to create with an element of chance.



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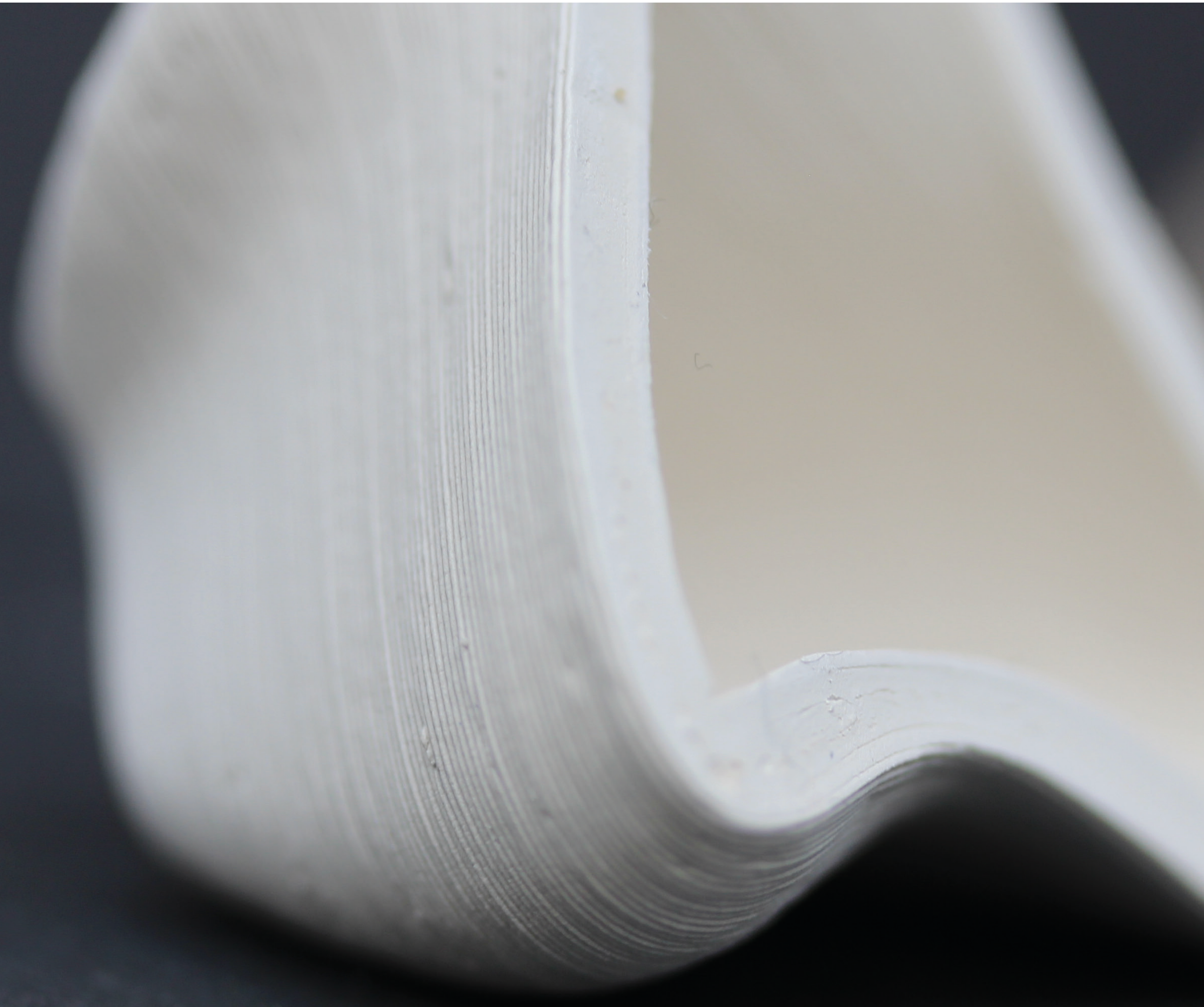


Consistency

noun

1. Conformity in the application of something, typically that which is necessary for the sake of logic, accuracy, or fairness.

2. The way in which a substance, typically a liquid, holds together; thickness or viscosity.

- Oxford Dictionaries

Introduction

The name of this project is consistency.
The word consistency can relate to the physical nature of a substance but it also means conformity in the application of something. Both meanings of the word have been central in the project. One as something I had to take into consideration, an inevitable aspect of any material. The other meaning, perhaps not so inescapable. The constancy of house typologies and the aim for uniformity in each of a house's components is put to question.

An example of a very consistent wall is the mass-produced, perfectly smooth gypsum board. It will always look the same. Board after board can be placed next to each other, hiding all other construction, uniformly. For 3D printing, this does not need to be a goal. Striving for that level of smoothness, talking about resolution of print, plastering and hiding any signs of construction serves little purpose. It is a logic borrowed from a different kind of construction. When building manufacturing became standardized, prefabricated, cheap and fast, machines offered a way to make every piece exactly the same. And when building with prefabricated components it is important with that level of exactness. But the digital turn happened and an increasing number of buildings are constructed in an entirely different way. Robots are building complete buildings based on computer generated code. New materials can be used and old materials can be used in a new way. Construction has definitely changed so why use the same logic?

Objective

The purpose of the project is to investigate ways to use computer programs and physical models in combination in the creative process. To find out more about how it affects the design process to see objects physically and not just in a computer program. If it is possible to combine the complexity that can be made in models using a computer and a 3D printer with the possibly more intuitive aspect of seeing and experiencing the model physically.

Research question

What are the benefits of using digitally fabricated physical models as a complement to computer generated models in a design process?

Digital fabrication in design practice

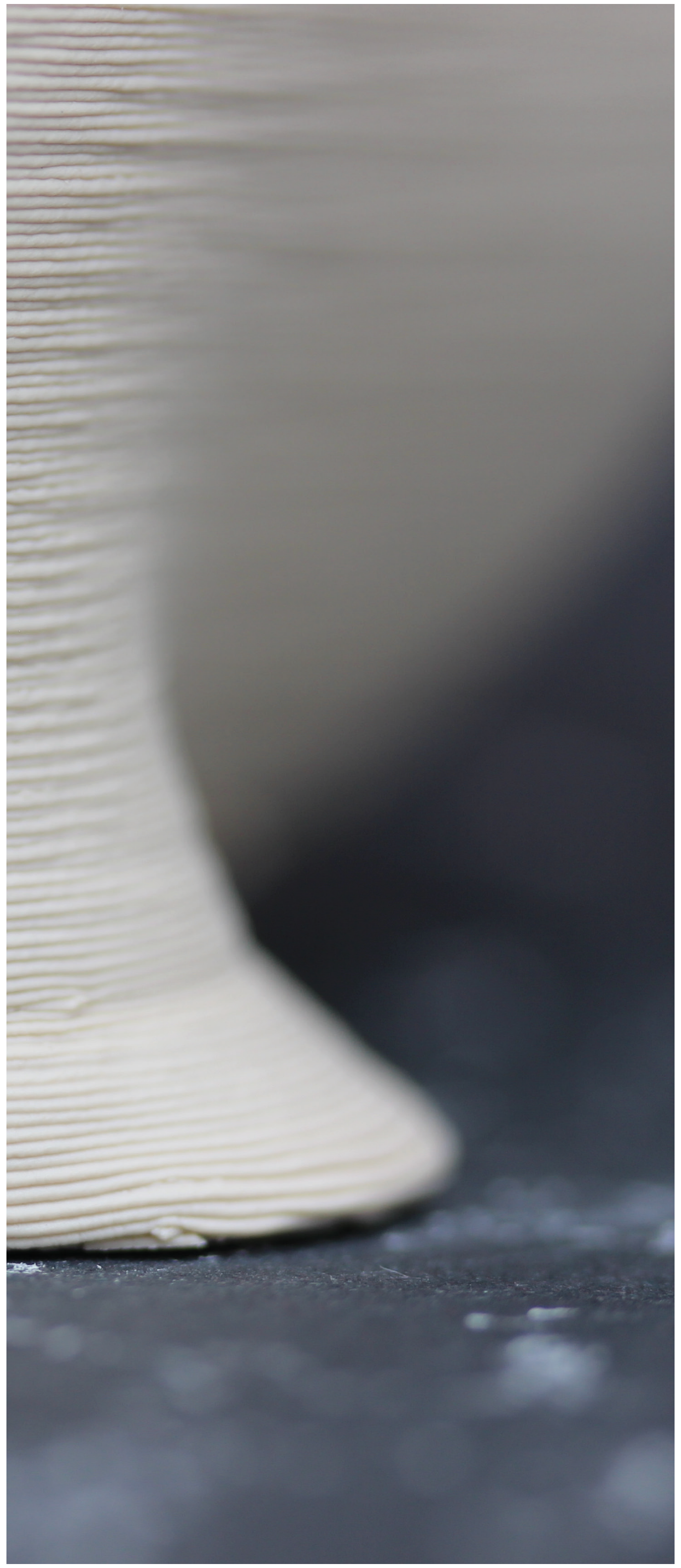
In design practice digital fabrication is often used at the end of a project, when making presentation models or prototypes. When the design is finished, we print it, with a desire to make it look as much as the rendered computer model as possible. In my thesis I question if digital fabrication could be used in other ways earlier and offer something in the design process.

Digital fabrication in construction

An established way of profiting from the potential of digital fabrication is by using digital fabrication to create elaborate shapes. Computer generated geometry with a vast degree of complexity which would have been impossible to create without this new mode of fabrication. Harnessing on the machines possibility to create something consistently perfect. In my project I ask if perfection is always meaningful.

Design research

The approach taken to answer the research question of this thesis is through an explorative design process. The questions asked differ from a design project which is client driven or with a set program and site. Design problems in those cases may regard a variety of functional aspects and there is the need for a level of compromise between different requirements of the project. A research driven approach opens up for a different way of designing. Answering other questions than are usually asked and potentially making a comment to the architectural discussion.



Point of departure

As the project has no site, client or user I needed another point of departure. Reading about creative processes was one way. Another way was to inform myself about possible advantages with physical models. Through this information gathering a lot of inspirational knowledge was derived and I will shortly recount some which have impacted the project.

From research by Olle Torgny I learned about a systematic and chaotic approach to creativity and how design methods can open up for intuitive processes (Torgny, 1998). Bryan Lawson writes about many similar design processes, one is the act of drawing and redrawing. While it is superior to for example a vernacular process in the way that many problems can be solved and experimented with on the drawing table Lawson finds a drawing's usability restricted in the end of a design process because a drawing is focused on how something looks and not so much on how it works (Lawson, 2006). As an example on a different approach in the design process the following quote by Robert Venturi has been inspirational ”We have a rule that says sometimes the detail wags the dog. You don't necessarily go from the general to the particular, but rather often you do detailing at the beginning very much to inform” (Lawson quoting Robert Venturi, 2004, p.15). A similar approach is taken by Eva Jiricna who often start her architecture projects by drawing full-size detail drawings of materials and their junctions (Lawson, 2006).

For the explorative process artists and the way they use materiality in their work has also been inspirational. The work of Tara Donovan and especially her creative process is an example of this.

Her work comprise of everyday materials which she isolates and perform experiments on. Her investigations involves working with the physical nature of any object and trying to find the magic in it. “I am striving to be an alchemist and to transcend the material” she says (Louisiana Museum of Modern Art, 2013). Her work plays with material but also with the way we, the viewers, interpret the materials. The movement of the body is always important in her work as it activates the sculptures usually by the play of light and reflections.

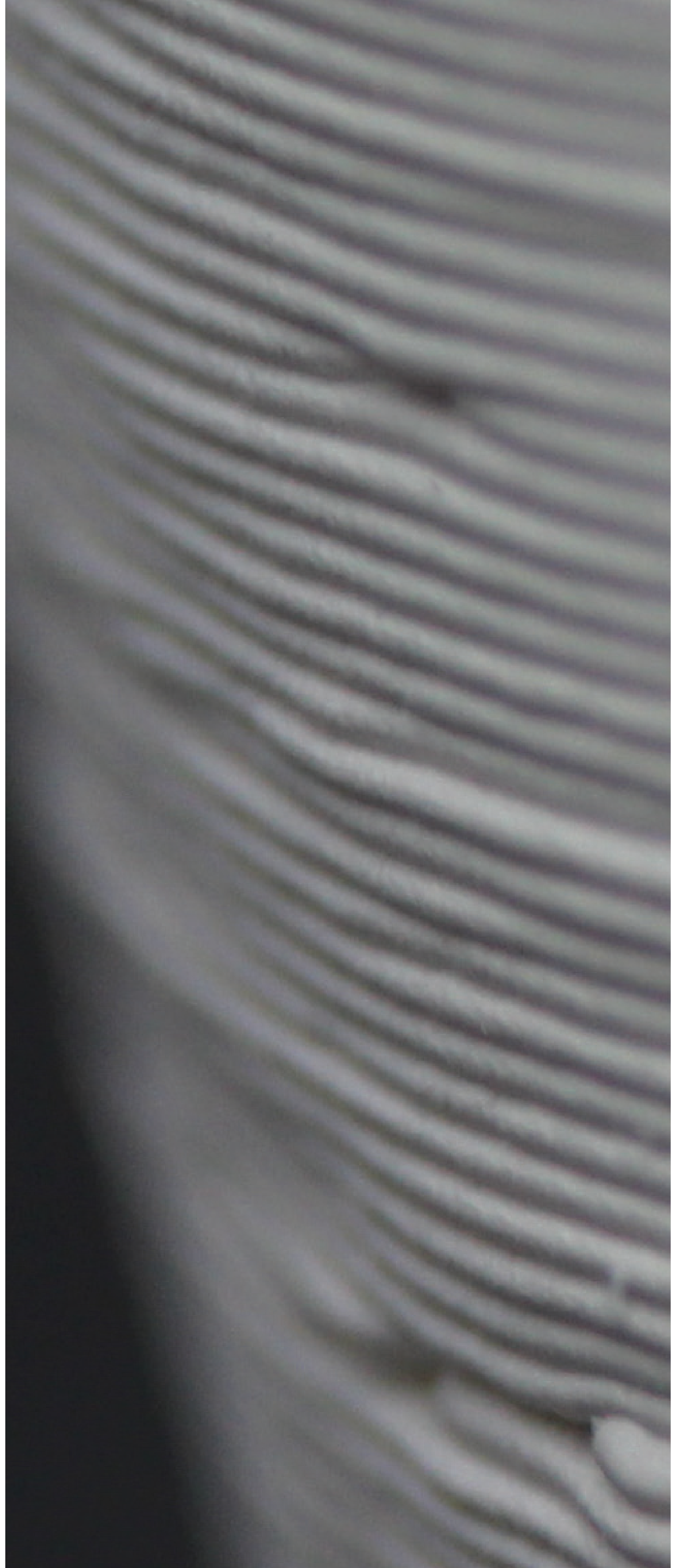
With an interest in the bodily experience of built space I also read architectural phenomenology and Juhani Pallasmaa. In his work an architecture for all senses with a tactile and bodily presence is advocated as well as the role of architecture as something to connect us to time and space. “Architecture is the art of reconciliation between ourselves and the world, and this mediation takes place through the senses” (Pallasmaa, 2005, p 72). This led to an interest to know more about how the brain reads information from the senses. An important aspect is that although there are unimodal systems such as the visual system, the tactile system and so on the way we experience the world is multimodal, combining the information from different systems. For example by touching an object we are also imagining how it would look (Lacey& Sathian,2014). The brain organization is not as divided into the different senses as previously thought. This is exemplified by the way a haptic texture perception will also activate the visually texture selected areas of the brain (Lacey& Sathian,2014). Neuroscience research indicates that the brain uses a multi-sensory approach to experiences. It is constantly comparing the information it receives with an internal representation of reality (Levent, Pascual-Leone, 2014). This could perhaps offer a neuroscientific explanation to art historian Bernard Berenson idea of ideated sensations. The notion that even if we simply look at a piece of art we will experience it with all of our senses. Imagining its tactile qualities, the way it smells or feel when touched for example (Pallasmaa, 2011).

The use of physical models in the digital design process was also relevant to examine. In a study by Youngjin Lee it is stated that physical scale models play an important part in the design process and that it has advantages over 2-dimensional drawings or perspective drawings because the viewer and the model are in the same 3-dimensional reality. Models help designers understand complex form and offer a tactile experience (Lee, 2015). Lee further stresses the need for an integration of design computing and digital fabrication in architectural pedagogy as computer modeling has been overly focused on creating images at the expense of construction (Lee, 2015). Stan Allen is in a similar way questioning computer visualization's usefulness. Pointing to that the reality simulated in a rendering can only be concerned with the visual sense and that it is aspiring to be like a photograph of a building not like a building (Allen & Agrest 2000). He is also encouraging the integration between computer modeling and digital fabrication in a design process. Arguing that when the capacities of the fabrication process and the properties of the material are taken into consideration in the design process, new possibilities for design can appear (Allen & Agrest, 2000).

Context

Examples of architecture in the realms of *research driven design, 3D printed architecture* and *vernacular earth architecture* provided a foundation to the project.

The research driven design projects were a support with methods, vocabulary and in their visionary approach to architecture. The current 3D printed architecture demonstrate both potentials of the construction process and possible problems. WASP earth 3D printer showcases that large scale 3D printing with earth is possible and offer a viable option for translating concepts from scaled clay models to reality. The interest in earth construction led to investigations into vernacular earth architecture as well as general information about clay as a building material. The views on earth construction in various parts of the world show the difference in status of earth construction depending on location. For this project it is also contextually relevant to look at different kinds of 3D printers and their distinguishing features.



Research driven design

Gramazio Kohler Research

With their "Remote Material Deposition Installation" Gramazio Kohler Research is showcasing a new technique in digital fabrication. A robot is shooting projectiles of clay from a distance. And while the robotics movement and the placement of the clay is exact the material will aggregate dynamically. (Gramazio Kohler Research, 2014)

Daniel Norell

Daniel Norell's thesis "Taming the Erratic" deals with material processes, material simulations and materialization. In his work he questions how material processes can offer new design opportunities and how material simulations might alter architectural representations. In his design work simulations make it possible for material processes to drive the design process. The combination of manipulation of real materials and manipulation in a material simulation program and the feedback loop they can create is important in his work. (Norell, 2016)

Anders Kruse Aagaard

The architectural piece named "Intermediate Fragment" by Anders Kruse Aagaard is part of his research regarding a material- and machining driven process. An experimental work-flow is important in his work. The work is driven by an accumulation of knowledge through different iterations. The iterations are made based on surprising features of material experimentations. Aagaard differentiates this process where the outcomes of the experimentations informs the next part of his process as an opposite to a work-flow where physical tests are done and altered only as a way to come to an already defined endpoint.(Aagaard,2015)

Andrew Atwood

In his research Andrew Atwood is building and manipulating digital machines such as 3D printers as a means to explore design processes and as a way to question architectural representation. (UC Berkeley)

3D printed architecture

WinSun

WinSun Decoration Design Engineering Co. are world leading in 3D printing houses. They are using the 3D print technology to print prefabricated parts in a factory off site. The walls and components are manually assembled on site while also adding columns and rebar inside the walls. Lastly the houses are grouted and finished by hand. The construction process enables quick and affordable production with less manual labor than an ordinary construction. The material used consists of construction waste, concrete, fiberglass, sand, and a special hardening agent. (Sevenson, 2015)

Digital Grotesque

Michael Hansmeyer and Benjamin Dillenburger's "Digital Grotesque", is a highly detailed piece printed in sandstone. The installation is printed as stackable elements. The prints consist of silicate and a binder printed in a powder-binder-jet type of printer and have a resolution of a tenth of a millimeter. After the print the pieces are covered in resin to increase structural stability and coated with shellack to ensure a smooth surface. 260 million individual facets are designed by an algorithm. The designers stress the unexpected in the design process and the algorithms power to surprise even though the algorithms are deterministic. No randomness in incorporated and there is no manual intervention in the computational design. It is a spatial experiment, investigating the potential of digital technology more in regards to aesthetics and experiences than to function. (Digital Grotesque, 2017)

World's Advanced Saving Project

WASP, World's Advanced Saving Project is a 3D print developer who was the first to print with earth material using their 12 meters high BigDelta. The diameter of the house is five meters and each layer of material is 135 mm. They are aiming at printing low-cost, sustainable houses made of locally sourced clay. The printed material consists of earth, straw, sand and limestone. The walls can stand without additional support and can take strong stress. (Wasp, 2016)

Vernacular earth architecture

The 500 years old, 8 story high, skyscrapers in Yemen city Shibam shows a variety of vernacular strategies to fulfill human comfort needs in the desert climate. The houses are made of sun-dried mud-brick, with a mud and straw mortar and the top and bottom floors are plastered with lime and straw plaster to protect the mud-bricks from rain. Other ways of protecting the buildings from water include tilting streets away from the buildings and having stone foundations. (Lewcock, 1986)

Photo: UNESCO

The Musgum Mud Huts in Cameroon is another example of earth construction. The shape of the houses allow for the buildings to stand for a maximum load with a minimal use of material. At the top of the 9 meters tall houses is a hole for ventilation purposes. Mud is used in combination with reeds to create the structure. One of the reasons for the complex geometry in the facade is as footsteps in construction and maintenance of the building. (Zilliacus,2017)

Photo: Carsten ten Brink (2010)

The old town of Ouarzazate, Morocco consists of buildings made of rammed earth. In this way of construction damp earth is compressed in layers in a form-work which is later removed. (Michon, 1987)

Photo: J Duval (2009)

Clay as a building material

There are many advantages in using clay as a building material most notably because it is a natural and sustainable material. It offers low energy consumption during the entire life-cycle of construction, use and demolition (Hall, Lindsay, Krayenhoff, 2012). Buildings made of clay are biodegradable. When they are no longer used they don't leave ruins, the material can be reused in a new building or simply go back to the earth it was dug up from. Earth and clay to use in construction can be found all over the world. This reduces the cost and environmental impact of transportation.The material itself is usually cheap and depending on the price of manual labor construction can also be inexpensive and fast. Walls made of clay have a high thermal mass which makes the indoor environment less susceptible to temperature variations. The walls stores heat from the sun during the day and releases it when it is colder during night. The material also creates a healthy indoor environment by regulating humidity in the air and by performing acoustically well. Earth constructions are low maintenance and durable. They work as fire barriers and can improve seismic stability. Most of the advantages of earth constructions are viable in both arid and cold climates and in both developed and developing parts of the world. (Hall et. al, 2012)

Earth construction in various parts of the world

In developed parts of the world the building industry is highly industrialized. Materials are often processed, mass-produced and uniform. Earth constructions are appreciated because of their beauty and simpleness. In developed countries earth constructions come with a high labor cost and are thus quite luxurious. A challenge is to be able to technically improve construction while keeping the positive aspects regarding sustainability and aesthetics(Hall, Lindsay, Krayenhoff, 2012).

In developing parts of the world earth construction has often been the cheap way of building because of availability of material and because manual labor is cheap. Buildings consisting of concrete, steel and glass are considered modern and something to aspire to. The old traditionally built towns are in many places abandoned in favor of air conditioned high-rises (Girardet, 2015). An aspect to consider when building in developing countries is the possibility to increase the status of earth construction. So that it can be viewed as new and as something desirable for a growing middle-class.

3D printing

Much of this project revolves around learning how to 3D print and use it in an architectural process. It is important to note that there are different kinds of 3D printers that work in very different ways. Each variety has its own advantages and limitations. The experiments for this project has been done using FDM (Fused Deposition Modeling) printing with clay. The findings will thus only apply for this type of 3D printing.

There are currently nine basic types of 3D printers: FDM, SLA, DLP, SLS, SLM, EBM, LOM, BJ and MJ. (Locker, 2017)

They can be further grouped into four types:

Powder based

A layer of powder is added to a print chamber. Parts of the powder is sintered or melted with a laser, electrons or a binding agent depending on the type of printer. A new layer of powder is added and the process is repeated. When finished the entire chamber is filled with powder and the part that make up the model is solid and the rest of the powder is loose.

Fused deposition modeling

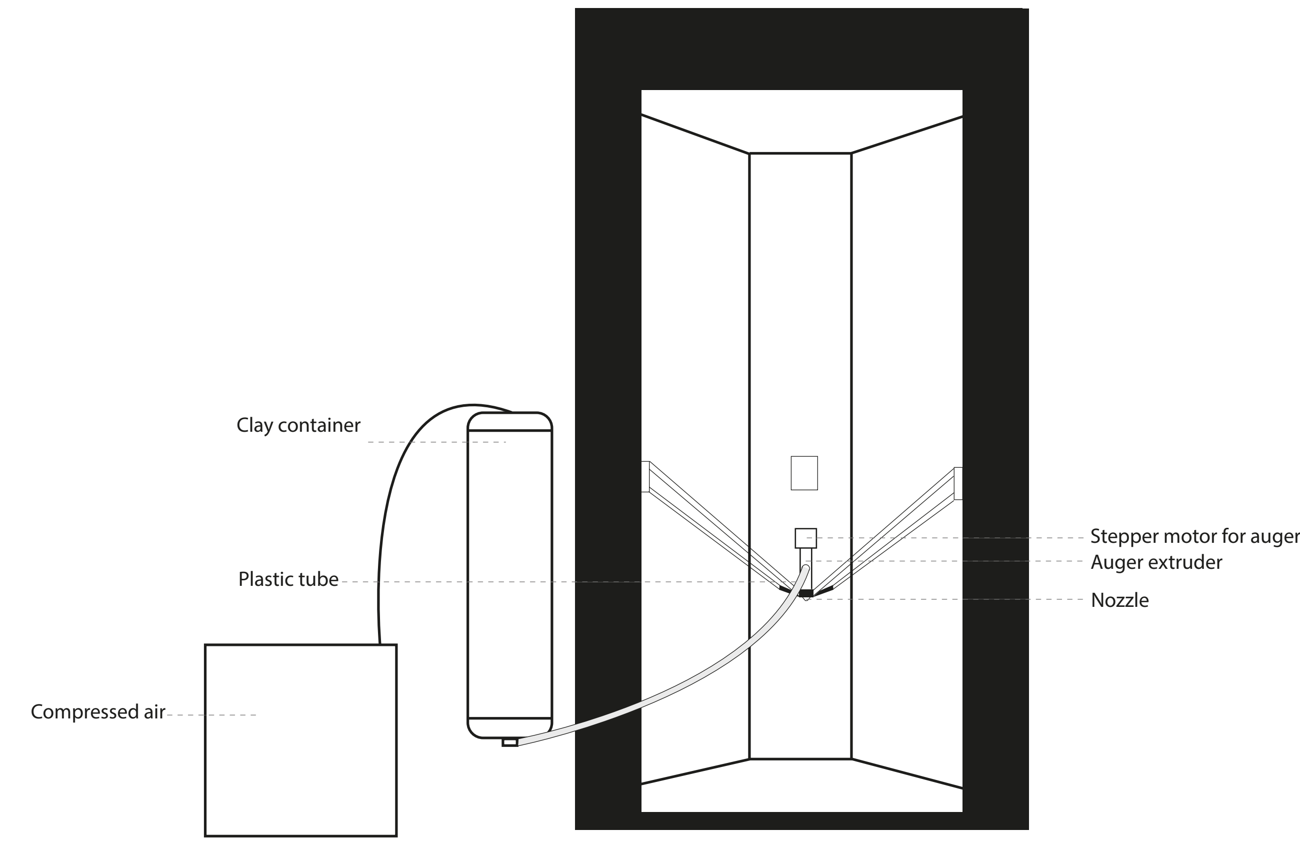
The material, most commonly a plastic filament, is heated and extruded through a nozzle. The material is deposited as a string and built layer by layer from bottom up.

Resin based

A light sensitive resin is used which solidifies when exposed to light. The model is built layer by layer and as each layer solidifies the model is lifted, one layer height, from the resin bath.

Laminated object manufacturing

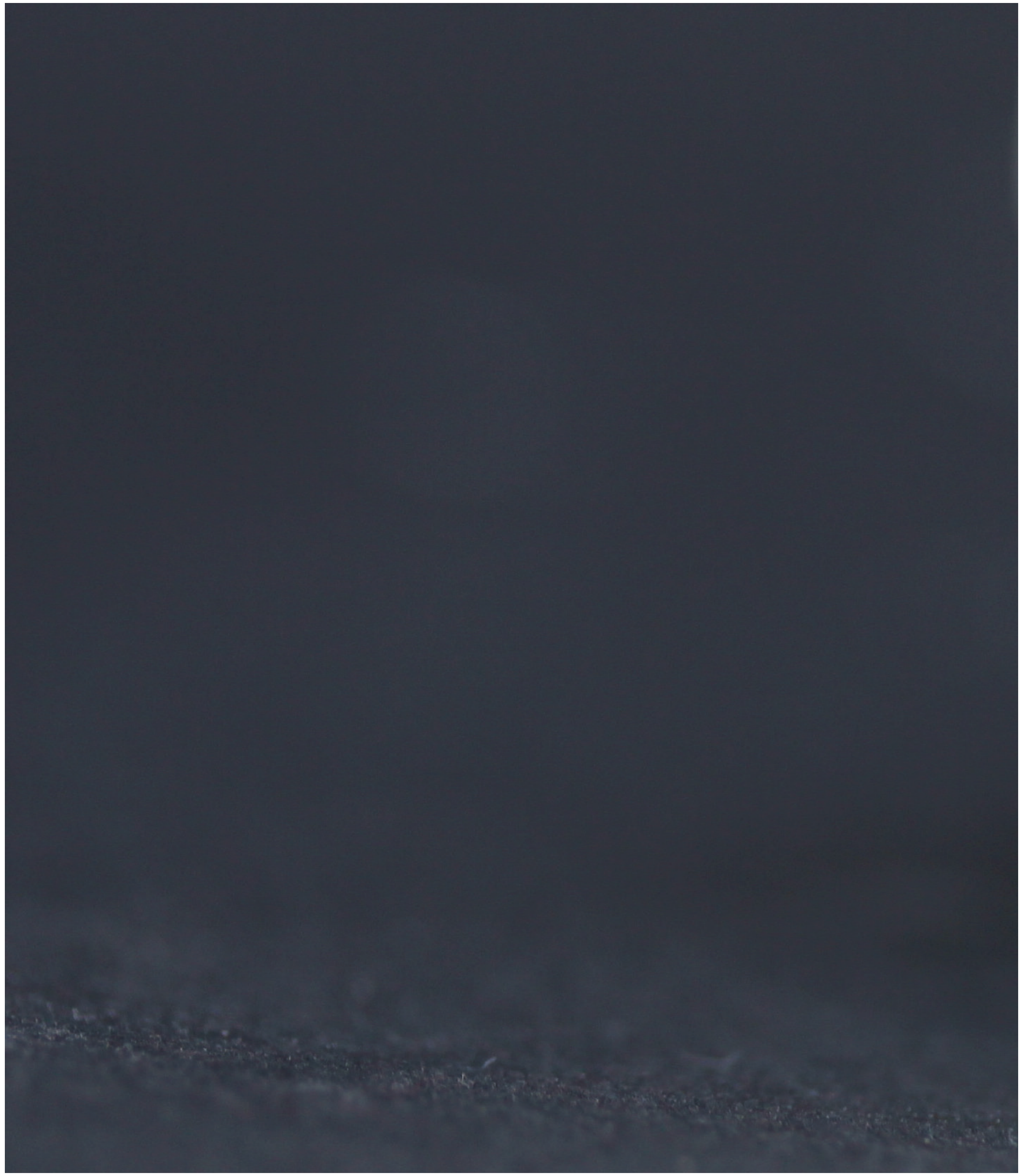
In this way of manufacturing sheets of paper, plastics or metal are heated and pressurized together. Each layer is cut with a knife or a laser to acquire the final shape.



Fused deposition modeling with clay

Work flow fused deposition modeling

Design CAD model → Export stl. file → Set settings in slicer program → Model is sliced into layers and a tool path is generated for the printer → Generate G-code for the printer to read → Print G-code



Results

The results consists of more than two hundred 3D printed models and of the acquired learning from printing them. The results are divided into 8 parts. Each part is an experiment with an objective, questions and findings. Each experiment is building on knowledge from the previous findings. The experiments are made with the intent of examining the physical nature of clay and how it is fabricated with a 3D printer.

The end product of this thesis is not a building or an installation or an object. I see the end result as an approach. An approach to a design process where iterations of physical models are impacting the final shape of the design. Both when the physical models are developed in accordance with the construction process but also when they are intentionally going against it, using the machine to create with an element of chance. The iterative process is to inform the end result, changing the result according to findings instead of testing and altering to create an already defined goal.

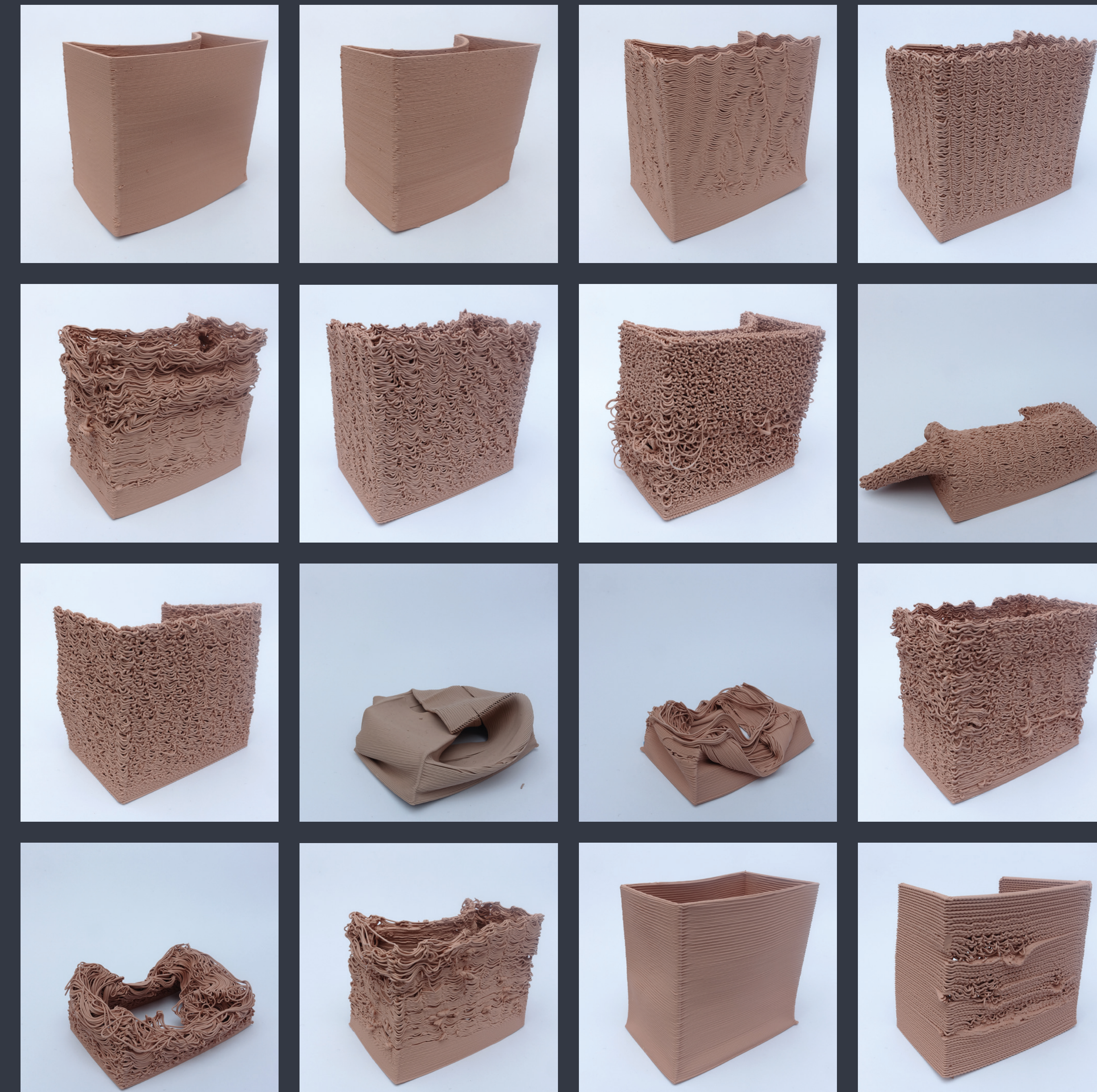
The overarching question which I am trying to answer is "What are the benefits of using digitally fabricated physical models as a complement to computer generated models in a design process?"

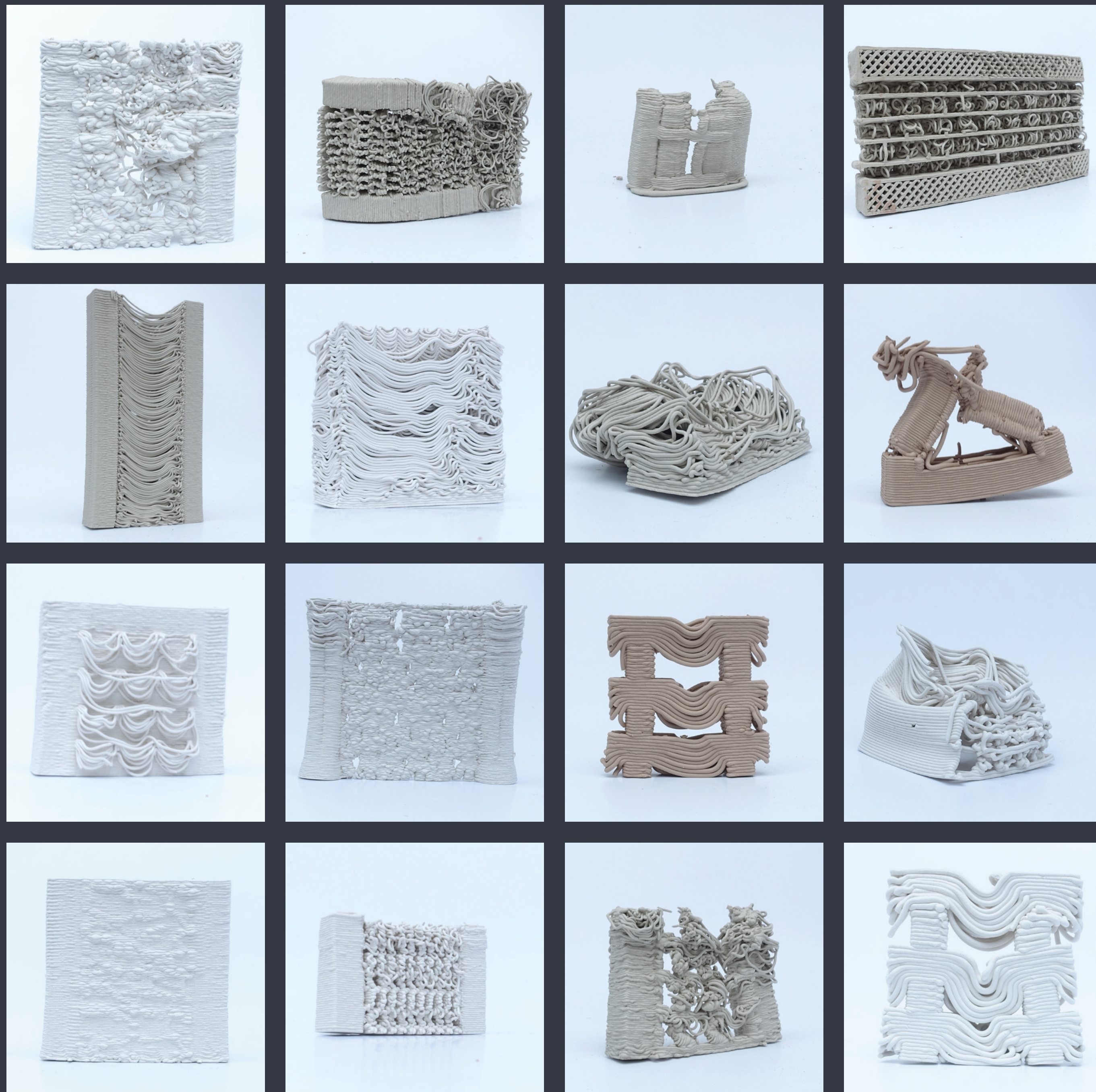
Many of the findings speak of the benefits. First of all this project could not have happened without physical models as it was the models that shaped the process. One positive aspect derived from seeing the models in a real three dimensional sphere and not in a made up reality in a computer program. This was a gain when deciding on a shape and when it came to more intuitive aspects of understanding how one will experience a space.

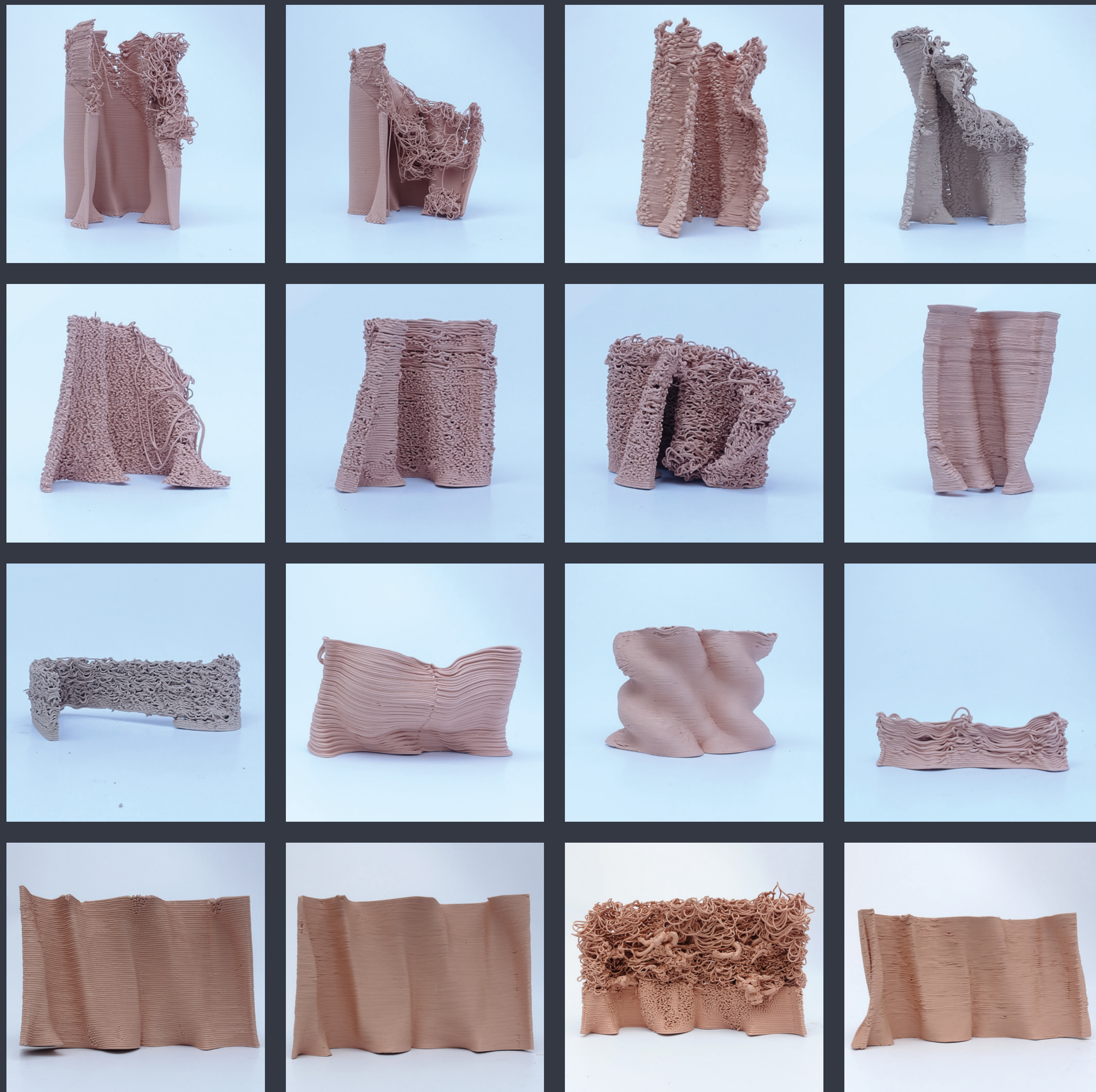
A possibility with physical models was as a driver for a project. The project started quite loose with no set program but the physical models quickly opened up for a range of ideas. Including new angles and ideas which I would otherwise probably not have thought of.

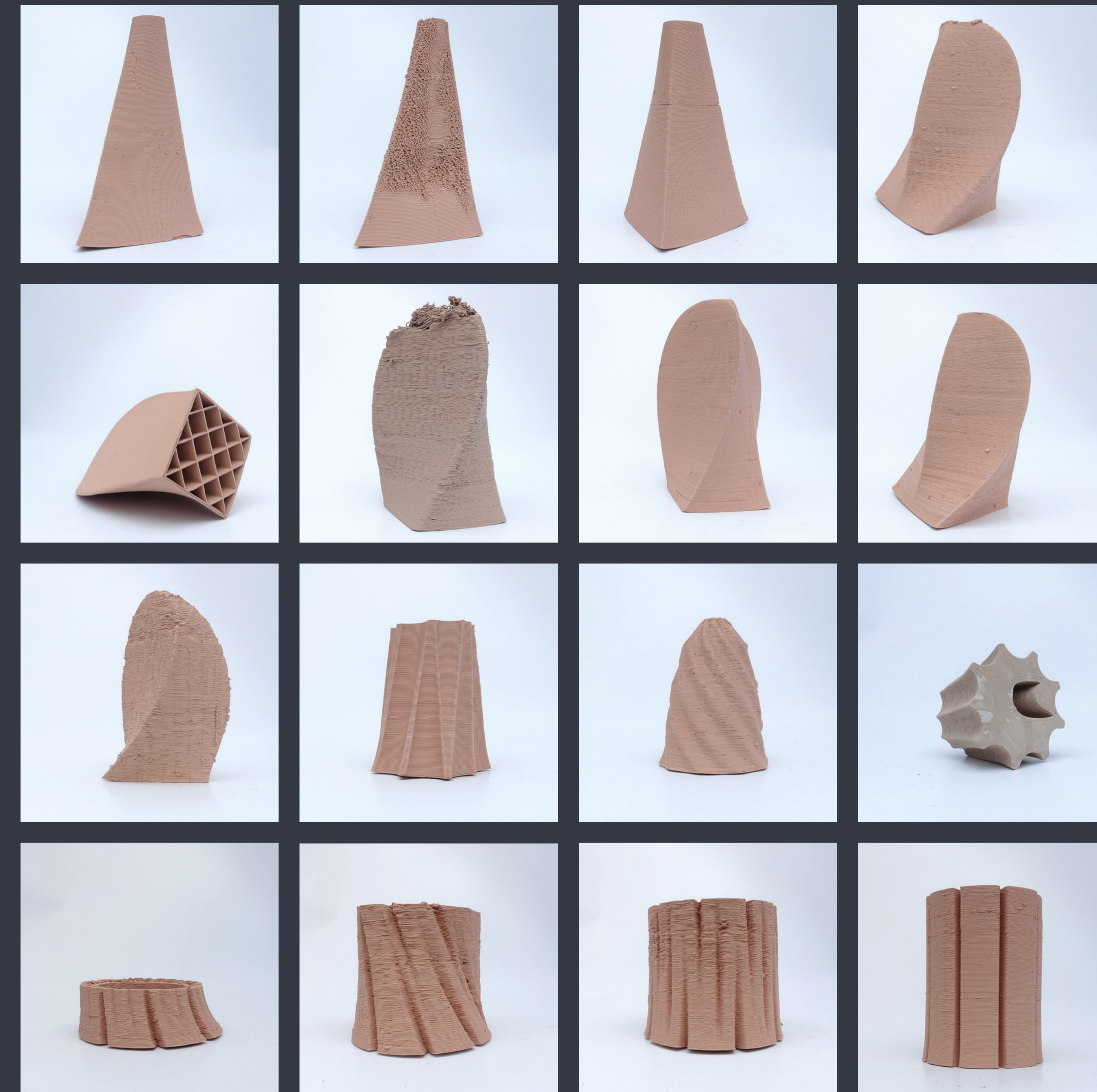
The most prominent benefit of the physical models lie in their very physicality. Their responsiveness to the environment is the major difference from the computer model. The way a beam cannot hang in midair, the way corners might collapse and the way small disturbances can create something different with the models. The tactility connected with the models is also something that cannot be translated in a computer but can be essential in a building. The physical properties of the material printed will innately affect the print adding a greater complexity to a model. When creating 1:1 prototypes one can experience the nature of the material. In scale models the material and its properties might be less directly translated but still has advantages of being alterable. It will change with time, it can have different consistency and stability and the material used will affect the model physically.

Another valuable part of using physical models is related to construction. The construction process became important in the design process because of the physical models. Instead of designing something and then trying to make it work with a construction process the construction will be incorporated early. The specifics of this type of manufacturing, its distinctive lines and small irregularities showed an appealing contrast in the printed models compared to the computer models. The construction does not need to be hidden and made to look like something else, there are performative and aesthetic qualities in the details that can be highlighted and used in an ornamental or functional way. In order to design with this in mind testing in the real world with real forces acting on the model is essential.













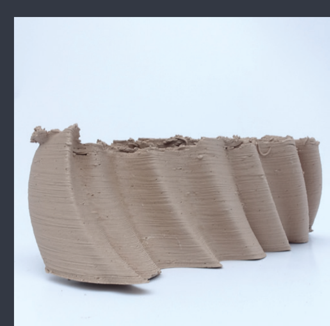
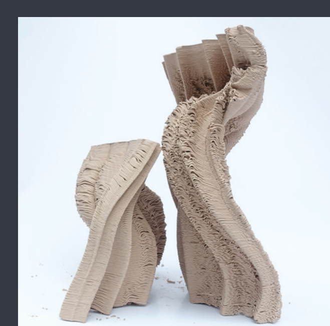


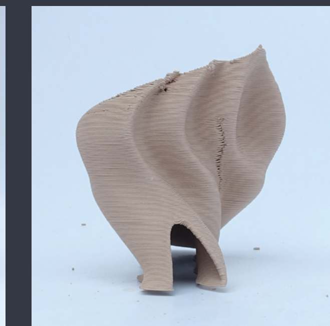






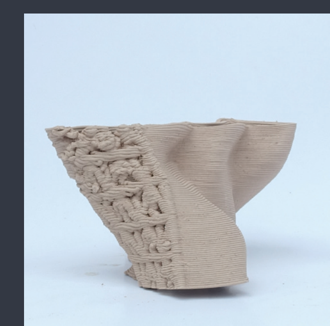


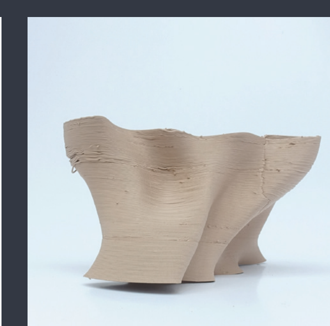



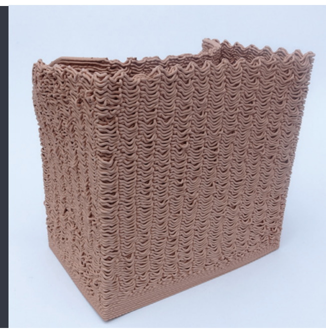


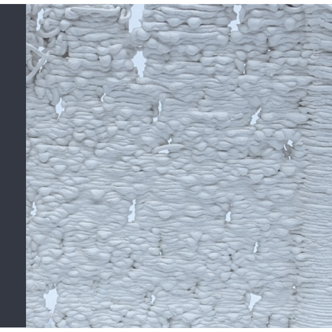
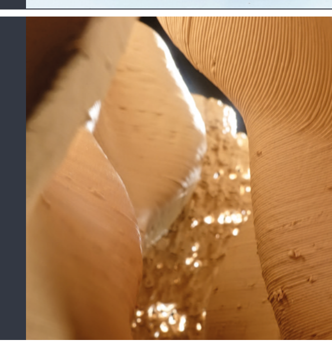






Part		Objective	Findings
1		To learn how to print a good print.	An interest in construction technique.
2		To be able to control the unexpected in the prints.	Models can be manipulated in construction phase.
3		To find out in what way different shapes affects the print.	Different shapes printed with the same printer settings have different outcomes. Curved walls print more stable than right angled corners.
4		To look at stability and internal structure in walls and models	Ways to create stability through infill, shell thickness, interlocking walls and curved walls.

Part		Objective	Findings
5		To design models that allow for unpredictability.	By allowing gravity to affect the print the physical model becomes something different from the computer model.
6		To try different versions of exported models and slicer settings.	Exporting surfaces instead of offset models is sometimes beneficial.
7		To design an enclosed sheltered space.	Printing curved walls open up for other kinds of shelter than a typical pitched roof.
8		To combine findings in an architectural model.	A set scale provided an opportunity to appreciate the bodily experience of architecture.

Part 1

The experiments are made with the intent of examining the physical nature of clay and how it is fabricated with a 3D printer. In my first tests I wanted results that were consistent with the computer model.

Questions
How do I print a good print?

What is the correct speed, layer height, flow rate, ceramic mixture, air compression and foundation material?

What kind of geometries can be printed, how much tilting, overhang and how thin can I print?

What are the benefits of the print? Does something advantageous happen in the transformation from virtual to physical reality?

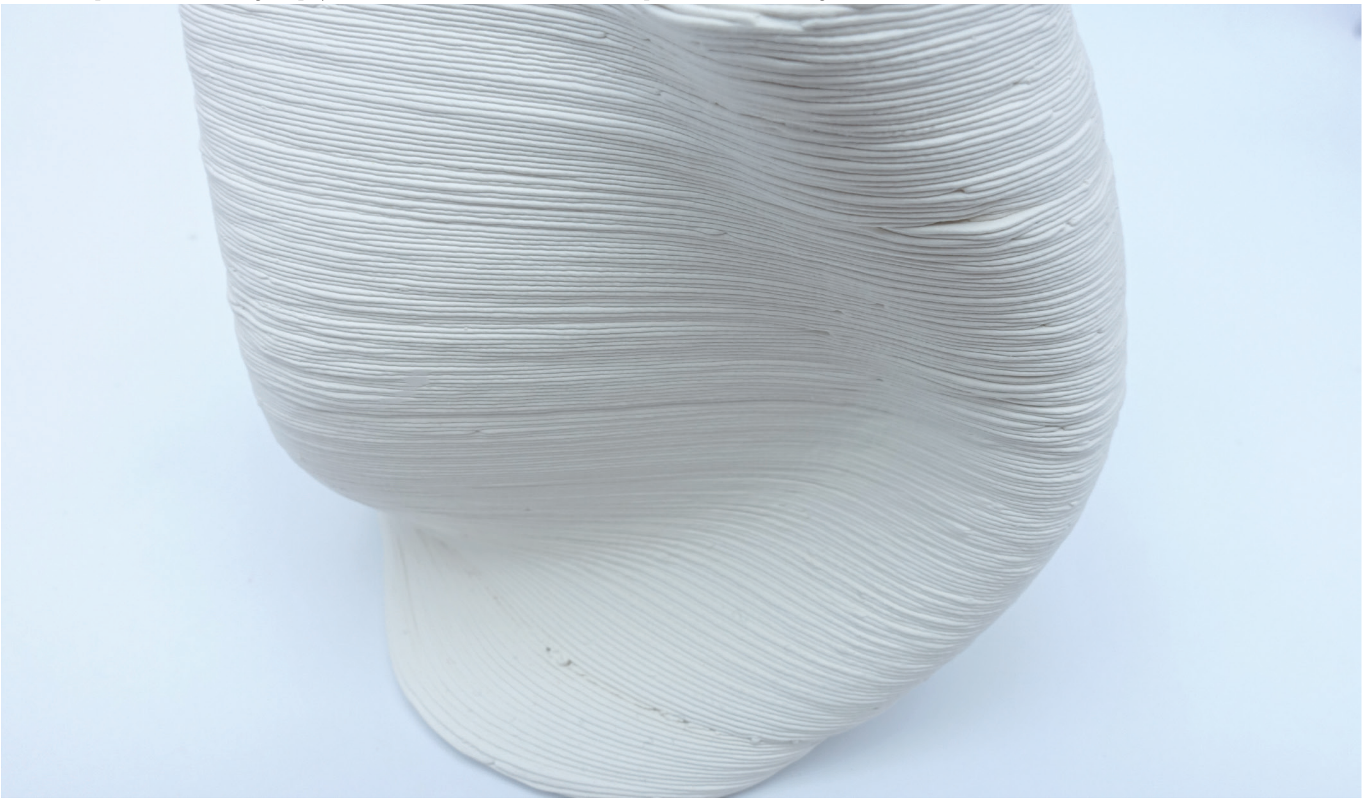
The first question is very broad but it was important to start there. To learn how to get the printer to print with a decent result. Printing with clay is different from printing with plastic. Plastics such as ABS or PLA quickly transforms from solid, to fluent when heated, and then solid again in room temperature during the print. The clay is different, it is added to the printer fluent and it is printed in a fluent state and then it dries slowly until it is stable. For maximum rigidity it needs to be fired in a kiln at about a 1000 degrees C. The natural material is not as easily controlled as plastics.

The clay mixture consistency caused a lot of trouble. More problems than anticipated would come from the clay being just a little too soft or too rigid. Speed, layer height, air pressure rate and more were also changed until it could print a model that resembled the computer model that generated the g-code.

The kind of geometries that can be printed depend a lot on the exact mixture of the clay and on the settings of the printer. Because of this no conclusive facts could be drawn about the limits of the printed objects regarding thickness or overhang. Even so the experiments were informative and showed a range of objects that could be printed as well as what happened when they could not print properly.

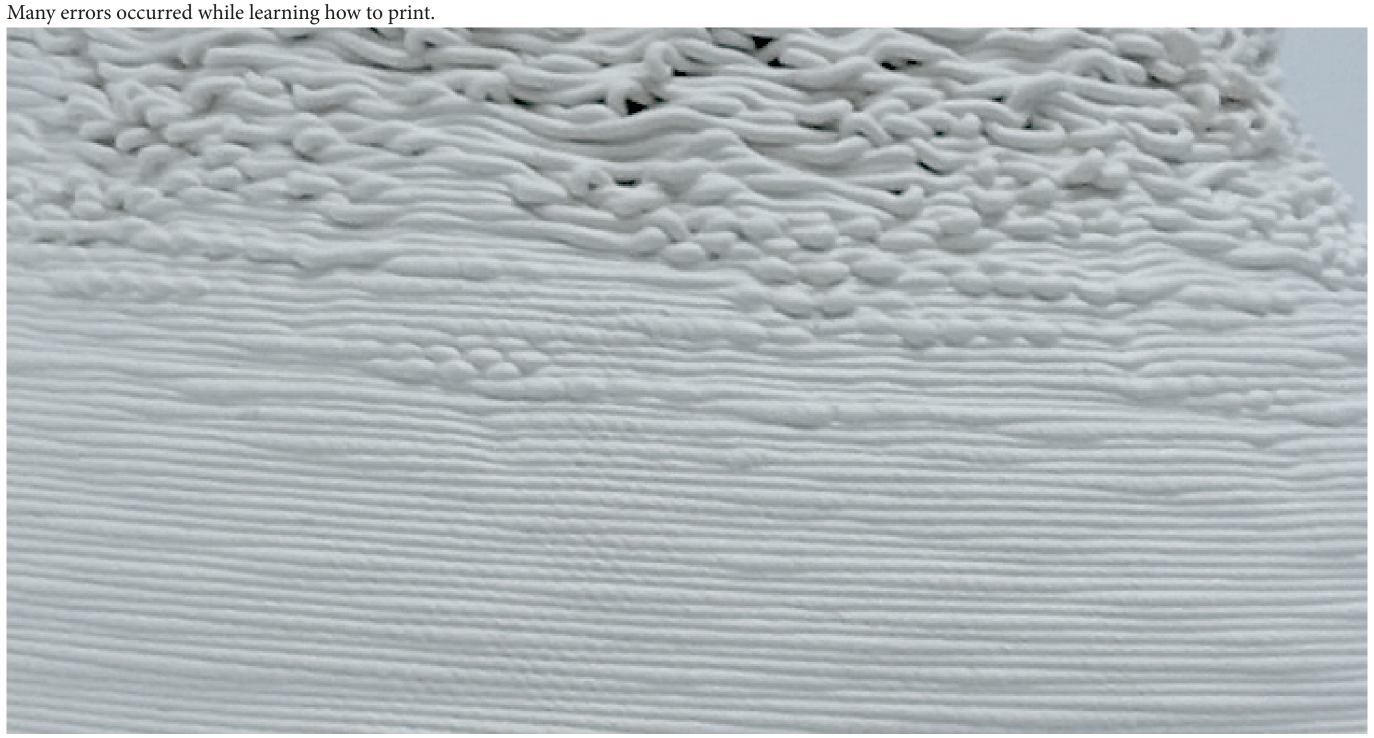
At this point what revealed itself as most interesting with the prints was the layering of each level of clay and the structure it produced. The display of the construction was an engaging contrast in the models when they were printed compared to only existing in the computer. Especially interesting were the accidents that happened when the settings were incorrect. The clay would behave in a diverse way from the original material. By the construction method of additive printing the clay would look more like a fabric. Light, airy and textured. This time the feature happened as an error but it sparked the ambition to learn how to control it.

In the first prints I was striving for physical models that looked like the computer models which generated them.



The visible lines from the construction process contribute with an ornamental quality.


Many errors occurred while learning how to print.


The question of what constitutes as an error was inspirational.


This generated an idea to be able to control the erratic behavior of the print.

Part 2

If the first number of experiments centered around creating a print that looked like the computer model the next set of experiments evolved around creating something that looked nothing like it.

Questions
Can I manipulate the printer in order to create different outcomes from the models?

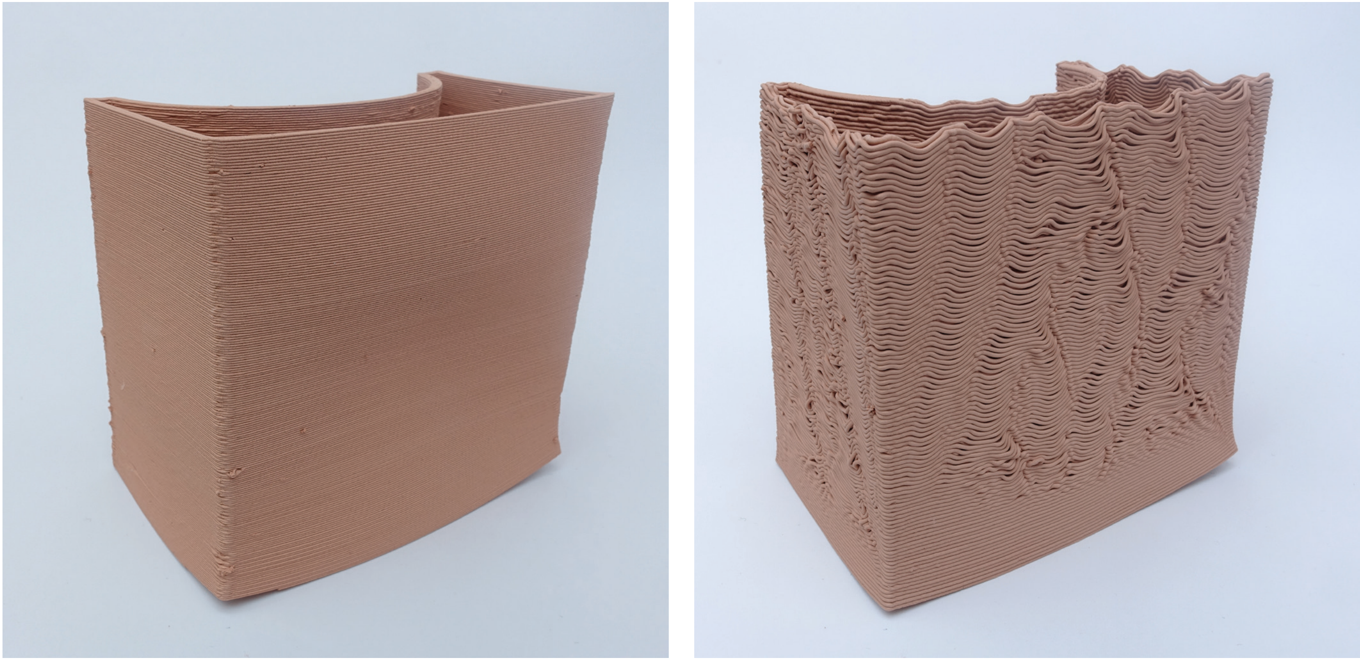
Can I use the construction as a part of the design process?

What are the benefits of these prints? Structurally, aesthetically or in other way.

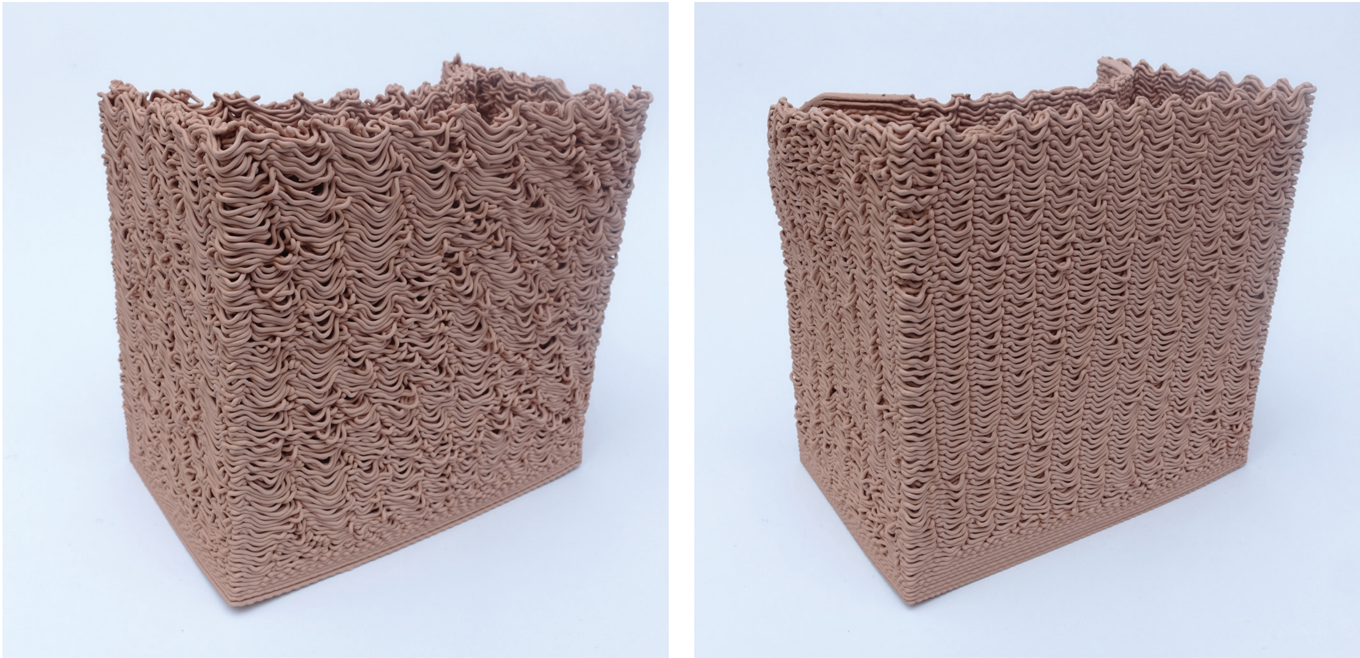
When trying to manipulate the printer knowledge about how it works and how different settings affect the print was gathered. By using a test model consisting of one simple shape and by changing the settings in the slicer program a lot of different outcomes could be generated. The construction method is used to further develop the model, making the printed model something different than a replica of the computer model.

One of the more interesting factors to change in the printer settings was the layer height. The layer height affects how much the extruder will move upwards in each layer. This will affect the thickness of each layer and how much it is pressed against the previous layer. Other settings such as flow rate can also affect the outcome of this. The optimal layer height is mainly dependent on the size of the nozzle, since it is the size of the nozzle which determines how much material will be extruded. For a smooth print the layer height should usually be around ½ of the nozzle size. Smaller layer height will press the material more into the previous layer. With a high layer height the nozzle will be printing in thin air rather than onto the previous layer. This can be seen in the models with a layer height of 0.8 or more. The loose positioning of the clay causes gaps to appear in the models and creates light permeable, textured models. The textures created can be seen as complex and elaborate but their appearance follow a logic as they are only affected by the layer height, gravity, movement and the material.

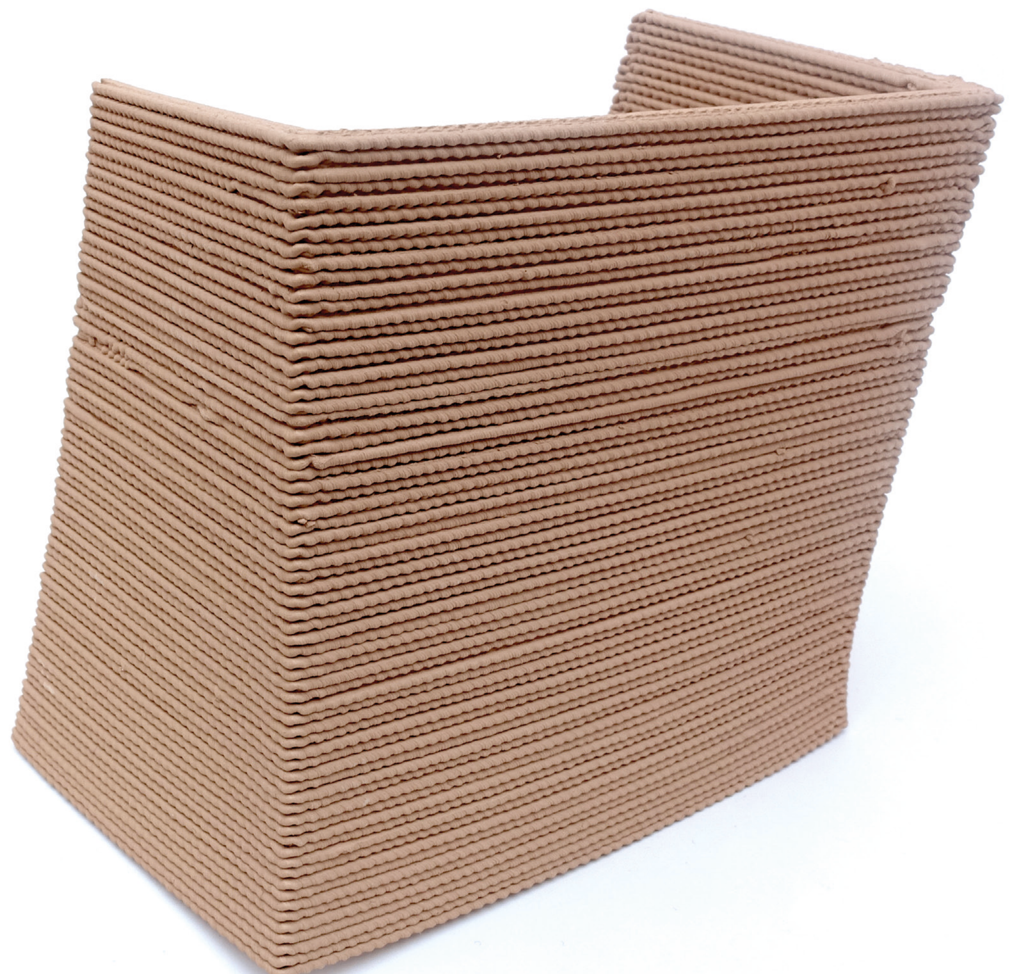
For this part of the explorative research mainly one basic model was used in order to see how the settings changed to model. The shape of it could have been a simple rectangle but a curved wall was added in one side in order to see if there was a difference between the straight walls and the curved walls. From the prints I could see a clear difference between the two walls. The effect geometry has on the print became more evident when I tried to print my test model without the curvature wall. It printed a lot more smooth than expected.



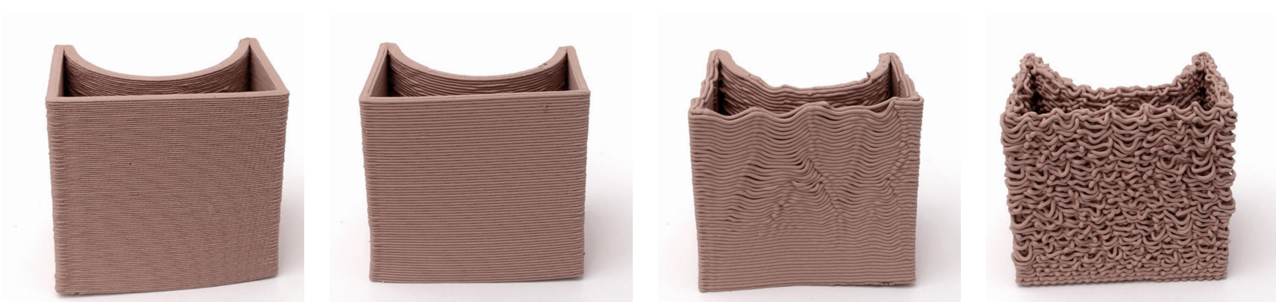
By changing the layer height from 0.4 mm in the left picture to 0.8 mm in the right picture the walls change character and become light permeable.



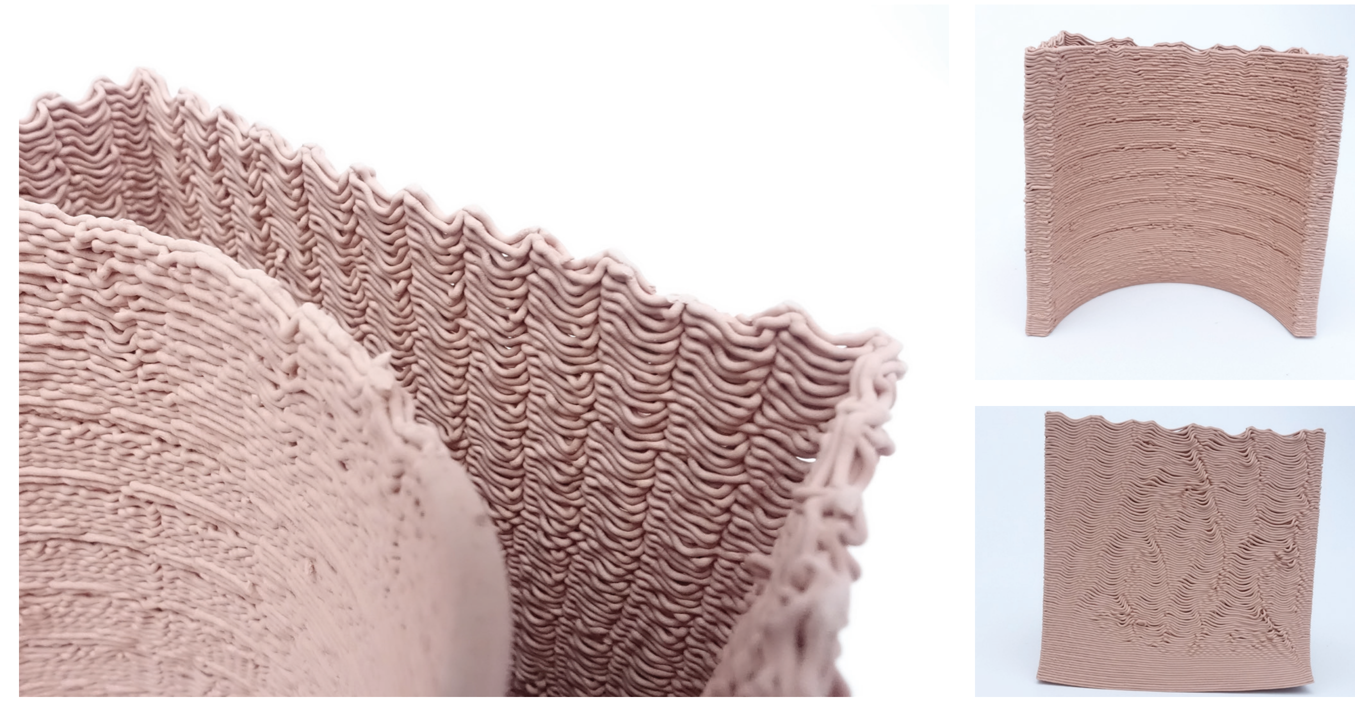
The two models have the same layer height of 1 mm but the left model has a thicker wall which is changing the character of the print.



When printing the same model but without the curved wall the print is smooth even with a layer height of 1.2mm.

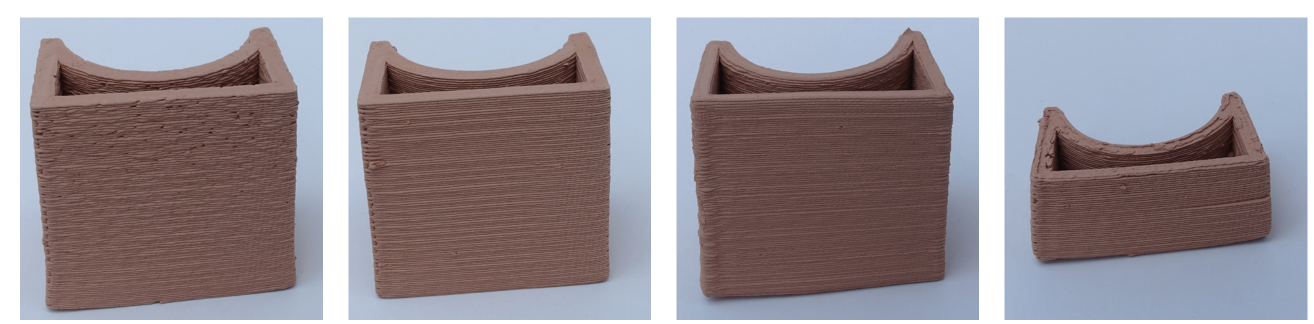


Layer height 0.4 mm, 0.6 mm, 0.8 mm, 1.2 mm in a smaller version of the model.



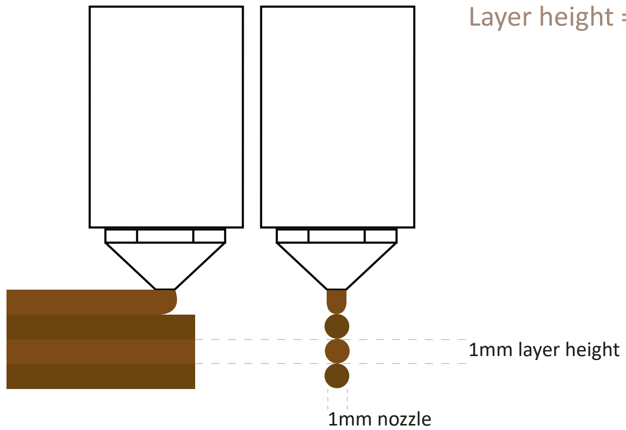
The curved wall is not affected in the same way as the other walls by the layer height change.

Changing the layer height affects different models differently. Here are layer height 0.4 mm, 0.8 mm, 1 mm.



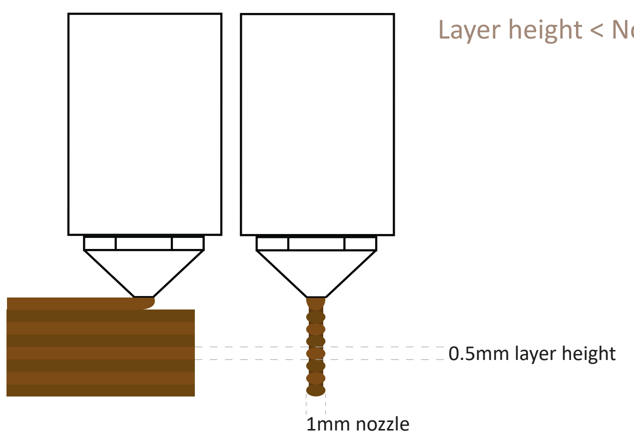
Not all setting changes made big impacts. In model 2 the air pressure is higher and in number 3 the flow rate is increased, in number 4 the z max is changed.

Layer height = Nozzle diameter



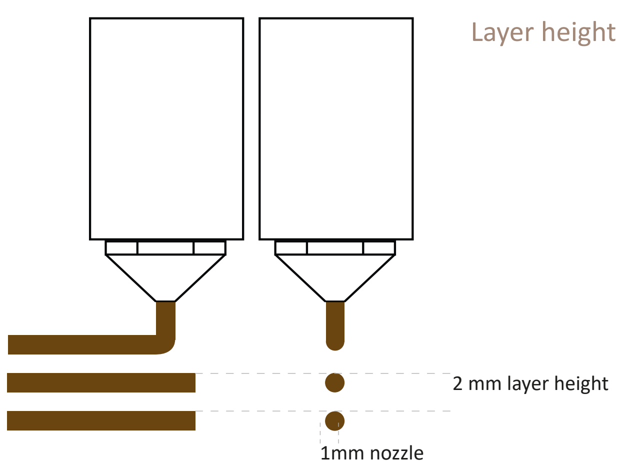
Each layer is placed directly on top of the other.

Layer height < Nozzle diameter



Each layer is compressed into the previous layer creating a strong bond.

Layer height > Nozzle diameter



The nozzle is printing in thin air above the previous layer.

Part 3

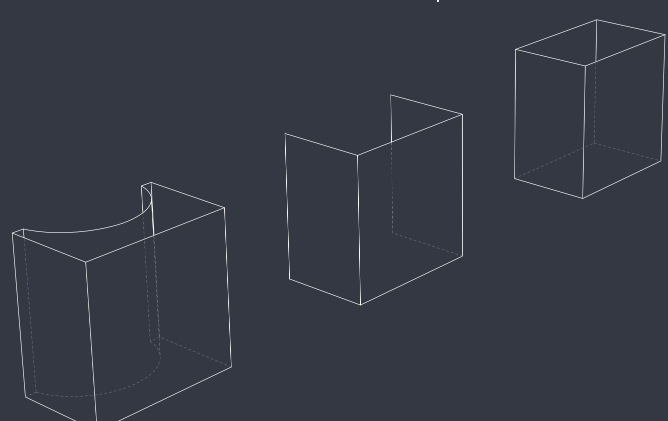
The way different geometry of the model changes the effect of the printer settings interested me and became the basis for my next set of experiments.

Questions
In what way does different geometry affect the print?

Are there shapes that work better than others when printed?

The experiments show that differently shaped models printed with the same printer settings will yield diverse results in the print quality. This can be traced back to the construction method. The printer extrudes clay, sort of like a string, and that string is then supposed to fixate itself onto the other similar lines already printed. How well the clay will manage to do this is dependent on the model, the movement of the printer, the clay mixture, the air pressure, the layer height and the print speed.

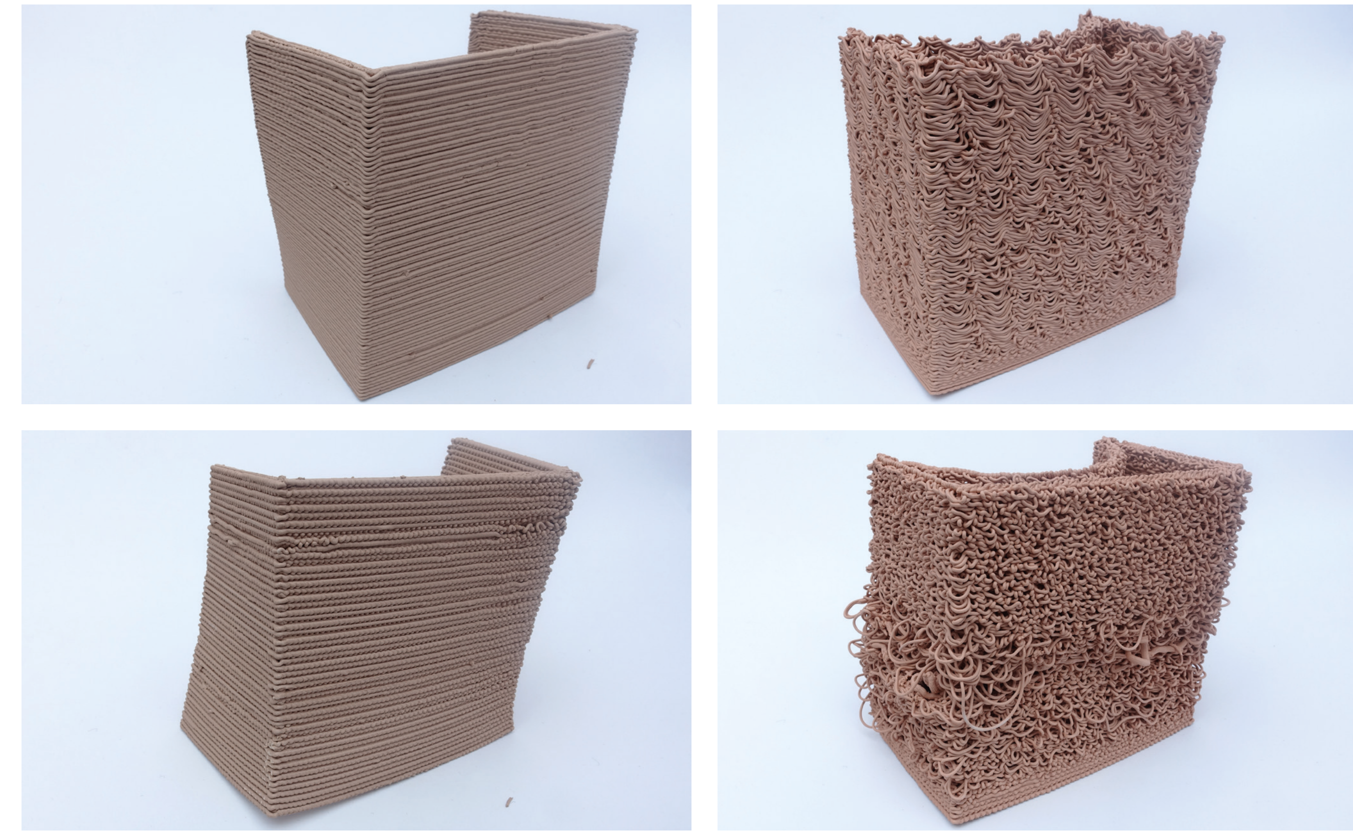
In the rectangular models it can be seen that the problem with clay not attaching is most prominent in sharp corners. If the clay fails to fasten to the underlying layer in that exact spot the abrupt change in direction, which happens in a corner, will cause more problems. This makes the corners the weakest part of the model.



The three models.

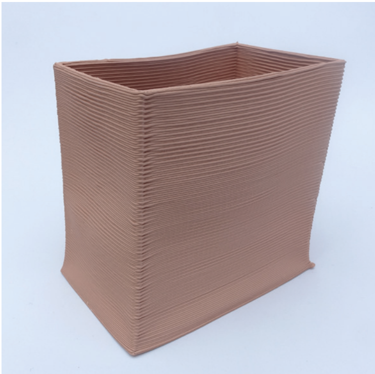
The print speed affect the possibilities of the clay to set to the underlying layer. With a lower print speed the clay will set better and if it misses a point the stray piece of clay will not travel as far before it sets in another place. This is most prominent in the rectangular prints which collapses at too high speed. In the curvature models, which prints better, there is less difference. Curvature models can be printed with a higher print speed while maintaining print quality.

The way of construction differs substantially from ordinary construction methods and the fact that corners are weak and curves can be printed faster changes the way one might usually think about designing walls.



Same settings different outcomes. The two top models have a layer height of 1 mm and the two bottom models have layer height 1.6 mm. They are printed at the same speed. The wall thickness is 3 mm.

Print speed also affect the print. The right model is printed at double speed from the left model.



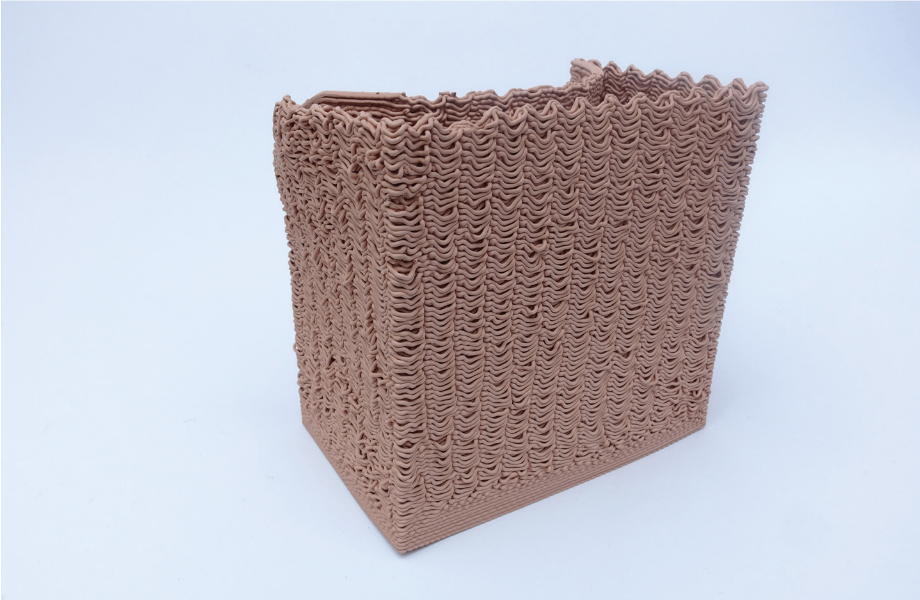

The four cornered model is printed at 100% speed, 200% speed and 300% speed. The collapse happens in the corners.

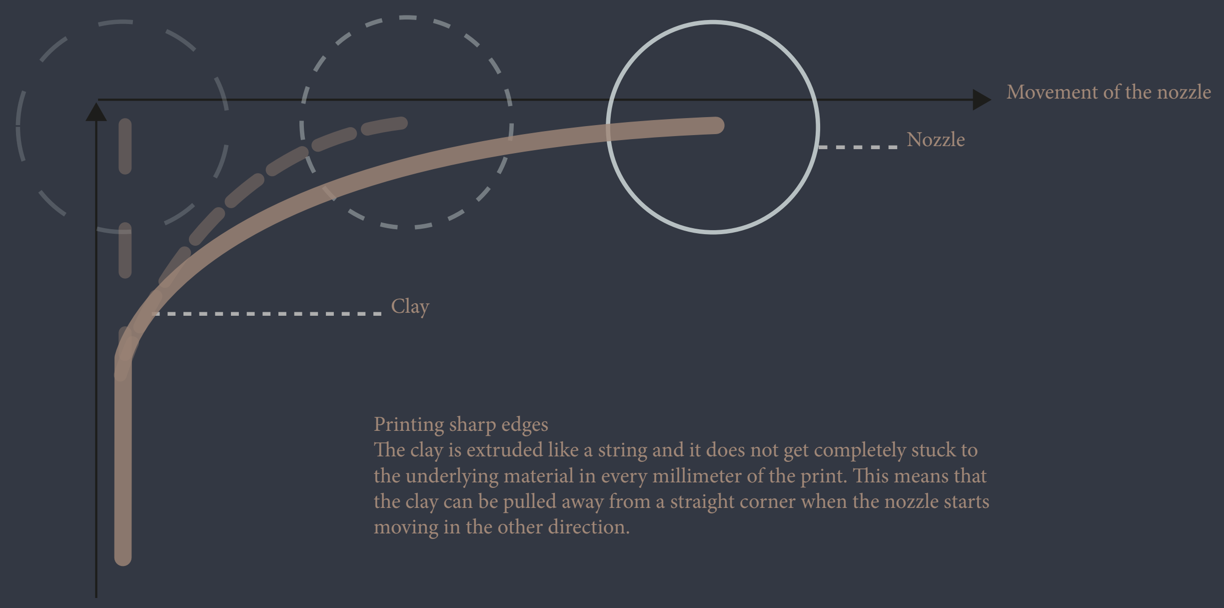


The right model is printed at 250% of the speed of the left model and little difference can be seen between the two.


In the four cornered model 0.8 mm layer height and a slower printing speed is creating a pattern similar to 1 mm layer height in the model with a curved wall.




The same speed and a layer height of 1 mm in the three different models with a wall thickness of 1.5 mm.



Printing sharp edges
The clay is extruded like a string and it does not get completely stuck to the underlying material in every millimeter of the print. This means that the clay can be pulled away from a straight corner when the nozzle starts moving in the other direction.

Part 4

The collapsed corners in the previous set of experiments created an interest to look into stability and structure more.

Questions
How can I create stable walls and internal structure?

How can I combine stability with the printer settings from previous tests?

In the previous experiments surface rather than structure was highlighted. The models printed here created an opportunity to find out more about infill, shell thickness and interlocking walls.

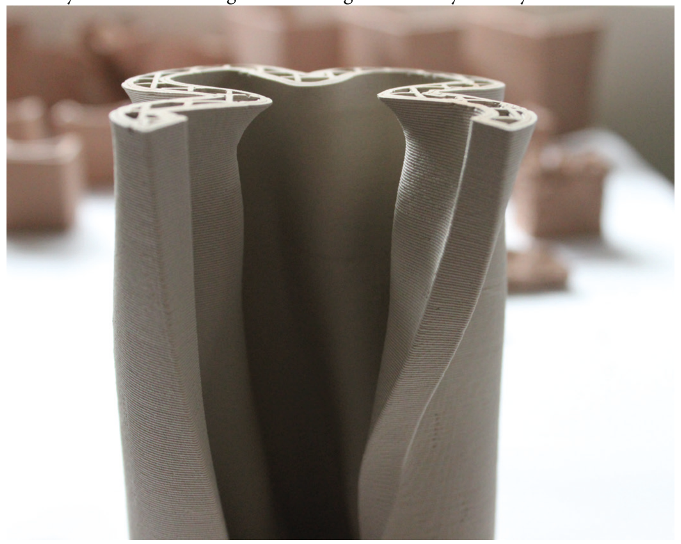
One way to produce the infill is through an automatic infill in the settings of the slicer program. The infill can be produced in solid models or in models with a wall thickness. The percentage of infill is decided in the program depending on how light or rigid model one desires. Different slicer programs also have different infill patterns, from a grid pattern to more elaborate hilbert curves for example. Another way is to design the infill manually in the computer program where the model is designed. The infill can then be added only where it is most needed. Interlocking walls and symmetry were also used as a way to create stability in models.

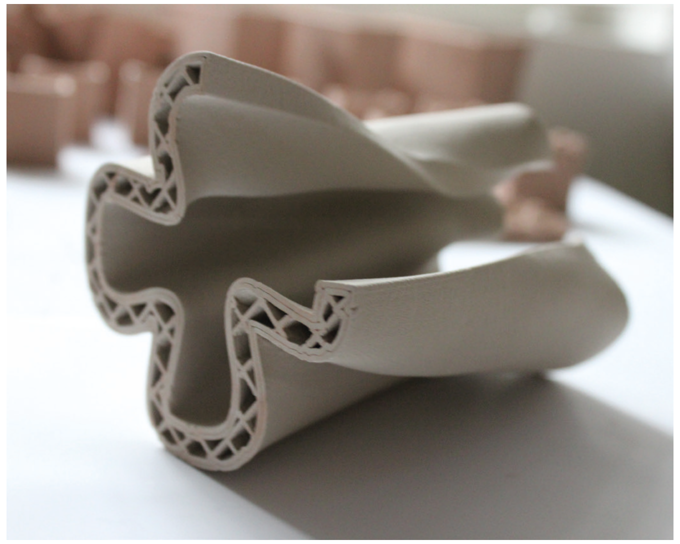
Using infill in a model is one of the advantages that 3D printing has compared to many other construction techniques. It would often be impossible to create by hand or with conventional manufacturing. The infill can create light weight models, using a small amount of material, while still creating stability. It also changes the thermal properties of the wall by allowing it to consist of a large amount of air. This is something which can be beneficial in small scale structures such as a brick but also in the walls of completely 3D printed houses.

The stability of the model also relates to shell thickness. The shell thickness is the outer layer of the model. If the nozzle diameter is 1mm and the shell thickness is 1mm the outer layer containing the infill consists of just one string of clay. By changing the shell thickness more stable models could be created.

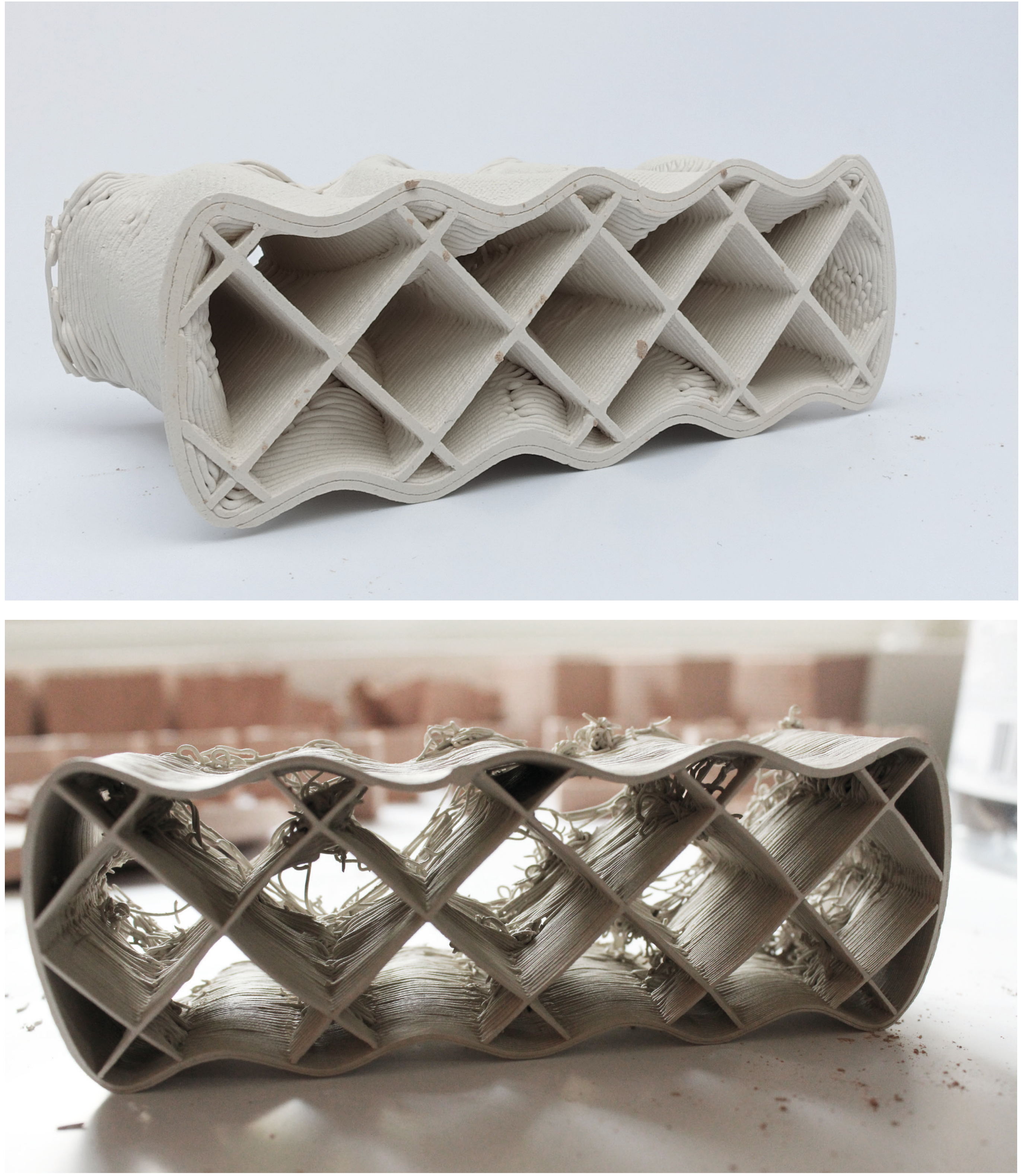
The models created showcased ways to create stability in the walls. The second question in this experiment regarded how to combine stability with the printer setting changes in previous tests. Trials in this aspect were not successful. No answer was found as how to combine the two ideas in one print. The main problem would be the slicer program. A more advanced slicer program or more knowledge about generating g-code could be a way to combine stability and erratic by having more control over how each part is printed.

Stability is obtained through intersecting walls and symmetry.



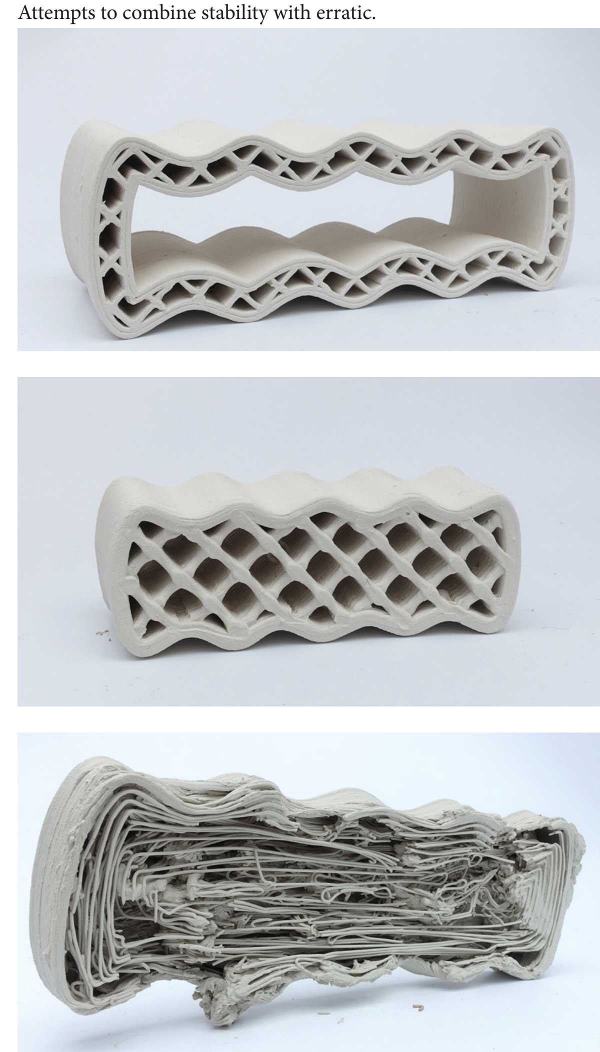


The curved continuous surface, the infill and the two millimeter shell thickness is what creates stability in this model.



The model in the top picture have a 2 mm shell thickness and the bottom model have 1 mm shell thickness.

Attempts to combine stability with erratic.



Different infill structures.

Stability can also be obtained through a double curvature wall.

Part 5

Previous inability to be able to combine structure with the irregular results from changing the printer settings made me want to look into other ways of creating something related.

Questions
How can I design models that allow unpredictability?

How can I combine the unpredictability with stable parts?

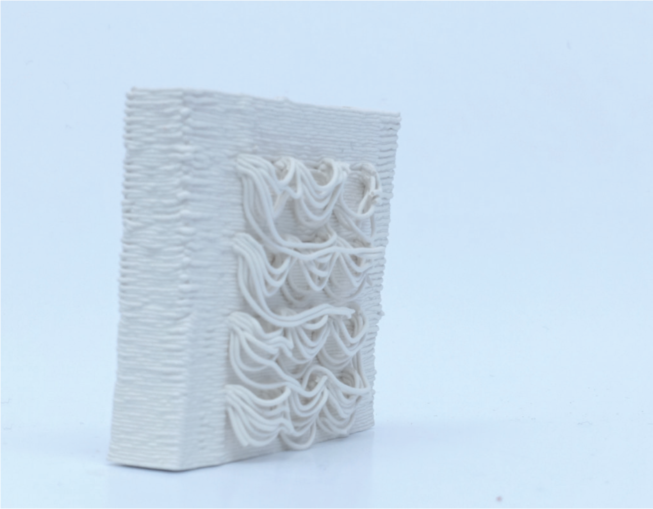
Striving to create models similar to those with changes in the printer settings the investigation started by designing models with the same logic as them. Their irregularities were often created by the extruder printing above the print, extruding in thin air rather than onto the previous clay. The idea was to mimic this by making models with thin layers and air gaps in between. With lots of trials they still did not look alike because they are not printed the same way. But the main idea is comparable. The notion of purposefully interfering with the way the printer prints in order to achieve something different from the computer model.

By altering the model in different ways a variety of outcomes could be achieved. Thin strings of clay with contrasting qualities from massive clay is one example. Intricate models where gravity is forcing bulging pieces of clay downwards creates something completely different.

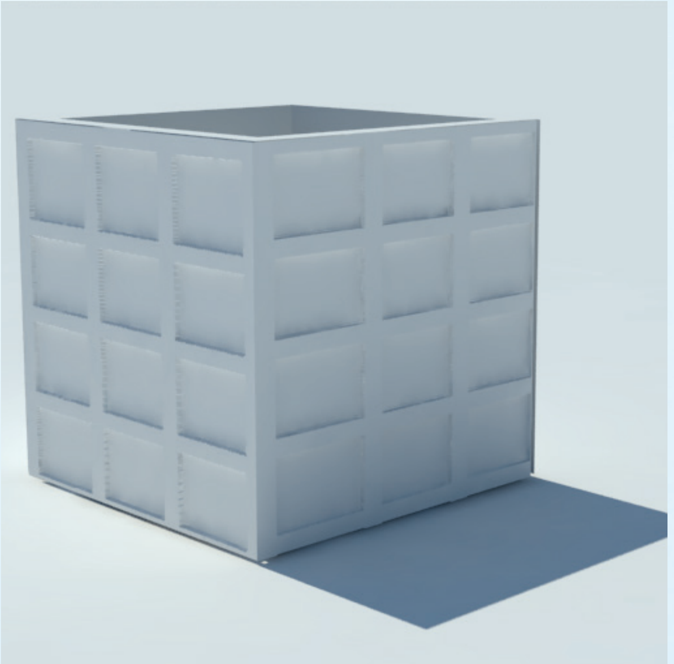
The alterations created in the modeling software can affect different walls in different ways. In this way stable structures can support the less stable parts and create an interplay between one another.

Similar to previous tests the computer model looks unalike the print. By bringing the model into reality with gravity, materiality and all that it encompasses the ideal model in the computer program is discarded. In the modeling software the model looks adequate, it can hold together, but when faced with reality all the perfect straight edges disappear.

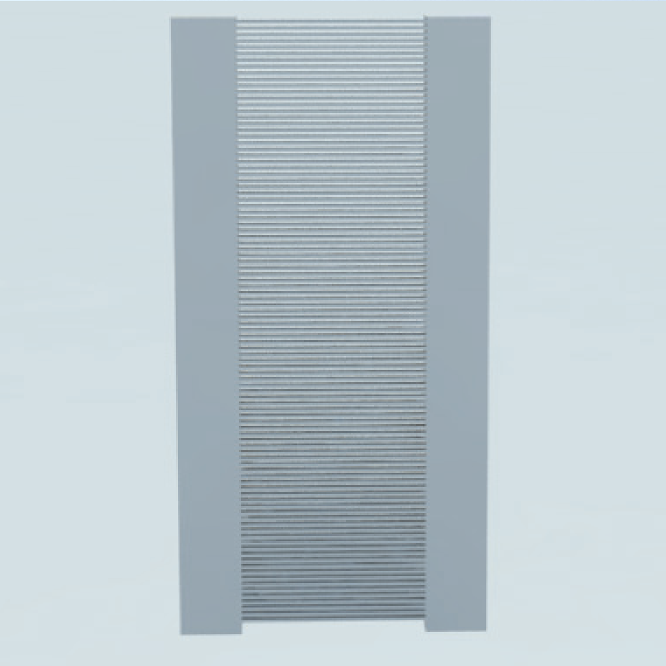
The models can have a range of benefits from aesthetic to the material properties of the objects. There can be a change in the perception on how to profit from machines in the idea that we can use machines to make something unpredictable.



The straight walls from the computer models are crumbling when faced with reality.

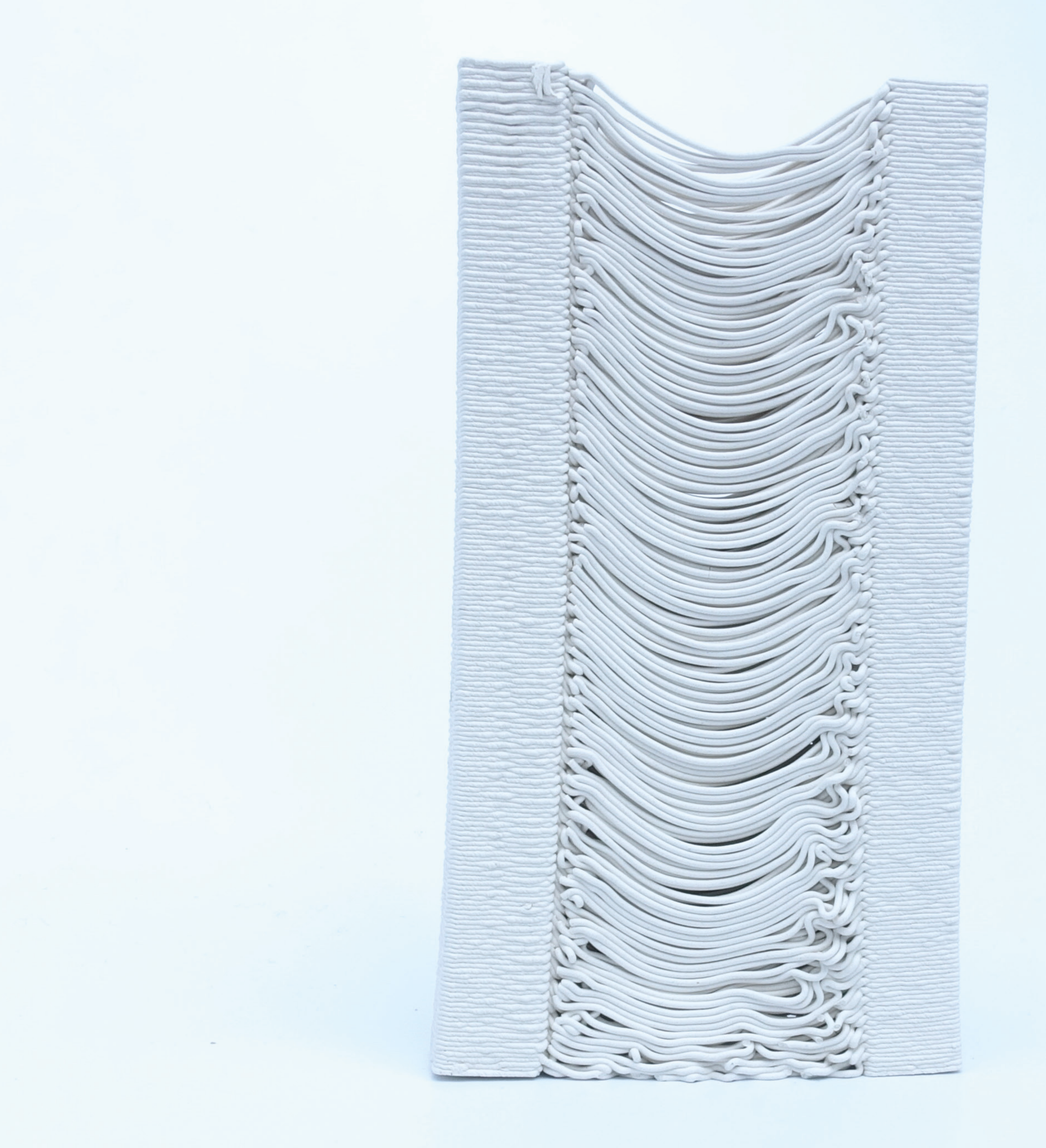


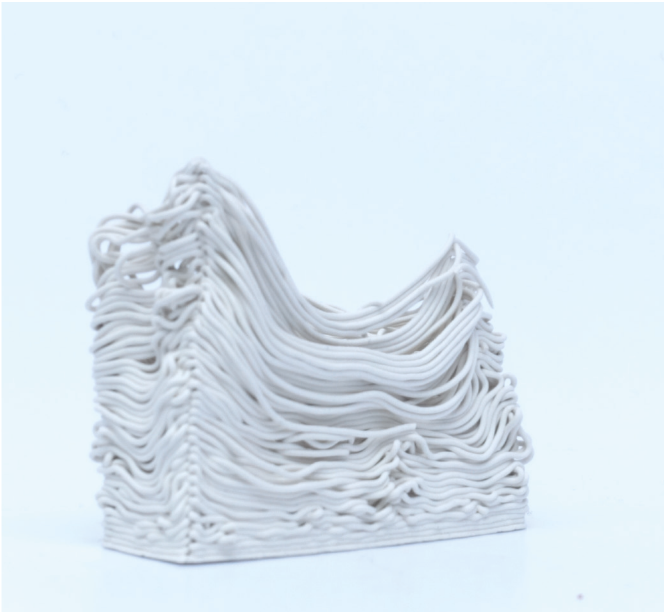
A box with a displacement map consisting of a grid.

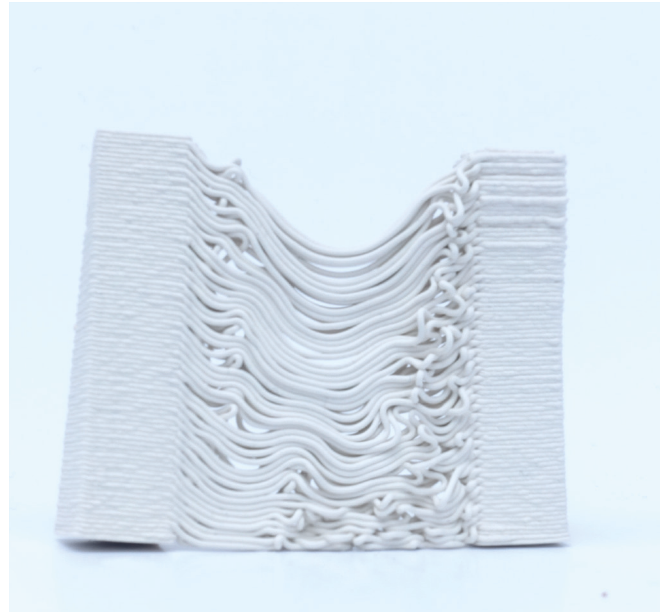


Two solid pillars support offset contour lines with intervening air gaps.

In a comparison between the printed model and the computer model the effect of gravity is visible.



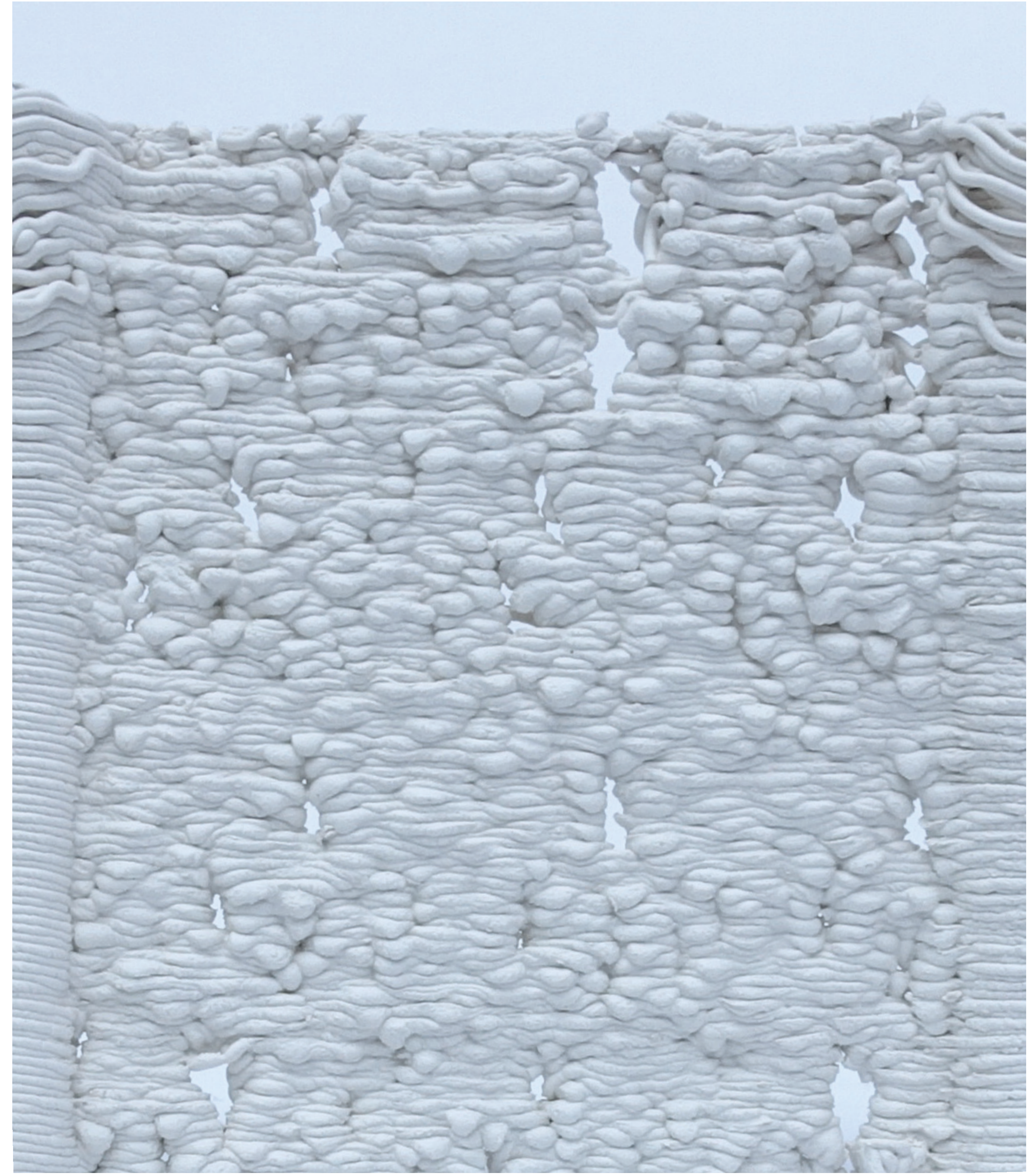


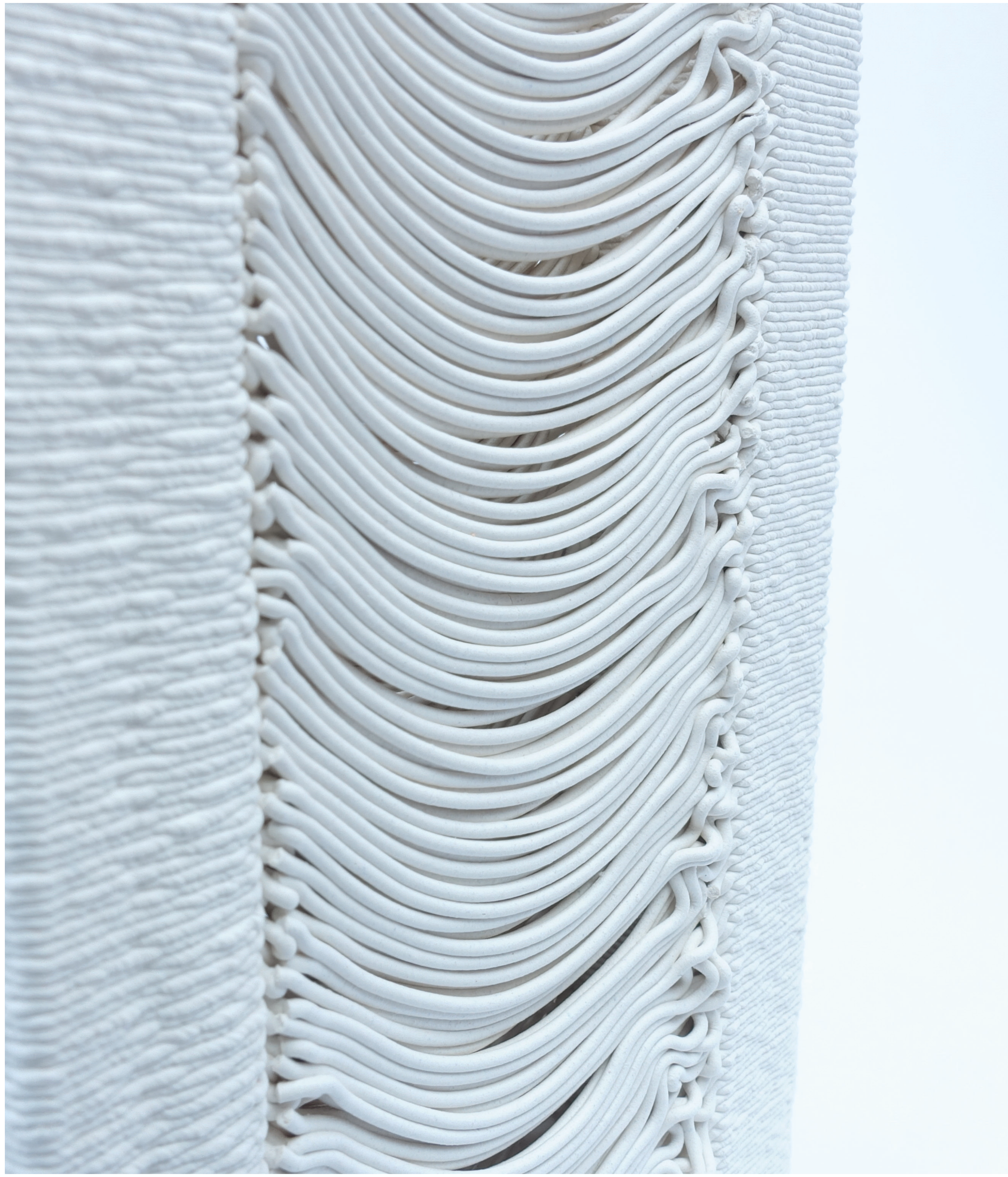


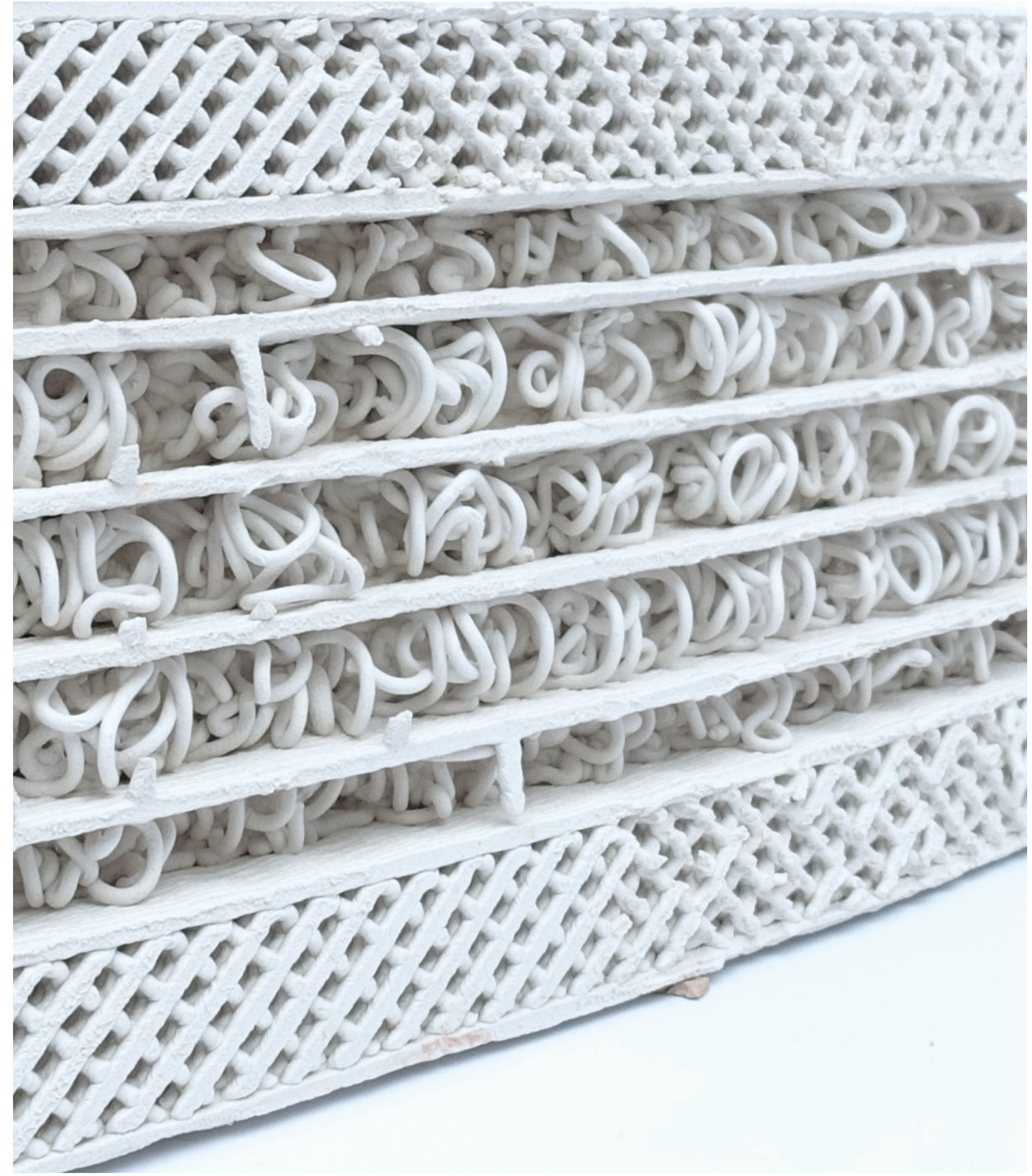
Lines with air gaps in between in an attempt to mimic a high layer height setting. Model to the left has no extra stability, the right is stabilized in corners.

Displacement maps can also be printed to form something new in the models.

In the models the predictable and the unpredictable can meet and coexist.







Part 6

This part connects to the last in the way that many of the variations in the models are created before exporting the model to a slicer program.

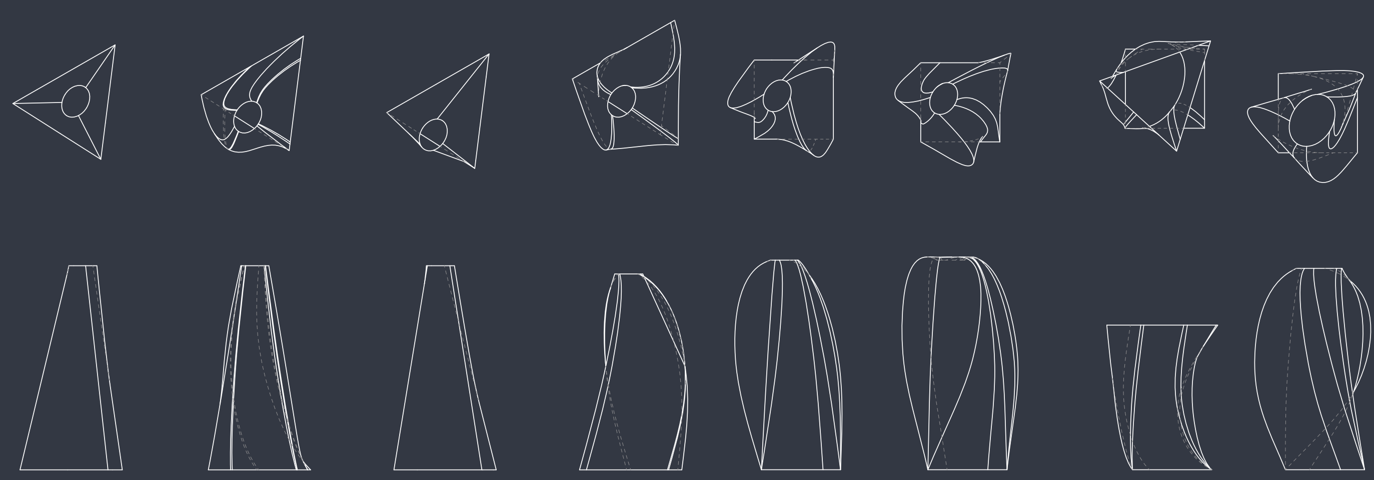
Questions
How does the print change depending on how the slicer program reads the model?

What is the difference between exporting a surface or an offset model?

What can I learn from printing the same model in different ways?

One of the main aspects that I wanted to examine in this part of the project was the difference between printing a surface or an offset surface. Models with sharp edges in combination with curvature were created in order to see how the edges were printed. Creating more complexity than previous test models.

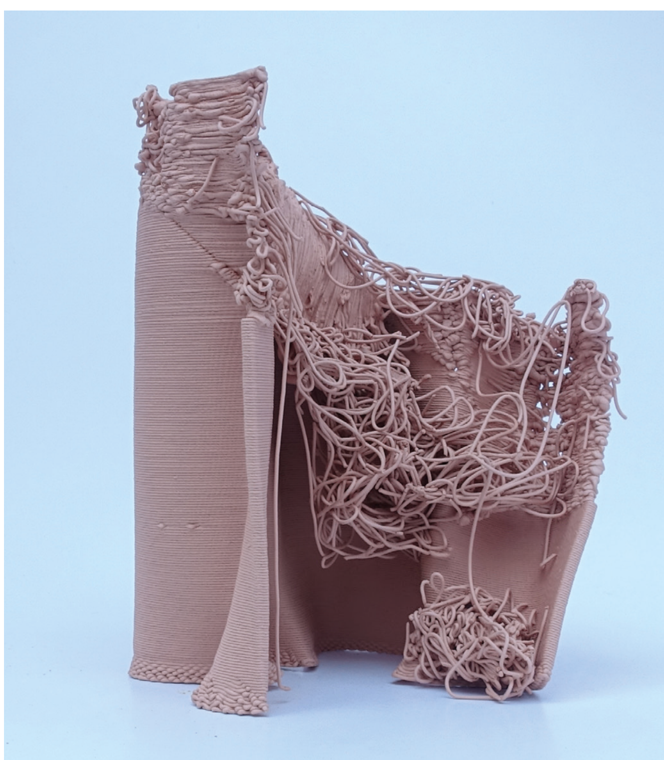
When exporting the model as a surface the slicer program can read it as a volume. The wall thickness can be decided through shell thickness instead of an offset. This creates a smoother model. It works better with the way the printer and slicer sees the world, in horizontal planes. An offset surface in Rhino is offset in line with the walls and not horizontally. The explorations also shows that the model with two millimeter shell and an infill has the sharpest corners. As one model shows, the infill could possess an ornamental quality while at the same time displaying the construction.



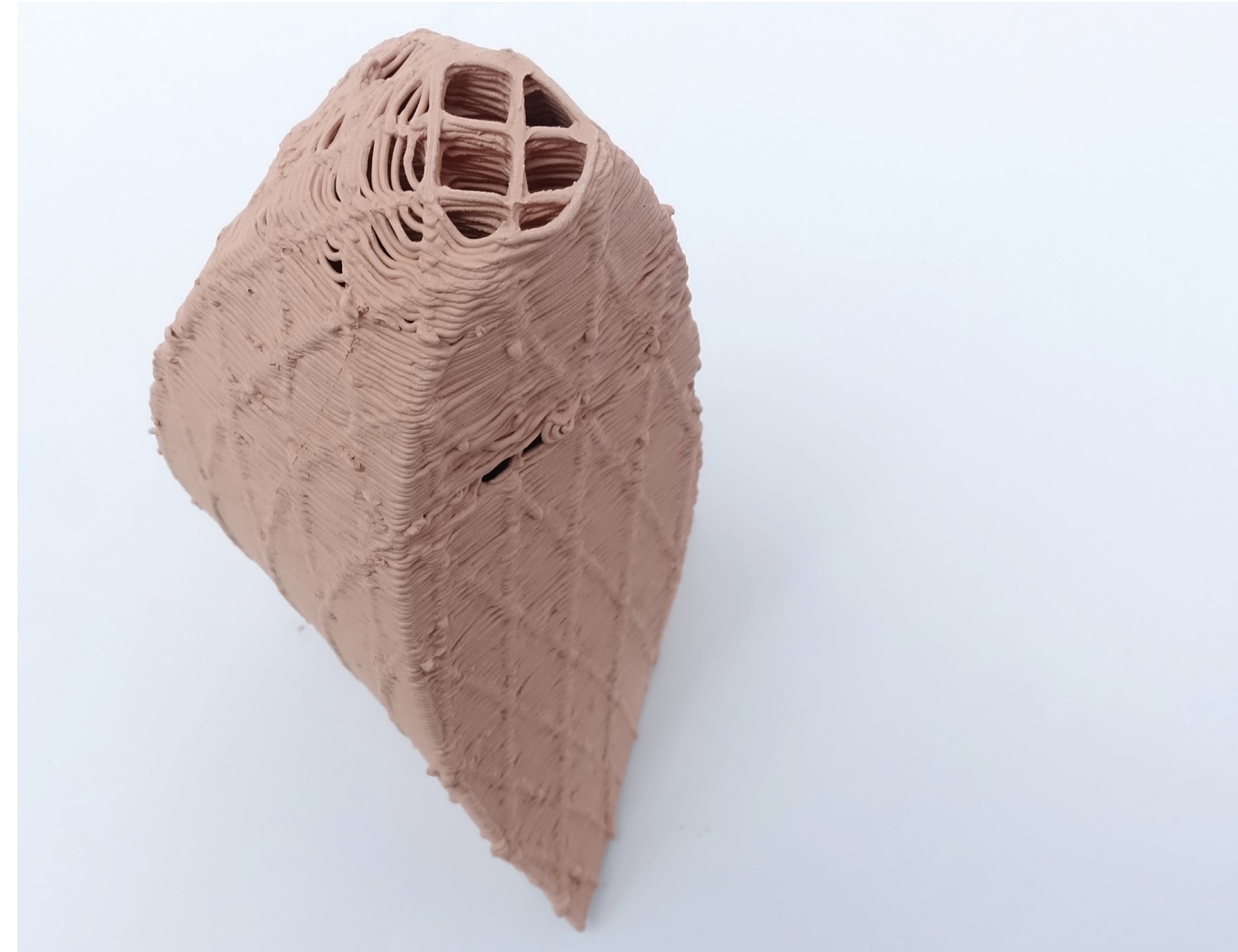
The middle model is exported as an offset model, the two other as a surface.

The first model has 4 mm shell thickness, the second has 1 mm shell combined with infill, the third has 2 mm shell and infill.

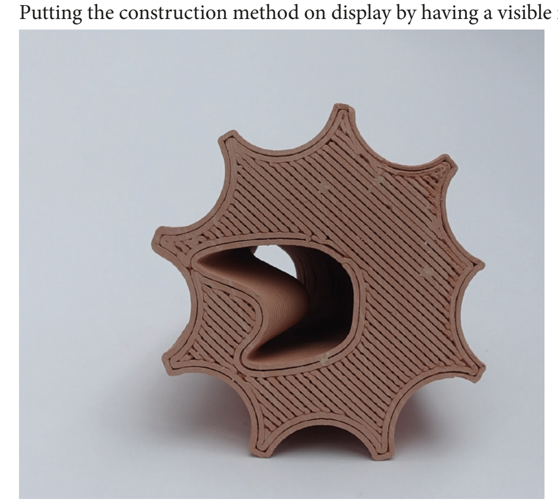





Different thicknesses in the model create a variation of stability and irregularity.



Putting the construction method on display by having a visible infill structure.




A model with a boolean difference interior.

Part 7

Previous parts have been mainly focused on the single wall. In this set of experiments focus is on creating more enclosed spaces.

Questions
How does the 3D printed wall become an enclosed space?

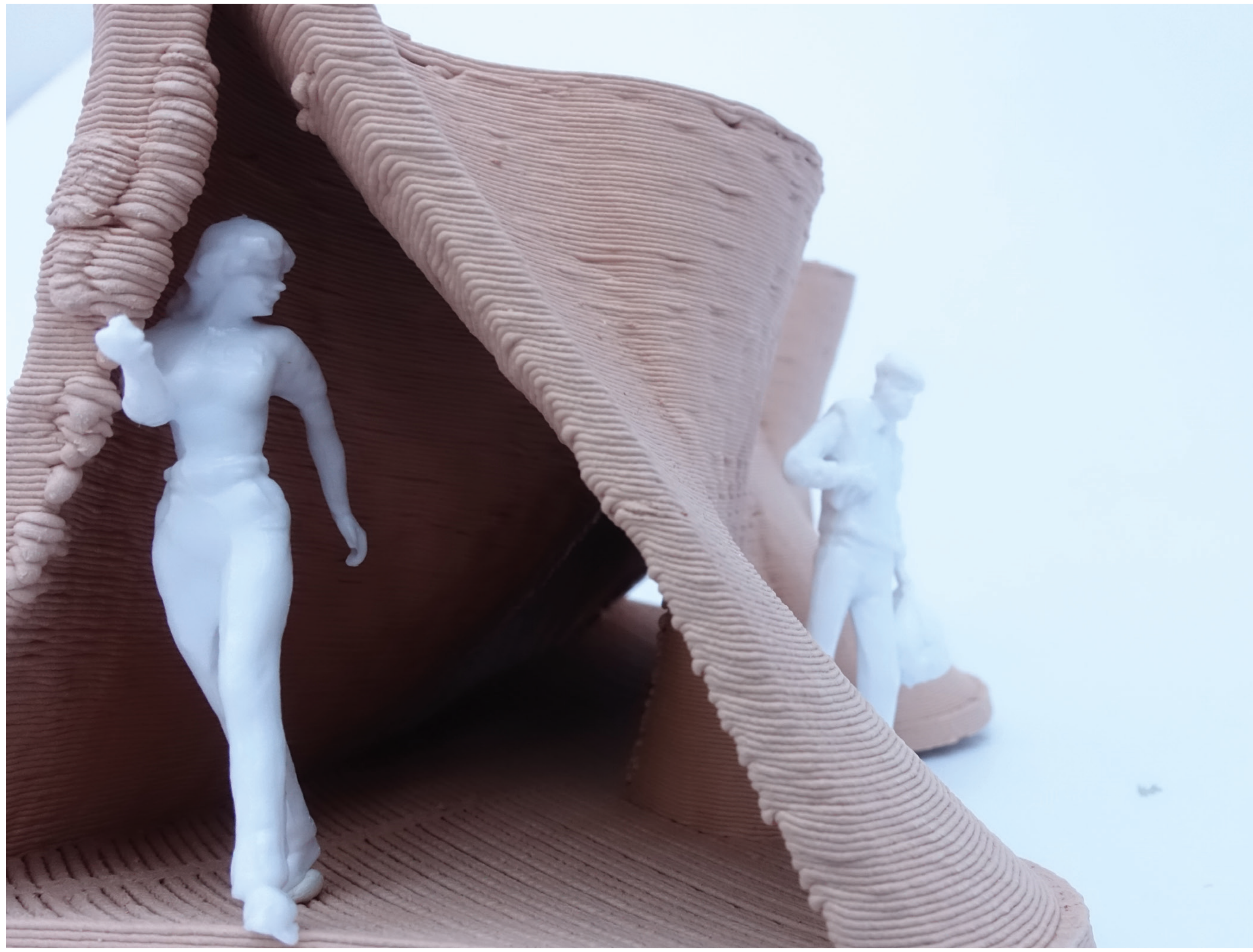
How does it become a roof?

The background to this set of experiments is previous attempts to design models with roofs. Since 3D printers build each layer on top of another layer printing a horizontal roof is difficult. Because of this ways to combine 3D printed earth walls with other sorts of roof solutions were tested in sketches. Usually ending up with a flat roof in a conventional manner or trying to hide the fact that it is a roof by using glass. Either way, in many respects missing the point of the project.

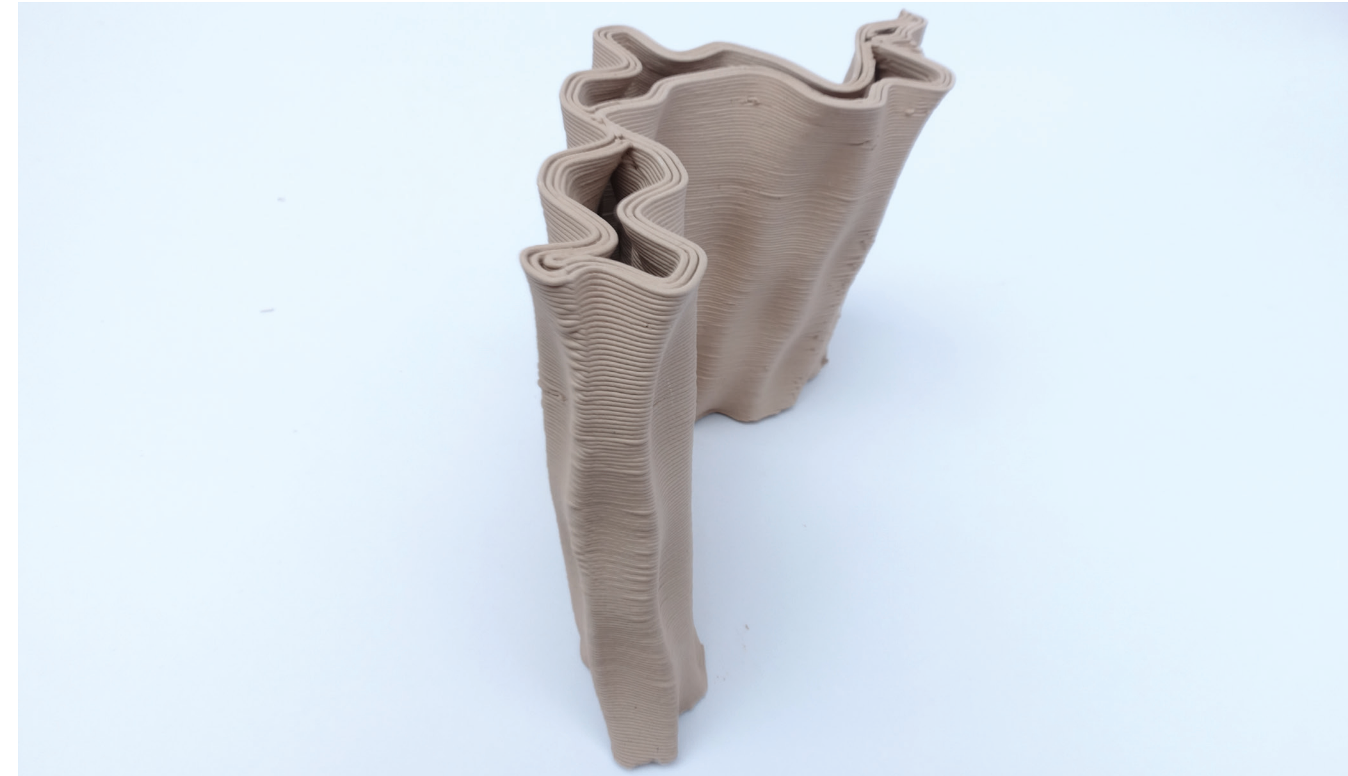
In attempts to print a roof covered space I started with dome structures as well as variations of a typical a-frame house. Constructions that can create a roof without large horisontal spans. What interested me the most in both sorts of models were not the roof per se but rather what happened before, when the wall became a roof.
In the models it was clear that a fully covered roof was not necessary to offer protection. Most traditional walls does not offer anything else, it is simply a wall. But a 3D printed wall could be many things. The notion that with just one double curvature wall one could find shelter and a roof was inspirational.

In this part of the project a greater emphasis was placed on a specific scale. Up until this point the project had been so open ended which caused it to be without a set scale for most of the times. One might look at the models and imagine a certain scale but really what is important in the models are the ideas and they are inherently scaleless. Depending on the size of the printer most of the findings can work in large and in small scale. The models offer the possibility of being using as fired clay in smaller components or as unfired earth construction in larger scales. In these experiments, as a scale is decided, and the models are more concerned with the human body than previously.

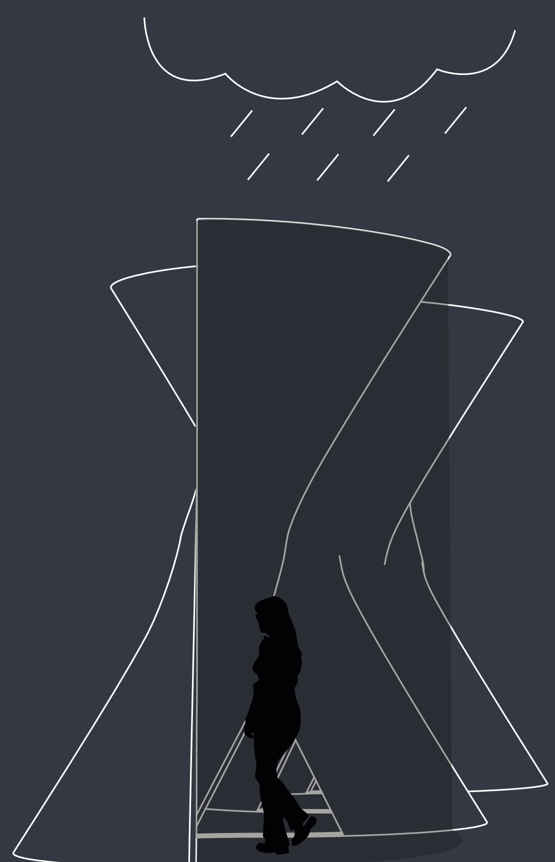
The two walls, although they are roofless, can provide shade and shelter.

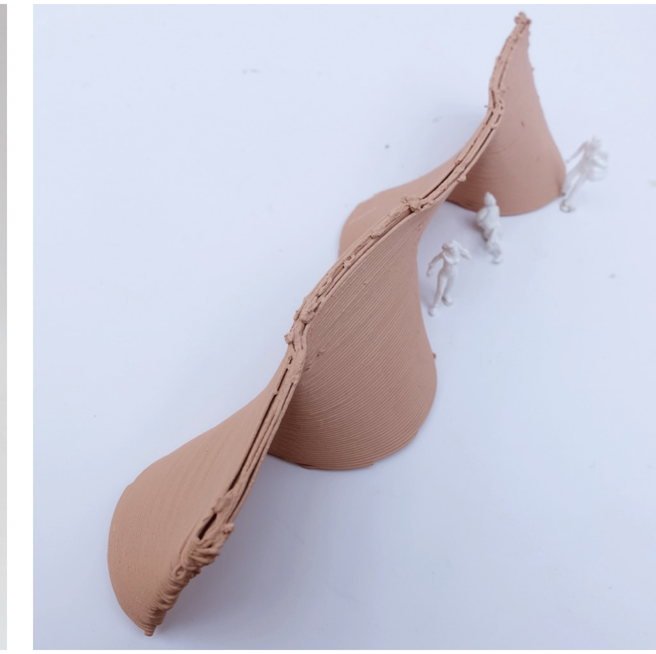


Variations of a roof. In the top picture model the two walls meet to form a roof and in the lower picture the roof is formed by a dome structure.



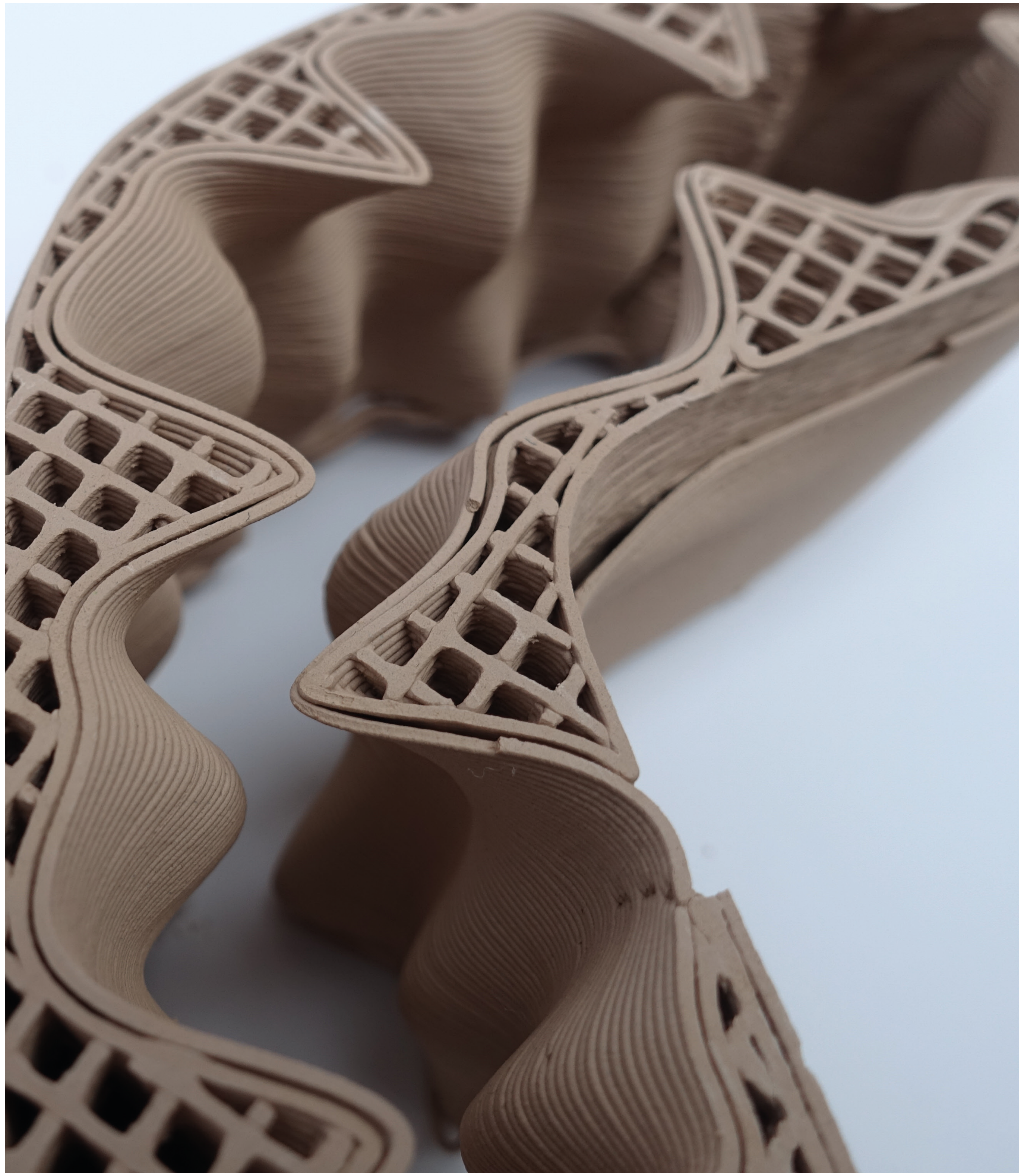
Walls develop into roofs.





With a double curvature wall the question of what is a wall and what is a roof, of inside and outside become elusive.

The tilting walls create a protected interior space while also opening up to the sky.



Part 8

In this experiment focus is on printing a model rather than printing an idea.

Questions
How can I combine findings in one architectural piece?

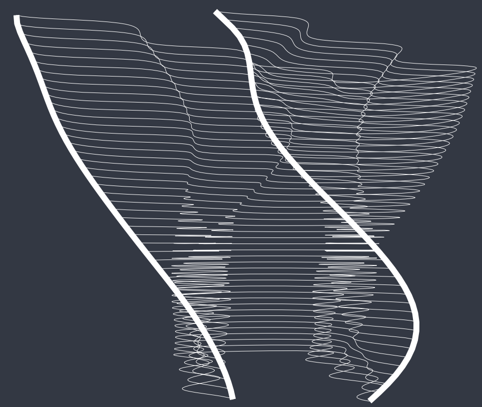
For the first time in the experiments I had a program. I had functional demands of the architecture I was to design. There needed to be a space and a person should be able to walk inside the structure and experience the space, because of this there should be a way to enter the structure, there also needed to be light and there needed to be shade or protection from the weather. Demands relating to the human body and mind. The difference between printing an architecture model and printing ideas.

The difference between seeing a model in a computer program compared to seeing it in reality was again revealed. This time there was a greater emphasis on deciding on one thing, printing many but deciding on one shape, one door and one light permeable wall. When printing variations of the shape it became clear that a computer program does not give the same sense of a model as when it is printed. When looking at different shapes it is beneficial to be in the same 3-dimensional reality as the model. When deciding on one shape it also helped to see how the printer printed each model as a way to see what works and what does not. Transferring findings from previous tests in the model, the model is aimed at being printed in line with the construction method. When seeing how well different parts print the model can be changed accordingly.

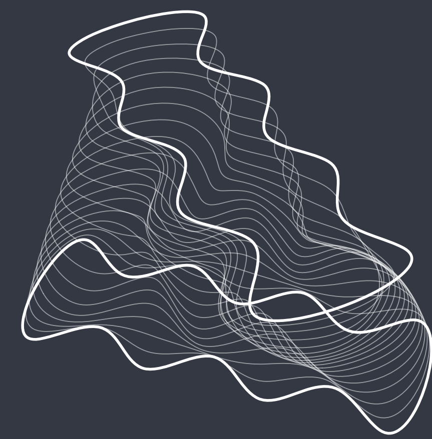
Variations of form and of openings were tested.

Variation of level of chaos in the model.

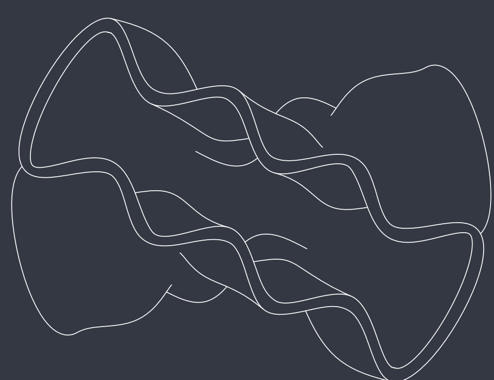
Deciding on a shape.



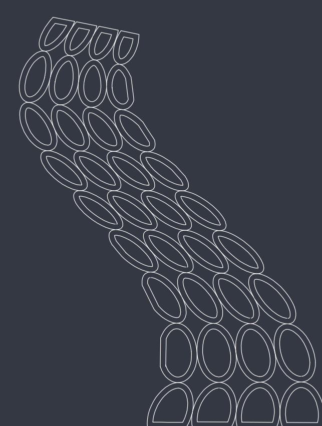
Walls become as roof in interior and exterior



The printer works best with closed shapes and soft edges

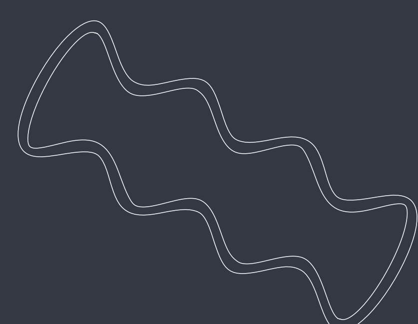


Symmetry for steadiness

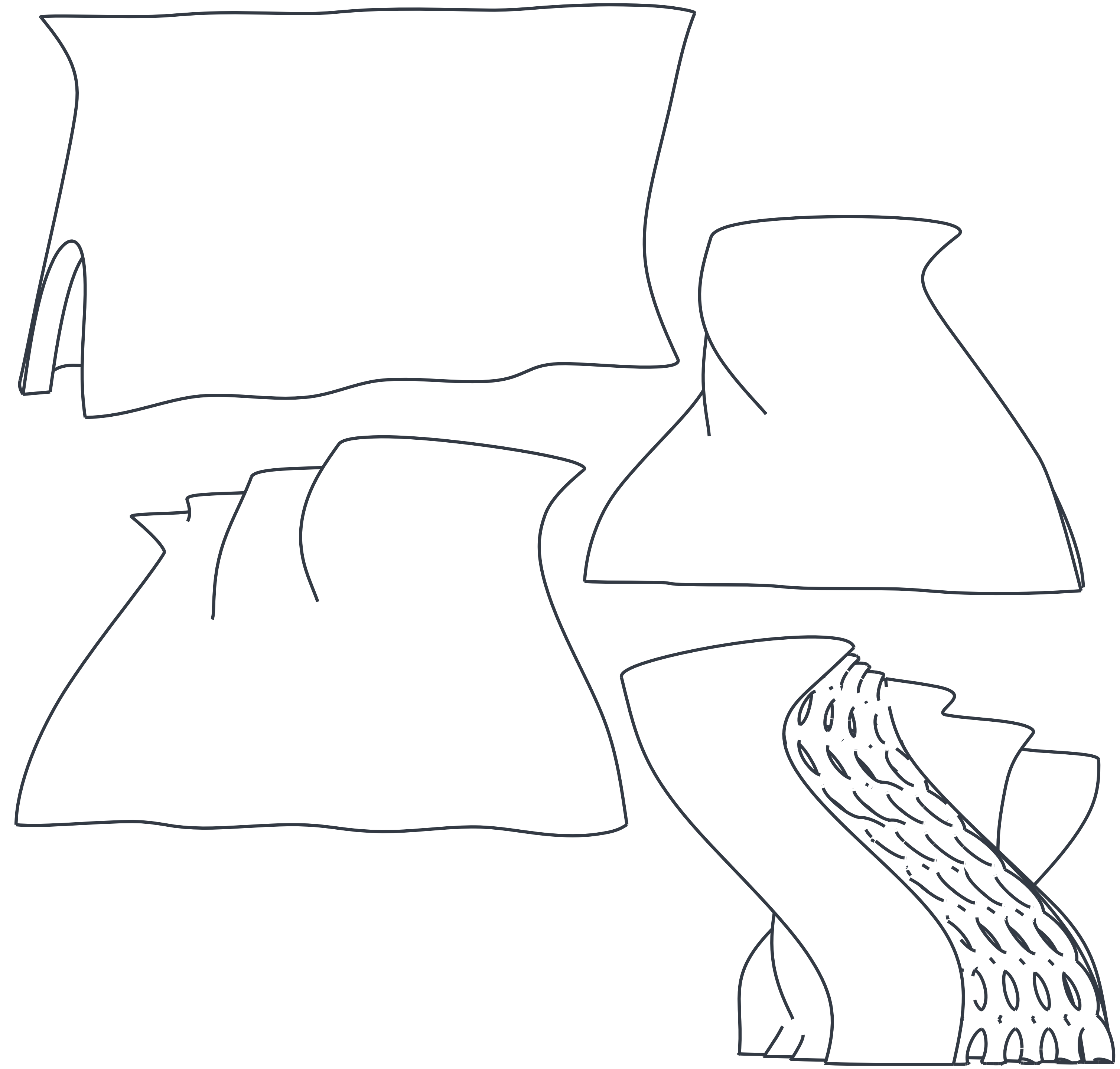


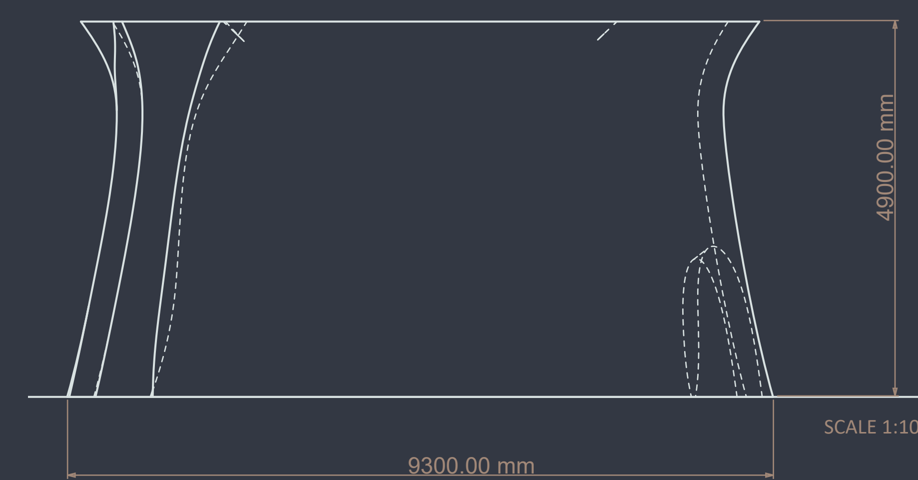
Air gaps in wall for light permeable wall

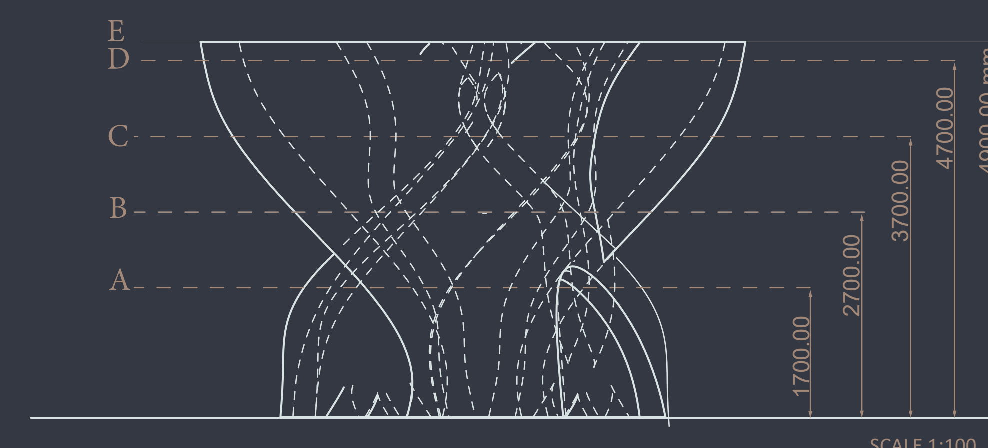
Entryway tilting back makes it more stable on the sides



Curved walls add stability




4900.00 mm
9300.00 mm
SCALE 1:100


E
D
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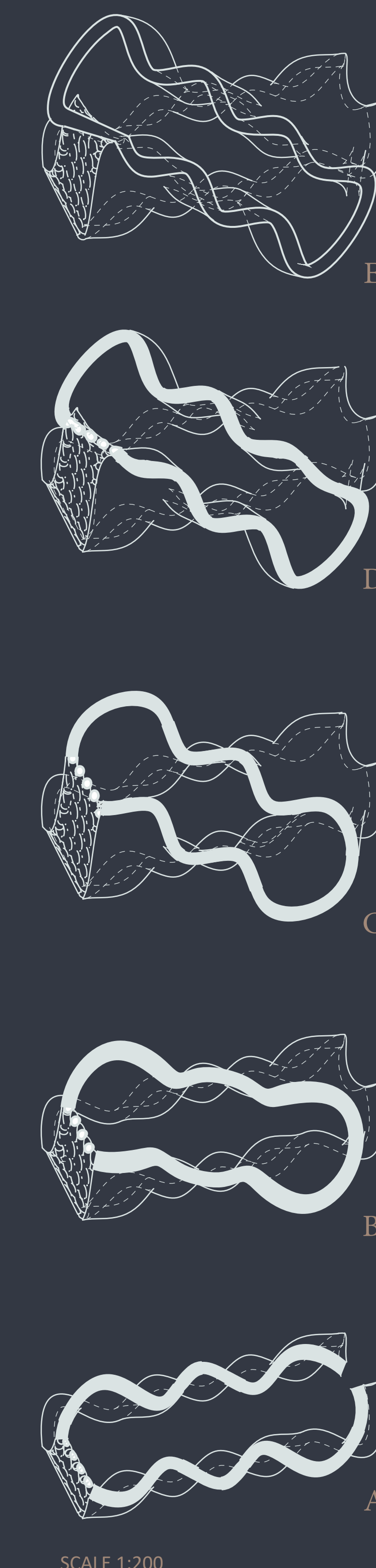
1700.00
2700.00
3700.00
4700.00
4900.00 mm
SCALE 1:100


E
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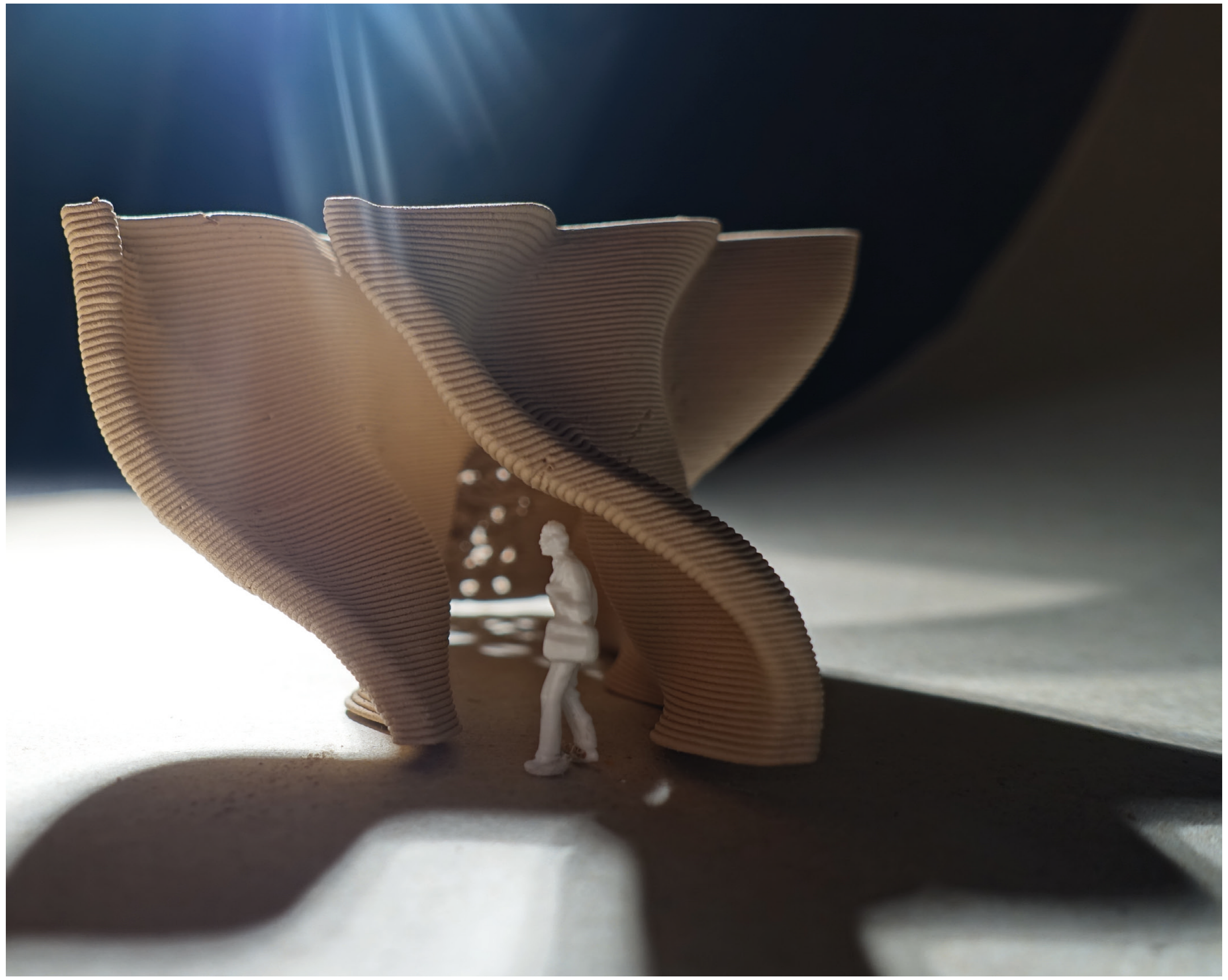
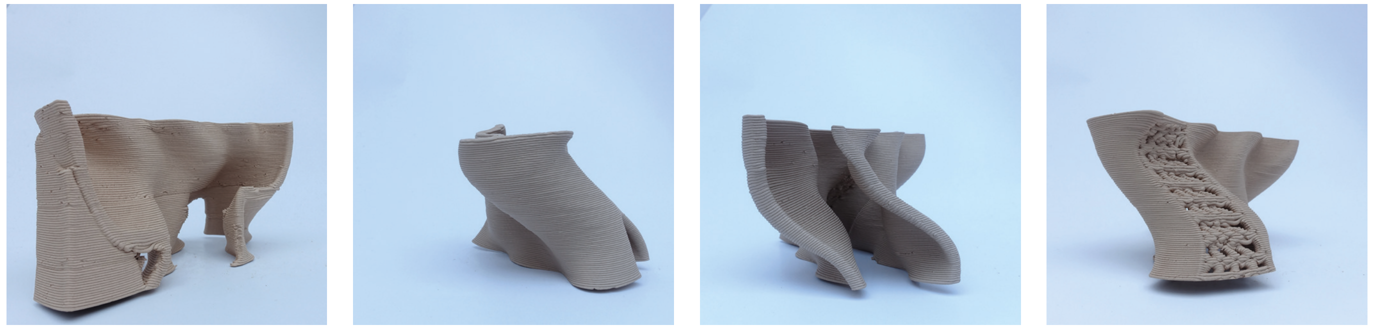
SCALE 1:200

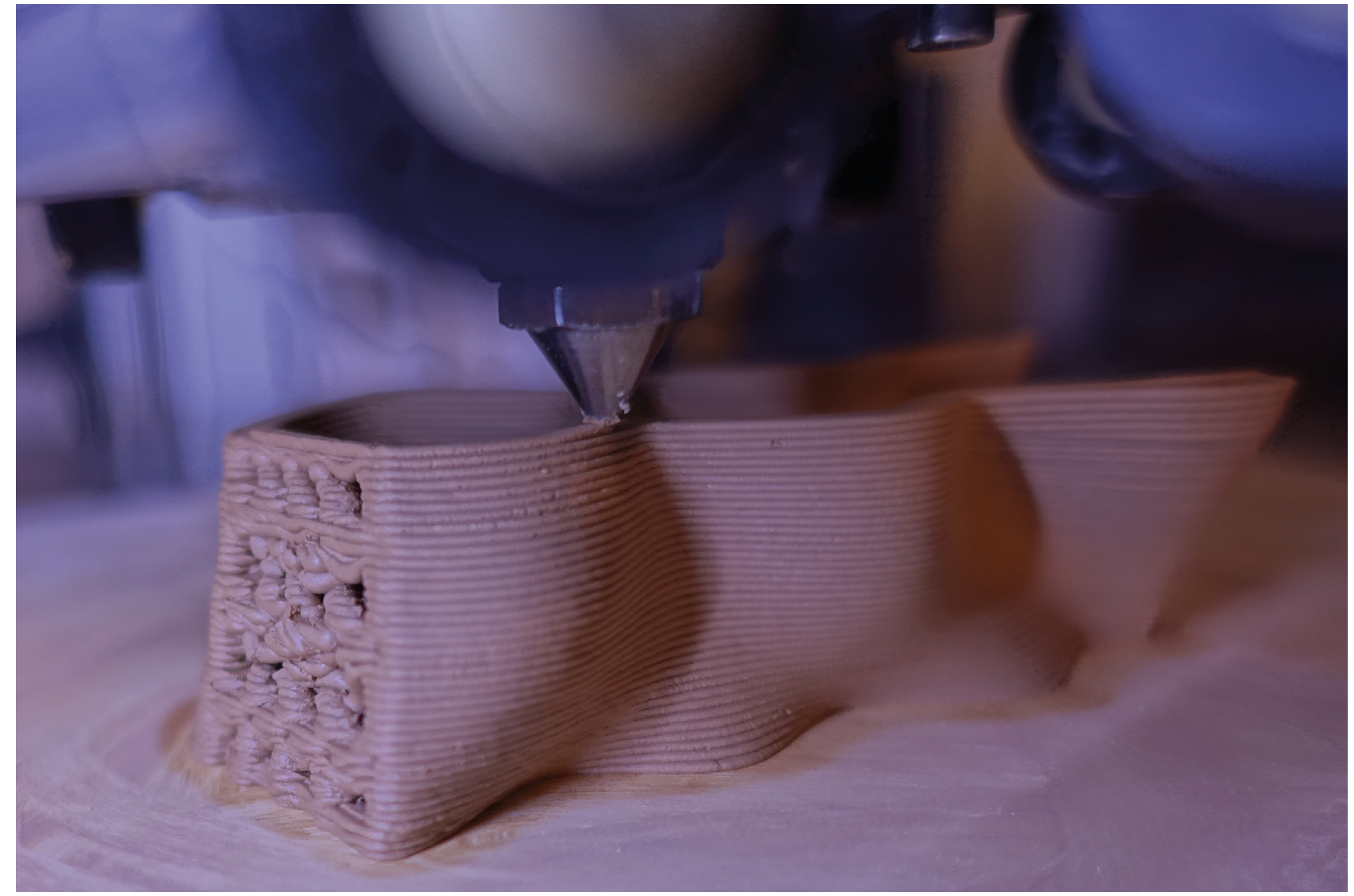


A section model highlights the tilting walls and the ambiguity between inside and outside in the model.

A top view shows the small amount of floorspace being in direct sunlight.



Section models.

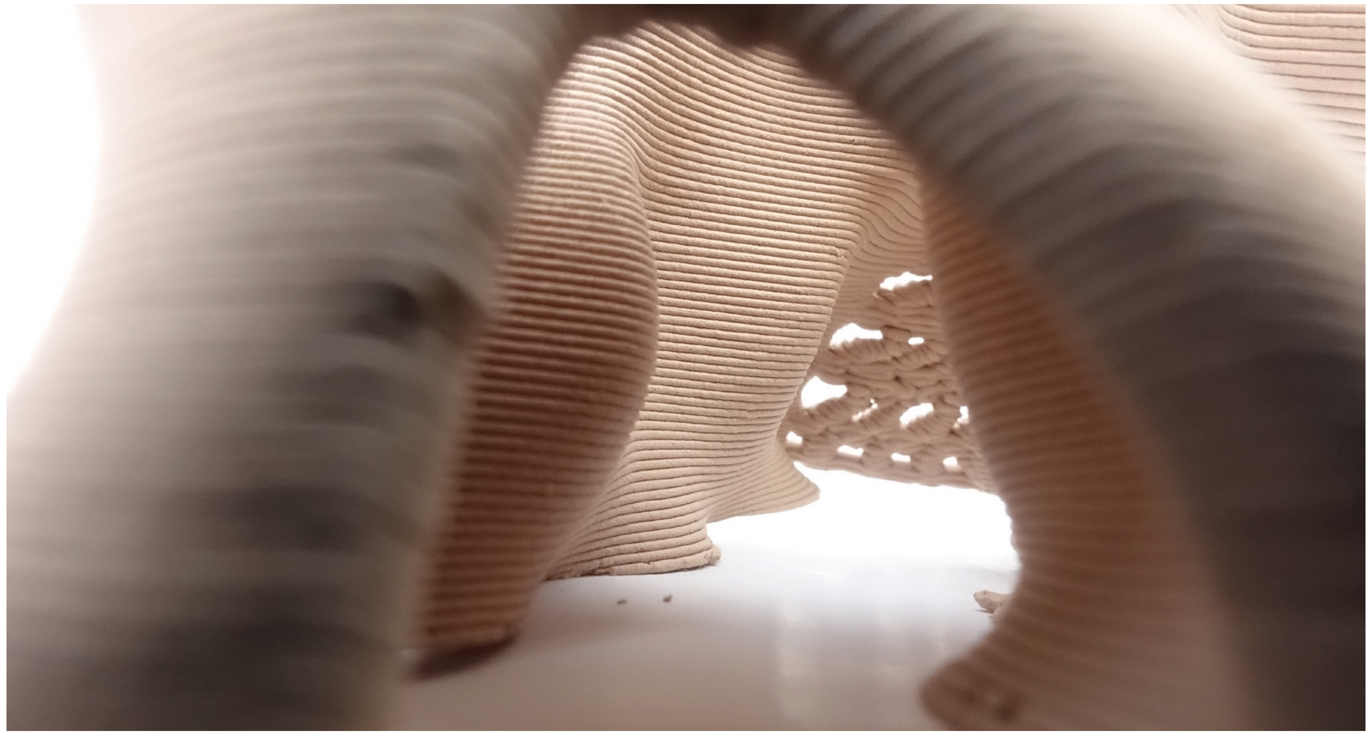


The models are printed in scale 1:100 with a custom made 1.5 mm nozzle in order to achieve the correct size of each layer.

In the interior the curved walls create a bodily experience of the architecture.

The layered walls are placed close to each other, inviting the visitor to reach out and experience the texture and materiality.

Looking up to see the sky and at the same time - the sense of being inside.



Light and darkness play important parts in the model.

Concluding thoughts

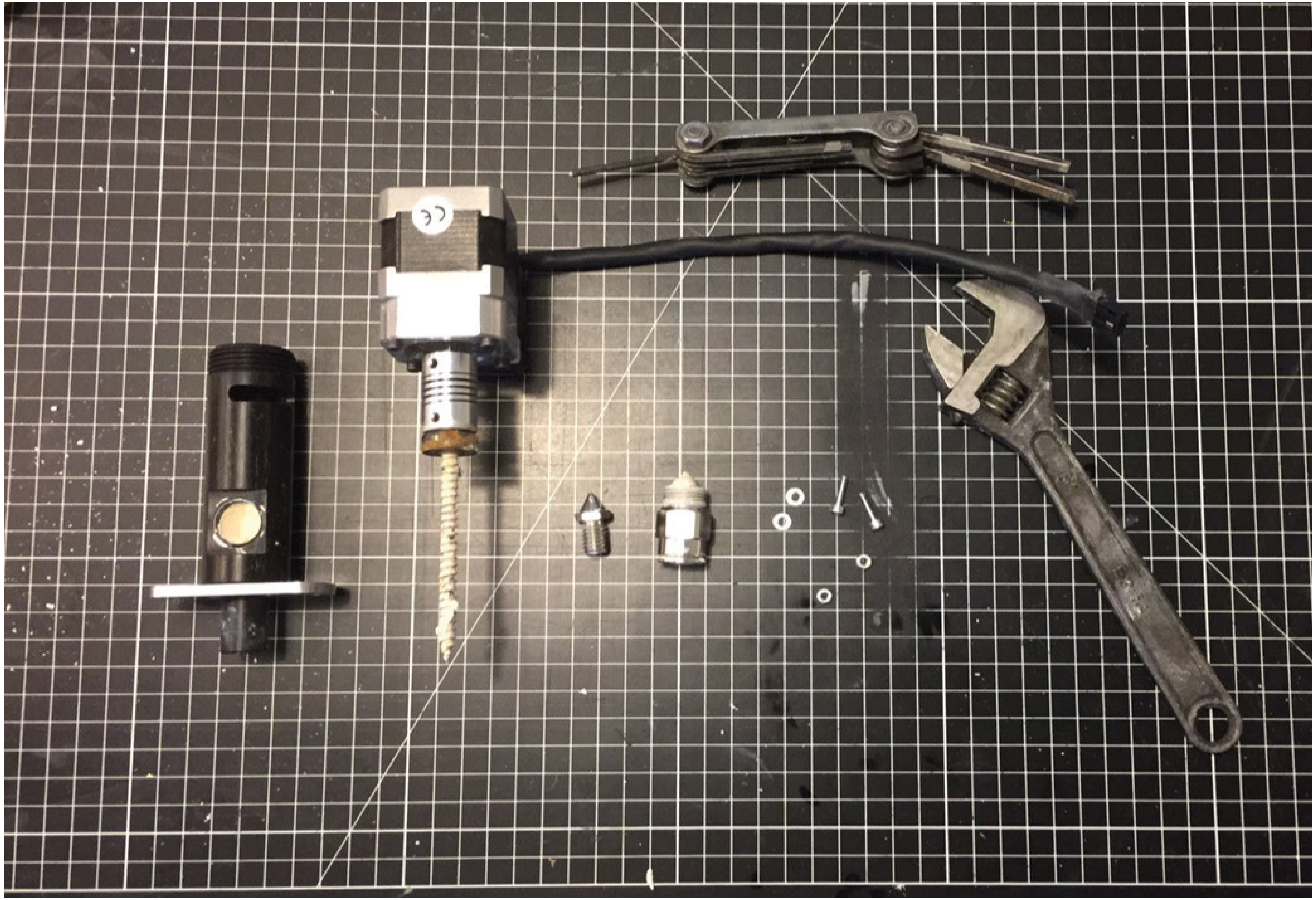
On the subject of; *Design method, Digital fabrication as part of a design process, A 3D printed wall, Choice of material, Leaving room for chance, Control vs. chaos* and *Printing the project* followed by a *summary* and *reflection.*

Design method

Digitally fabricated physical models were the driver of this project. This could be done by distancing the project from any functional and performative demands established by a site, a client or a user. The method of research-driven design liberated the project from such demands and opened up for other questions to be raised. It has allowed the project to ask more questions than it answers. To be visionary rather than buildable and to use architecture as a way to test ideas.

Digital fabrication as part of a design process

When digital fabrication is used as an integral part of the design process the design doesn't stop with the computer model. The construction method, here additive manufacturing with clay, can be used to further develop a model. The print is not a replica of a rendered model but rather a new object with new properties and advantages. These can be modified by programming the printer in different ways and they are also linked to the material properties of the clay. Instead of using new technique to build something human hands used to build the design is created with the construction technique in mind and the potential of the new ways of construction is harnessed.

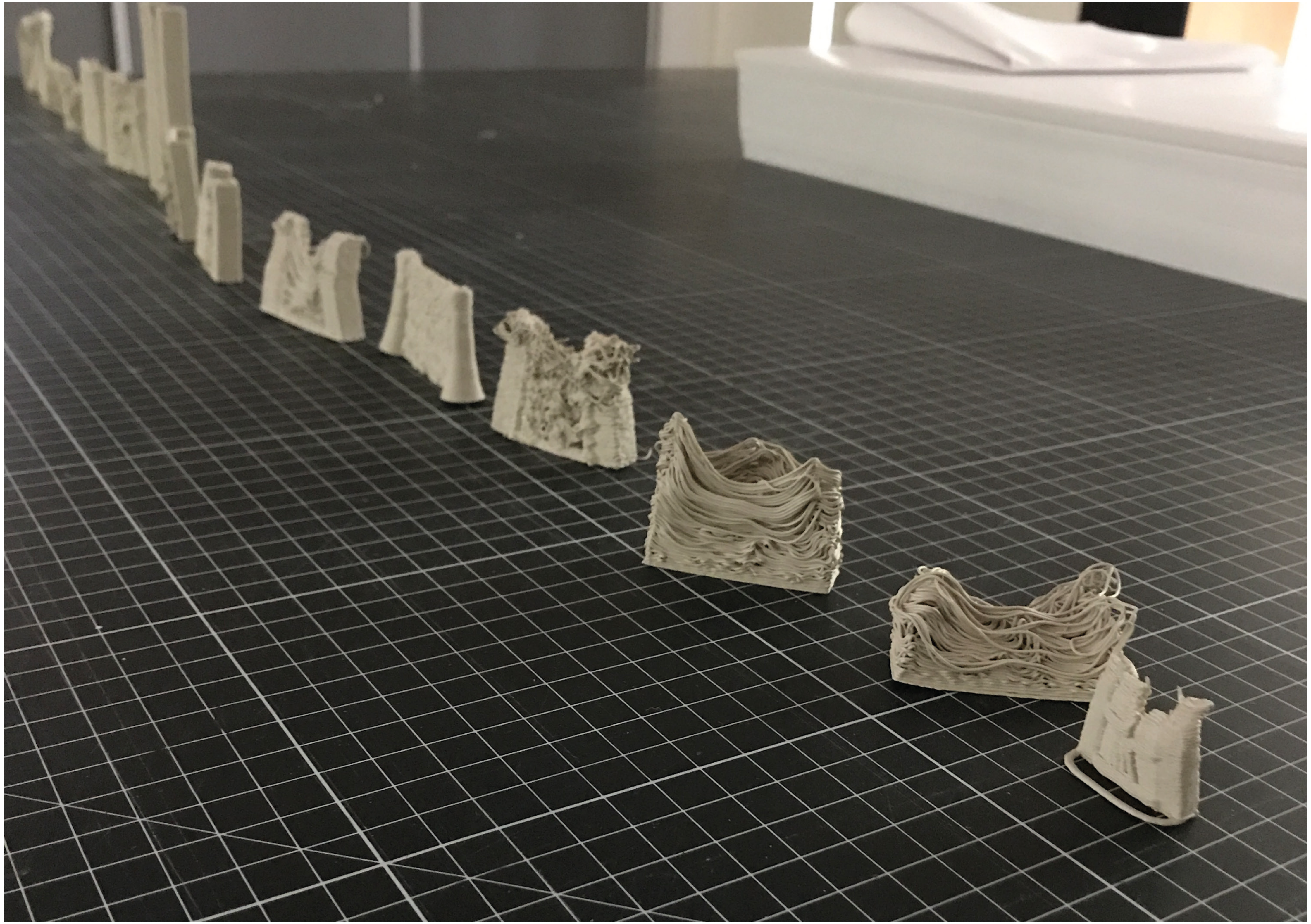


A 3D printed wall

What does a 3D printed wall look like? In a way it could be anything. Unlike a human the printer does not care about the complexity of a model. Printing 100 identical pieces is not any easier than printing 100 different ones. This opens up for the possibility of a lot of complexity in the models, but there are limitations of the printer and of the material. The geometry of the object affects the movement of the printer which in turn affect the print for example. In my findings I am trying to find what can be argued for as logic for a 3D printer to print. One thing relates to the movement of the printer in sharp corners. Showing that printing boxes is actually more difficult than printing round shapes. Another thing which is logical to print is in relation to stability. A curved wall will stabilize itself so it could make more sense to print than a straight wall. Being aware of what the printer prints best also opens up for the possibility to combine stability with

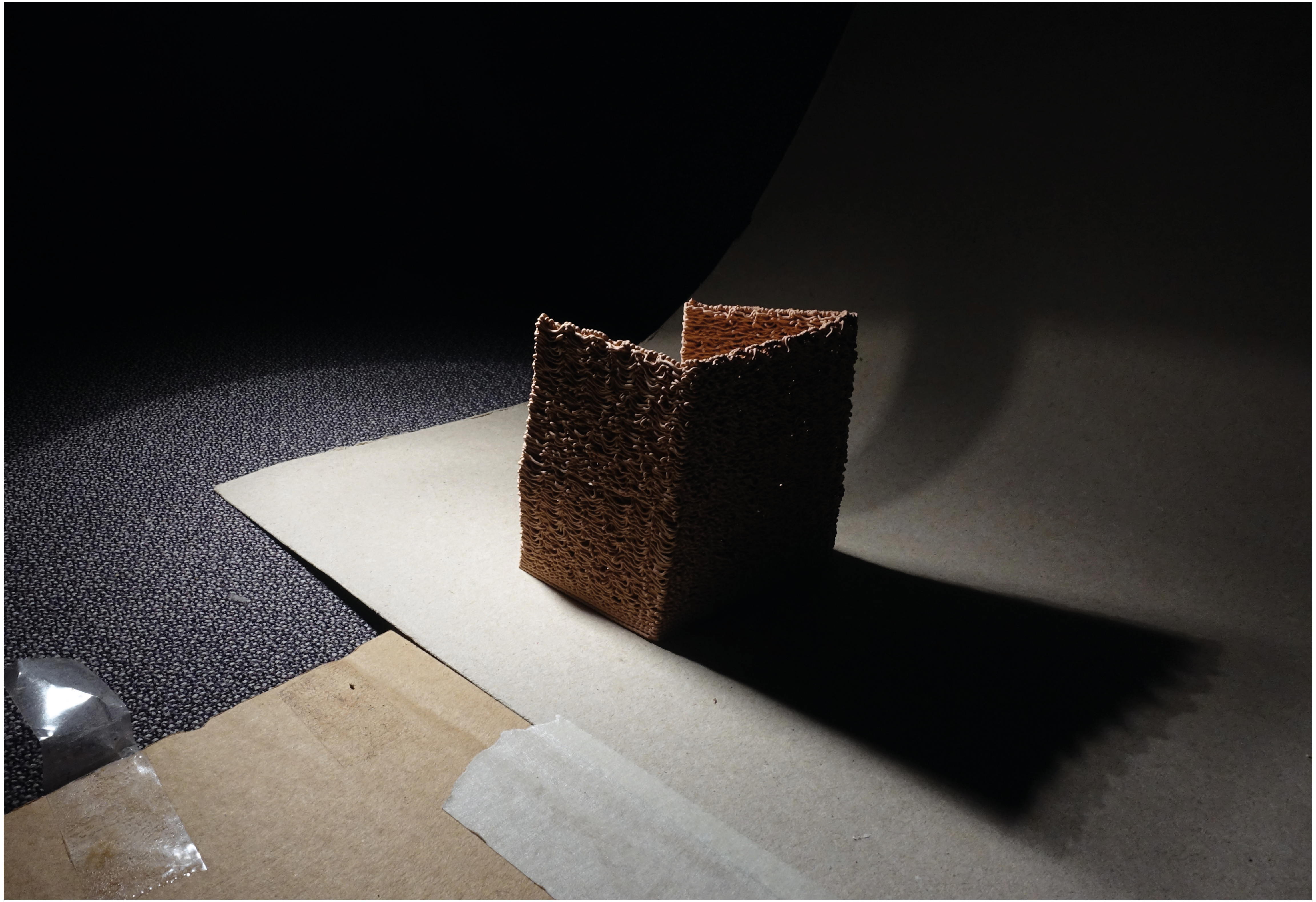
Choice of material

Early in the design process it became clear that earth/clay as a building material would work well with the approach of the project. The material is suitable to 3D print in large- as well as small scale. The print can be a smaller part of a construction such as a tile or it can make up the entire building envelope. Ancient vernacular building tradition can serve as inspiration and the material is also highly relevant today for sustainability reasons. The clay material is different from other common materials used in 3D printing in the way that it is fluid and does not solidify at room temperature. The fact that it is a natural, low processed material and not easily controlled makes the result varied and interesting. The physical nature of the material introduces an act of chance or the coincidental in even the most planned objects.



Leaving room for chance

Digital architecture, 3D printed architecture and really any architecture is generally constructed striving for perfection. Trying to make the building just as the model. We usually use machines to make things with more precision and flawlessness. But here it is the opposite. Leaving space for something else to happen. Something the designer has not controlled completely.
This project presents a way to use a machine and computer models in combination to introduce an element of chance. The erratic.



Control vs. chaos

When the uncontrolled clay meets the absolute control of a 3D printer there is an intriguing interplay between the two features. It is in the combination of the two opposites that something interesting happens. Using the control of the machine to create something otherwise unimaginable with that material. The machine is used, not as a way to create a static, predefined shape but to embody material processes. This is done without adding anything or changing the material in any way, it is only the homogeneous material and its inherent properties used but in a new way. The component which is created always demonstrates both the construction method and the material. It is both engineered and organic.

Printing the project

The physical world and all that it encompasses has been of most importance for this project. With the focus on construction and materiality the printer and the physical nature of the models is essential. It is through an iterative process of printing and learning from the results that the project has developed. It is a project which would never have happened using only renderings and drawings, computer programs and my own mind. It needs the effects of the real world to exist and to come into form. It needs the effect from gravity, from the material and the movement of the machine. In the process there also needed to be the excitement of not knowing what was going to happen because it is that curiosity that led the project in this direction.

Summary

The project started with an interest to explore the use of digitally fabricated physical models in a design process. The project is not about finding a perfect form or creating something beautiful or optimal. There is no end result in the shape of a building and it is not a manual for how to 3D print a house either. The physical parts of the project are only as important as the ideas they can generate. The project began in an opposition to the way buildings are often designed solely in computer programs and then built to mimic it, with the presumption that values goes missing through this practice. By introducing physical models early in the design process they can contribute in the feedback loop and offer new insight in the design work. In the most extreme cases, such as this, the models can be the driver of the entire project. Letting experiments with construction and the findings derived spur new questions and studies. By having the fabrication as driver there was a greater opportunity to experiment with construction processes. More important than the geometry that was printed was the way it was printed.

Reflection

The most important part in this project has been the design process. To have created a process where I set the boundaries of the design but the machine and the effects from material aggregation allow it to be something different. It introduces a complexity which would have been impossible to create in any other way. This is making me think that a machine can create with a sentiment of the hand-made but without trying to mimic it. For me the walls have things in common with the small irregularities in a handwoven fabric but also with water erosions effect on a mountain. Finding parallels in grand as well as small scale, in the handmade and the natural alike.

Architectural inspiration is not found in the last 100 years, instead it could be about looking back in history. To a time when uniformity was lacking because of the hand crafted way of construction for example. Reimagining vernacular building strategies that may have been lost because they cannot be mass-produced. Creating them in a different way, a digital vernacular.

The precedents for the form is not to be found in a previously created house but instead in the logic of the construction. Using the construction to create stability but also chaos in the building. A new architecture where the simplicity in material meets the complexity in a computer program. Where current need for sustainable construction can be met through a combination of new and old ideas and a combination of natural materials with new construction.

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