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Integrating Additional Elements in Clay 3D Printing with Human Intervention

Agit Coskun[1], Mads Brath Jensen[2],
[1,2]Aalborg University
[1]acosku21@student.aau.dk, [2]mbje@create.aau.dk

The research demonstrates combining permanent wood structures and steel joints with concrete-clay 3D printing. The study aims to investigate methods for the insertion of additional elements during the 3D process and explore methods for how to inform the 3D printed geometry towards the integration of external elements, including spatial, structural, and aesthetic requirements. As a step in the design process, the ideas of various infill patterns are executed through hand sketches at the beginning; then, the drawings are exported to Grasshopper parametrically at the scale. The connection types, infill density, and nozzle size are all considered when designing infills, and it is thought to specify the required lengths between print paths on each print layer, nozzle size, and extrusion speed. Grasshopper is essentially used to test and simulate how 3D printing works while drawing with clay. Upon selecting the required form, openings are created on both sides of the walls where the additional elements are placed. Thus, a greater understanding of the material-fabrication process interaction and the possibilities offered by computational design is required to integrate with these elements, which are timber, concrete, and steel. The subsequent phase of the investigation also included adding more features to the wall while printing it with human intervention, such as steel placements for the wooden structure. In this paper, during the 3-month investigations, the research produced many physical prototypes with different infill strategies. The variations of the infills were enumerated and compared based on structural stability, aesthetic and functional purposes, infill density, and connection types in the infill (self-tangent, half-overlap, and full overlap). One of these variations was chosen to create two walls for the design of a shelter as a case. The final prototype will give details of how the timber structures will be integrated into 3d printed walls with human intervention during the 3D printing process.

Keywords: *Clay 3d Printing, Wooden Structures, Steel Supports, Infill Strategies, Arch Openings.*

INTRODUCTION

In recent years the building industry has been using three-dimensional printing (3DP), and today's 3D printing technology is expanding to include the utilization of materials such as concrete, clay, wood, and more. It is even feasible to employ pre-existing local resources, increasing construction project sustainability. The reason that 3D printing technology can be very useful in replacing

traditional construction methods and the ability to build is a faster, more efficient use of materials, cheaper, and gives possibilities to create more complex geometries and becomes easier to achieve (Geneidy 2019). Additionally, the proximity to the material, the ability to recycle, and the technology's accuracy make it a more environmentally friendly construction process (Polvi Zackary Bryson, Ganem Coutinho et al. 2021). Although 3D printing technology has many advantageous features, many points still need to be investigated. One of them is the integration with other building systems and their discrete elements and how this can inform the 3D printing process.

In previous studies, the incorporation of additional structures with additive manufacturing has been the subject of several investigations in the clay 3D printing process. For instance, wooden supports were used in the process of additive manufacturing with clay to obtain structures like domes, vaults, arches, and cantilevers (Coutinho, Polvi et al. 2021). The temporary structure was used to support the final construction until it can support itself. In addition, as in the case of `Architecture of Continuity, ` the wooden structure was also used permanently by interlocking to the wall in the 3D printing process (Chen, Datta et al. 2018).

This research aims to integrate additional elements in 3D printing with human intervention during the 3d printing process, such as wood and steel, and explore methods for how to inform the 3D printed geometry towards integrating external elements, including spatial, structural, and aesthetic requirements. This study will look at methods for the permanent wood structure integrated into 3d printed walls by merging concrete/clay 3D printing with the wooden elements. Therefore, this research attempts to find out how timber is being supported by concrete by investigating the potential of traditional connection techniques.

This paper will present design solutions for the integration of wood supported by 3D-printed concrete structures and how to approach these two systems being connected in a tectonic manner. The first step in prototyping is to create infill patterns. Due to structural stability, infill is essential for the wall to be 3D printed with clay. Therefore, eight modules of various infill patterns were produced. The variations of the infills were enumerated and compared based on structural stability, aesthetic and functional purposes, infill density, and connection types in the infill (self-tangent, half-overlap, and full overlap). One of these variations was chosen to create two walls for the design of a shelter as a case. The wooden structure bearing the roof was integrated into these walls, which are load-bearing concrete structures. The variations of walls were created based on height, the angle of the wooden structure, and aesthetic values.

Research Questions

1. How can more components be included in concrete/clay 3D printing with human intervention taking place during the 3d printing process?
2. How can concrete/clay 3D printing be informed to acquire the geometry combined with additional elements?
3. How can concrete/clay 3D printing facilitate the connection between these elements?

METHOD

Research methods

The aim of this project is to investigate methods for incorporating more components into 3D printing with human intervention during the 3d printing process and explore methods for how to inform the 3D printed geometry towards the integration of external elements, including spatial, structural, and aesthetic requirements.

The method is used to direct a combination of a computational design method and robotic manufacturing. Because of the possibilities offered by computational design, hands-on explorations such as sketching various infill patterns are created. The parametric geometry of the digital model is easily modified by using Grasshopper to translate the model into a G-code toolpath. Thus, various prototypes are produced in 3D printing architecture with an experimental approach. Accordingly, an iterative evaluation process is taken to analyze structural properties such as connection type and infill density compared to the digital properties of 3D printing, that is, printing time, speed, height, flow rate, and tool path. Additionally, it is crucial to examine and analyze the previous studies being done by IAAC and used as case studies to see the integration of additional elements in the 3D printing process.

The final model emerged because of the data gathered from rigorous observation and testing of the prototypes. Due to the constraints of the available fabrication technology, all prototypes have been printed in clay and at a smaller scale of 1:10 on an off-the-shelf clay 3D printer. However, the properties of these prototypes (layer width and layer height) are based on the properties for concrete printing on a real scale, thereby ensuring their geometric accuracy and comparability to full-sized concrete printing.

Specific Printing Setup

Delta Wasp 40100 clay printer is used throughout the printing process at Aalborg University's laboratory. Due to the availability of a nozzle type instead of concrete, natural pure blue clay is used during prototyping. There are three different nozzle diameters available at the laboratory for 3D printing that is 4mm., 6mm., and 8mm. The present industrial concrete 3D printers can extrude with a layer width between 30mm. and 300mm. based on COBOD 3D printers' specifications (Stevenson 2019). As the Wasp clay printer allows for nozzle sizes in the range of 4-8 mm., the scale of the clay model prototypes is chosen as a 1:10 scale, which means that the chosen nozzle size of 4mm. equals 4cm on a 1:1 scale.

Computational design model

The advent of 3D printing technology into the design industry has provided architects with new ways to create and manufacture their designs. The production of a 3D-printed object is accomplished via the use of an additive process. 3D printing, also known as additive manufacturing, is the method of creating three-dimensional solid items from a digital file (Giraud 2016).

As a step in the design process, the ideas of various infill patterns are executed through hand sketches at the beginning; then, the drawings are exported to Grasshopper parametrically at the scale. It is considered to specify the necessary lengths between print paths on each print layer, nozzle size, and extrusion speed. This is basically tested and simulated on grasshopper how the 3D printing draws with clay. Grasshopper script enables the translation of the curves drawn into points and makes the parametric form printable.

The initial stage in controlling the precise movement of a 3D printer is to get the curves for the pathways. The curves will then be converted into a machine-readable format known as g-code.
The text file called "g-code" contains the instructions that inform the machine how to move and how much to extrude (G. Cuevas Diego 2020) It is a communication tool between grasshopper and 3D printing. The geometry of the walls is created by using grasshopper. It makes it easier to develop a script to print the ideal geometries, and it enables to translation of the parametric geometries into the G-CODE toolpath for 3D clay printing (see Figure 1).

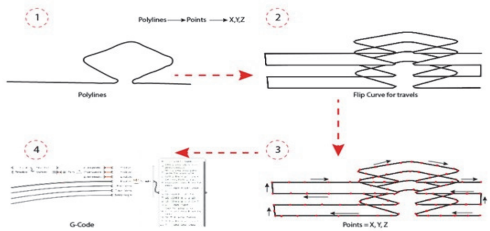


Figure 1
The translation of the geometry into the G-code.

1:10 Clay prototypes

The starting point for the prototyping is to create infill patterns by hand sketching. Infill is required for the wall to be 3D printed with clay due to structural

stability. Infill patterns play an active role as a structural element that bonds the structure together (Giraud 2016). By designing infills, connection types, infill density, and nozzle size are taken into consideration. The Wall thickness is 40 cm. Eight variations of the wall are created based on different infill patterns.
The following prototyping step is to start printing with the Delta wasp clay printer. It is also important to see and test the geometries with the 1:10 scale and how it works with 3D clay printing (see Figure 2). Many prototypes are produced, and a catalog of the geometries is created. These geometries are enumerated based on some criteria and will be compared in the next stage.

DESIGN EXPERIMENTS

The initial design phase

With the knowledge gained during the printing phase, all prototypes with different infills are evaluated and compared. The comparison is based on curve length, nozzle size, layer height, infill density, printing time, speed, and connection type. This is demonstrated in the diagrams below. Connection tests in the infill are taken as inspiration from IAAC (Chen, Datta et al. 2018). Connection types are implemented to infill patterns and evaluated according to joints, such as self-tangent, half overlap, and full overlap, for increasing structural stability (see Figure 3).

After the completion of the first prototyping phase, all fabricated prototypes were compared according to the properties given below. Additionally, prototypes are also evaluated based on some criteria, which are the aesthetics of the surface, material efficiency, and their potential for
opening and closing. The layer height should be low to get a smooth surface, but it increases fabrication time, and the suitable layer height should be 2mm for time efficiency. Infill density is directly related to the quantity of material utilized during printing. Besides influencing material consumption, the infill density also affects the strength and the total weight of the print element.

The denser the infill pattern, the longer the print time. A shorter toolpath length reduces material consumption and printing time. Self-tangent joints increase structural and lateral stability (see Figure 4 and 5).

As a result of making comparisons, the second prototype is selected depending on the provided criteria. These are aesthetics, the ability to create gaps in the wall for timber structures, and the capacity to resist transverse loads, which are evaluated visually and based on analysis. One of the parameters is printing speed, which influences printing time. Several prototypes are printed and tested at various speeds using the selected toolpath to see and understand how it affects the layer connection, width, and time. The lowest speed takes less time and material, but the layers are not connected to the material. In contrast, the greatest speed requires more time and material, and making the toolpath wider is illustrated above (see Figure 6). The best results are obtained at a layer speed of 2mm/s and are used for the following phase of prototyping.

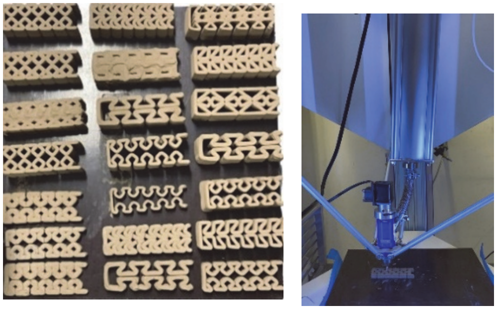


Figure 2
Variations of infill patterns created with the Delta Wasp Clay Printer.

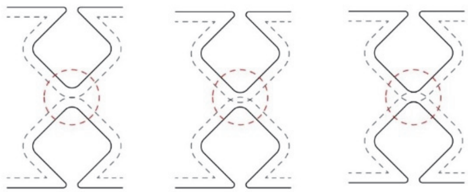
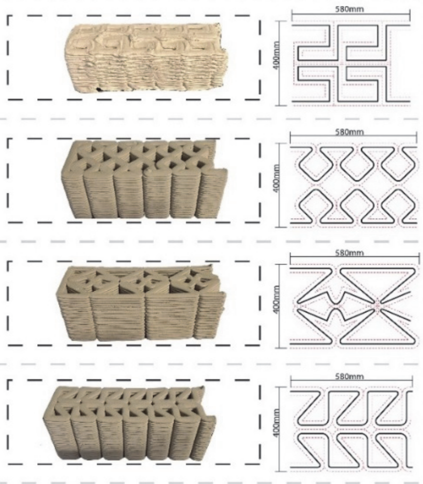


Figure 3
Connection Types

Figure 4

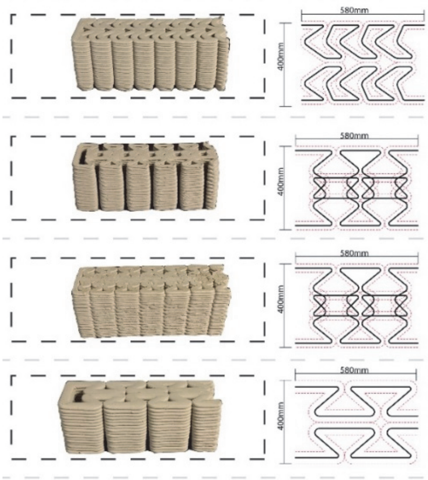
3D CLAY PRINTING, PROTOTYPES TESTS
SCALE: 1-10

Self-tangent Half overlap Full overlap



Curve length (mm)	Layer height, width	Straight or Curved	Infill density	Printing height flow rate	Printing time, speed	Connection type
905	2mm 4mm	straight		48 mm 100%	11 minutes 0.16mm	half-overlap
639	2mm 4mm	curved		48 mm 70%	8 minutes 25 seconds 0.2 mm	self-tangent
813	2mm 4mm	curved		48 mm 70%	11 minutes 0.2 mm	half and full overlap
798	2mm 4mm	curved		48 mm 70%	10 minutes 0.200mm	self-tangent

Figure 4 and 5
The prototypes are compared based on the given parameters.



Curve length	Layer height, width	Straight or Curved	Infill density	Printing height	Printing time, speed	Connection type
928	2mm 4mm	curved		48 mm 70%	15 minutes 46 seconds 0.168 mm	self-tangent
1062	2mm 4mm	curved		48 mm 60%	13 minutes 17 seconds 0.2 mm	full intersecting
1062	2mm 4mm	curved		48 mm 70%	15 minutes 10 seconds 0.2 mm	full intersecting
618	3mm 6mm	curved		48 70%	5 minutes 20 seconds 0.3 mm	self-tangent

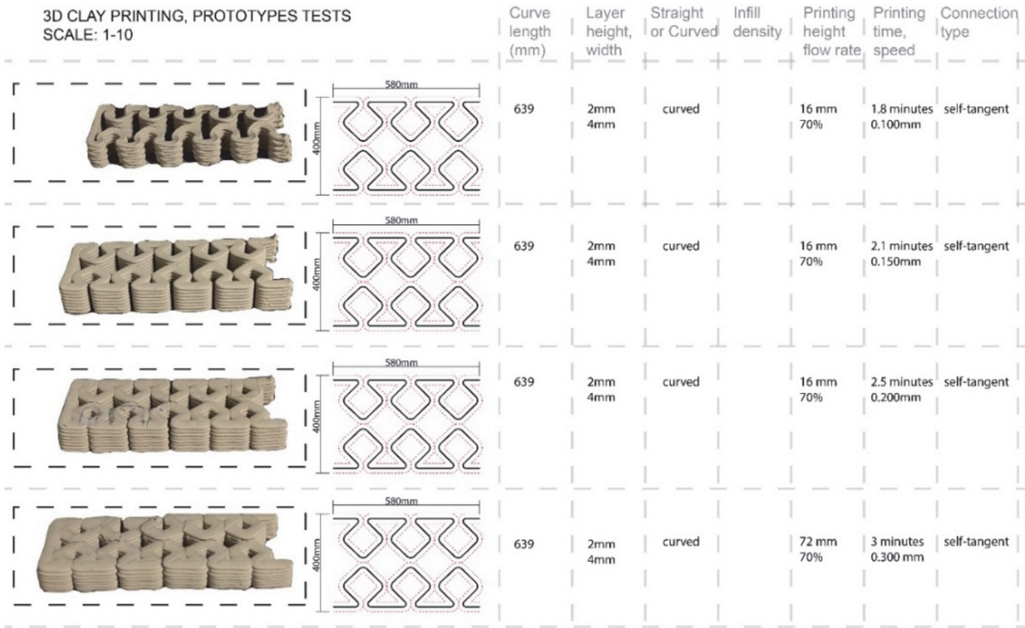


Figure 6
The selected infill for the final prototype tested.

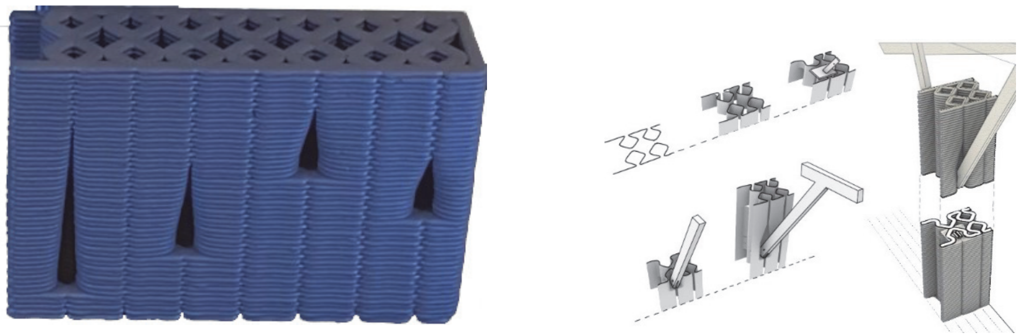


Figure 7
Creating openings on the wall.

Creating openings

After choosing the desired form, the following phase of the design is to create openings in the wall where the timber elements will be placed. In this stage, Grasshopper enables control of the parameters for the parametric geometry. These are considered how to design the gaps and how max. and min, and the opening might be. The timber structure's dimension is 5x10mm on a 1:10 scale. Additionally, the inner layer has the effect of strengthening the clay, and each layer adequately bonds to the layer below. Hence, it makes it possible to create openings and overhangs in the wall without collapsing (see Figure 7).

Furthermore, the following stage of the study will involve incorporating more features into the wall during the printing process with human interaction. After the openings are created, the purpose is to create a shelter as a case with two walls as load-bearing concrete structures. Tova is the first architectural construction taken as an inspiration for the final phase (IAAC TEAM 2022). A catalog of various shelters is designed for the final prototype.

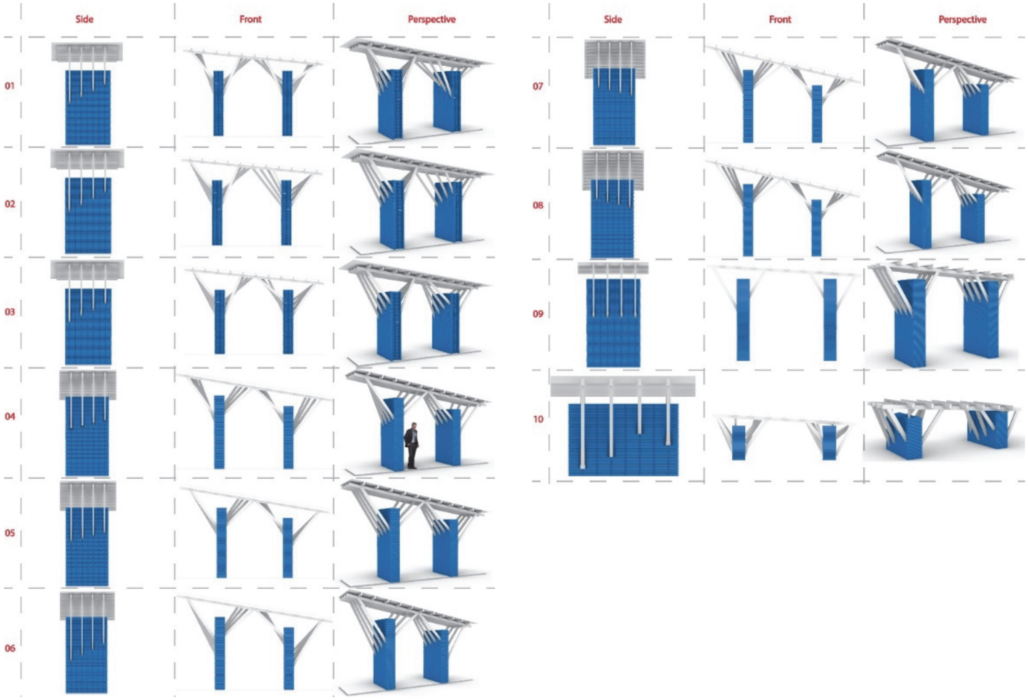
The illustration demonstrated below is listed and compared based on the arc openings with different levels on both sides of the walls, the angles, and the different heights of the walls.

The aim is to create more options to see and understand how it affects aesthetic value without compromising structural stability. The openings for the timber can be identical, random, or dynamic, so ten variations of the shelters are created (see Figure 8).

Joint design

The study proceeded through a solution for the connection of timber and concrete. It is applied to the metal joint, and it provides support for the wooden structures to lie on, which allows the load of the diagonal timber structures is supported by the concrete. The seats for the steel plates are created on both sides of the walls. The steel plates

Figure 8
The several types of final shelters.



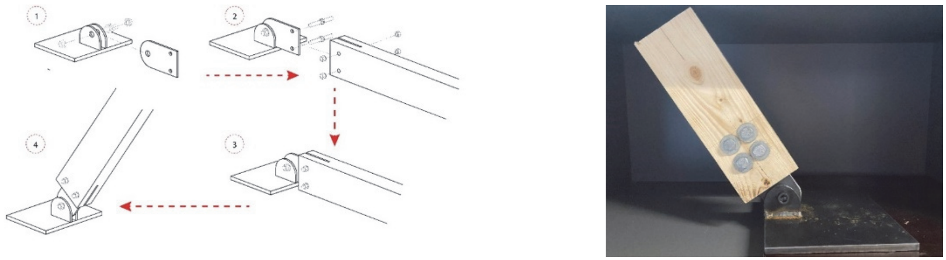


Figure 9
The steps of metal joints with the timber structure and 1:1 scale model.

are placed during the printing process with the aid of humans and interlocked to the wall. When the clay dries out, the wooden structure is connected to the steel plates with pinned joints horizontally to facilitate screw installation and push the system further into the wall. Once the installation is completed, the timber structure takes its shape diagonally and is ready to bear the roof structure. The diagonal wooden structure is supported by steel plates interlocked to the wall, and steel plates safely transmit both the lateral (horizontal) and axial (vertical) loads back into the foundations of the structure (see Figure 9).

RESULTS

The final prototype represents a design solution for incorporating additional elements in 3D printing with human intervention during the 3d printing process, such as wood and steel. The outcomes of physical prototyping and testing refer to wood structures integrated into 3d printed walls by merging concrete/clay 3D printing with the steel and wooden elements. Thus, a greater understanding of the material-fabrication process interaction and the possibilities offered by computational design is required to integrate with these elements, which are timber, concrete, and steel. For instance, timber structures inform 3D printed concrete walls to open specific gaps, and steel plates also report 3D printing to stop inserting the joint into the wall with the aid of humans while printing the model.

Following a thorough design phase, prototype number four is chosen for the final shelter as an optimal solution due to the aesthetic values, structural stability visually, and the appearance of the gaps (how max. and min. the gaps open in the wall for the placement of the timber structures (see Figure 10). The ultimate result of the shelter provided both aesthetic and structural qualities. It is also essential to see and understand how those additional elements would involve in the 3D printing process. The steel plates are interlocked to the wall with human assistance during the printing. The timber structures are connected to steel plates with a pinned joint. The system is supported by 3D-printed concrete and integrated into the 3D-printed walls.

Figure 10
The final shelter. 1:10 scale

DISCUSSION

1:1 prototype

With the knowledge gained throughout the design process, three months of investigations, and physical prototyping with a 1:10 scale, it would be more beneficial to shift the focus 1:1 scale prototype. The reason is that each scales show differently due to material properties, and it would give a better understanding of surface and spatial quality with a 1:1 scale concrete prototype. During prototyping, clay was used instead of concrete, and these material properties are entirely different. It is essential to start integrating with a 1:1 scale concrete prototype to see how 3D printing at large scales changes with other materials and how 3D printed concrete influences the overhangs. Although the prototypes have the same infill pattern with different materials, it gives a different expression with the clarity of surfaces. Furthermore, the physical placements of the joints are also crucial on a 1:1 scale in how the steel plate would be placed accurately. Steel is heavy, and how it affects material behaviors. For instance, it would sink into the concrete more during the printing as not desired.

Metal joint

The investigation moved forward by finding a solution for joining wood and concrete. It is applied to a metal joint with pinned rather than a fixed joint. Based on the knowledge, concrete is good at compression and fixed joint transfer moments into the joints, so there is more reaction. One side of the steel plates will be under compression and hold it down, while the back side will be exposed to tension, pushing upwards, so the steel plates tend to rotate. It is predictable with pinned joints, no moments in the connection, and the loads are distributed more evenly than fixed joints, so pinned joints are chosen for the connection of these materials. It is also arguable that if there is a need to research the joint, how can joints be made? Different materials might be used by not following traditional techniques. If there is more time, the research would look at more alternative materials and types for the connection. Additional material joint is not necessary, because it might be possible to overcome with the joint two different materials geometrically in the concrete component, for example, with a notch, toothed connection. The benefit of this approach is precisely its straightforward adaptation to the wooden components.

Structural analysis

One of the research objectives was to have a structural analysis to understand and see how the structure behaves. Due to time limitations, the structure was evaluated visually depending on the knowledge. From the structural point of view, it might be beneficial to simulate the structure. It would better clarify the structure’s strengths, how much force goes through in connection with timber, and how much KN the wall structure can bear. It might provide a deeper understanding of the capacity of the load-bearing.

Adaptive infill

As mentioned, infill patterns perform an active function as a structural element that bonds the structure together. The chosen infill follows an iterative strategy and is the same as the whole path. It also refers to structural analysis. Based on the investigations, the center of gravity of each layer is different when incorporating the cavities. Therefore, infill patterns might change to adapt to the design because more loads in the cavities are created. The infill can be denser when it takes up more force. Conversely, it can be lighter when there are no more forces to adjust the center of gravity by increasing or decreasing the material utilized. Due to the constraints of time, the structural analysis is not made. Otherwise, it would be efficient to create an adaptive infill, which is also essential for material consumption.

Future Studies

Regarding the procedure for printing concrete, the use of 3D concrete printing technology can be very helpful in replacing conventional construction techniques and the capacity to build. It permits the construction of extremely effective, exact, and intricate structures, which are challenging to construct using conventional techniques. Because of its faster, more economical, and easier-to-achieve material use and capacity to create more complicated geometries than traditional construction processes. This actually enables us to investigate novel construction possibilities, creating new construction scenarios.

Current Limitations

As mentioned earlier, physical prototypes with a 1:1 scale might be more useful to observe how large-scale 3D printing with alternative materials alters. For example, the inability of concrete printing to create significantly overhanging sections is a drawback. Structural behavior is entirely different from clay. There is also a necessity for concrete prototypes. The reason is that material characteristics affect overhangs and surface quality.

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