BE-AM

Built Environment
Additive Manufacturing

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SYMPOSIUM AND EXHIBITION

TECHNISCHE UNIVERSITÄT DARMSTADT

DDU
Digital Design Unit — Digitales Gestalten

ISM+D
Institute of Structural Mechanics and Design
Institut für Statik und Konstruktion

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INTRODUCTION

PREFACE

Just like the technology we are concerned with, BE-AM has matured from a niche product to one with relevance at the industrial scale. When we started in 2015, additive manufacturing was still for nerds and believers. Applications in the construction industry were experimental and specialized solutions.

Today, we are witnessing robots printing entire houses and AM products enabling free-form facades of multi-storey buildings. New technologies are constantly emerging, new products are entering the market, and new construction methods are not only conceptualized up, but also applied. Additive manufacturing has become relevant to every aspect of the built environment. It is a truly disruptive technology.

BE-AM was born from a gathering of friends and geeks. It has grown into a symposium for the exchange of knowledge, into a network for the exchange of resources, and into a platform for exhibiting the latest developments of additive manufacturing in the built environment. With its symposium, exhibition, publications, website, and research cluster at TU Darmstadt, BE-AM is a platform for innovators, inventors, dreamers, and makers, all united in the aim of improving the way we envision and materialize our built environment.

Philipp Rosendahl

ESSAYS

Figure 1: Magic Queen and its robotic gardener caring for the entirely biodegradable structure printed on-site at the Venice Biennale 2021 (image: Zita Oberwalder)

MAGIC QUEEN: A FULLY BIO-DEGRADABLE, IN-SITU SOIL 3D PRINTED STRUCTURE

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Abstract

The building industry's current ecological and environmental impact led to a renewed interest in sustainable processes such as earth-based construction. Traditionally, soil materials rely on standardized construction processes such as rammed earth construction, cob work, or assembly of compacted mud blocks. Despite the low environmental impact and benefits of soil construction, current techniques present various limitations. These limitations include restricted design freedom and standardized fabrication methods that allow only the use of particular soil compositions. A critical response to these limitations comes from the additive and robotic manufacturing domain. Soil 3D printing showcases a novel robotic binder-jetting process for earthen granular materials that combines bio-based polymeric binders with common granular soil substrates. This method is suitable for architectural and landscape components. To showcase this potential, we built a 90 ton soil 3d printed soil structure at the Venice Biennale 2021. This structure, named „Magic Queen," was built in-situ and was fully bio-degradable.

Introduction

The imminent need to reduce the environmental impact of the construction industry has led to a renewed interest in sustainable building materials.

One of these rediscovered sustainable materials is earth and soil-based materials [1-3]. Soils are a resource available almost everywhere in the world. Due to their low environmental impact, they offer the potential to create buildings with a very low carbon footprint and high sustainability benefits [4]. Soils are usually classified through their stratification, which starts with a top organic layer where plants grow and end at the hard bedrock of the earth's crust. Beneath the initial organic layer, one can find clay. This clay mixture gives soil its malleable character, which is used for most soil construction techniques. Traditionally, the three most common soil construction techniques are rammed earth construction, cob work, and assembly of compacted mud blocks [5]. The primary benefits of all these soil construction techniques lie in using a material that can be sourced locally, used immediately on-site, and does not require any additional industrial process or treatment. Despite the low environmental impact and ecological benefits of these soil construction techniques, these fabrication processes present various limitations. One of the limitations is restricted design freedom [6]. Another limitation is that most conventional soil construction technologies require a specific clay-based mixture. Other soil compounds or reused soil mixtures can not be easily used. A potential answer to both is computational design, robotic fabrication, and, more specifically, additive manufacturing [7-10]. These processes offer the potential to extend the design space toward more complex geometries and precise building structures. Furthermore, these technologies may allow for more efficient and cost-effective production.

Automation and fabrication with earthen materials

Most additive manufacturing techniques applied to earth-based materials focus on processes of earth deposition, similar to cob construction [11]. Cob construction traditionally consists of a masonry wall structure built up in horizontal layers using a mix of gravel silt and clay [12]. Each layer is compacted during construction until a desired density and bond between layers is reached. The difference between a traditional and a 3D printed cob wall is the use of an automatic and continuous material deposition process. One example of a digitally fabricated cob structure is TECLA [13,14]. It is a dome structure fabricated using raw earth and a multi-crane collaborative Wasp printer. The structure was fabricated using contour crafting and a design strategy that combines roof, structure, and cladding in one single fabrication process. Another digitally fabricated cob structure is the Caly Rotunda [15]. The project combines the traditional knowledge of clay constructions with contemporary digital design and robotic fabrication processes. The project is a free-standing cylindrical clay structure that spans 15 meters and is 5 meters in height. It was built in situ using a mobile robotic system aggregating 30.000 soft-clay bricks.

Both projects show the potential of pairing earth construction and material development with contemporary in-situ design and fabrication processes. Despite the innovation, these projects resulted in construction of cylindrical structures with limited design freedom. In other research projects, the innovations come from the methodology of earth deposition. "Terramia" shows an in-situ additive manufacturing spray protocol for constructing monolithic earthen shells [16,17]. The project uses temporary fabric formwork and drones to carry out earth spraying and drying.

Even though these research projects show the potential of sustainable, digitally controlled soil construction, most research in this area focus on either linear wall extrusion or dome-like structures. Furthermore, most fabrication processes that integrate earth-based materials with digital manufacturing are not entirely adaptive in using different soil types as they require very sticky clay mixtures. These limitations are difficult to overcome by standard contour crafting 3D printing processes or the assembly of clay bricks. Other processes, such as binder jetting, may offer an alternative; however, they require extensive research on bio-based binding agents to ensure an entirely biodegradable fabrication process [18].

Figure 1: Magic Queen and its robotic gardener caring for the entirely biodegradable structure printed on-site at the Venice Biennale 2021 (image: Zita Oberwalder)

Figure 2: Soil 3d printing process with a custom end-effector for compressing soil and distributing binder

Soil 3D printing method:

Soil 3D printing focuses on sustainable robotic soil fabrication for geometrically complex structures. The fabrication setup allows the design and fabrication of entirely biodegradable load-bearing granular structures (Fig. 1).

Research on soil 3D printing focuses on three main components, (1) binder-jetting process for granular materials, (2) biodegradable material systems, (3) design process, and (4) robotic fabrication processes.

(1) Binder-jetting process:

Soil 3D printing is based on an additive manufacturing process similar to binder jetting [19]. Binder-jetting is a process that uses chemical binding [20]. A printhead or a robotic setup carefully deposits a liquid binding agent onto a thin layer of powder particles — foundry sand, ceramics, metal, or composites to create high-end, complex 3D geometries. We use soil as a granular material and biopolymers as binding agents for this specific process. First loose granular soil is distributed within a predetermined boundary condition. Afterward, this layer of soil is compressed into a thin layer, and the binding agent is deposited following a predefined data path (Fig. 2). Therefore, this distribution of binding agents only happens at specific locations, critical only parts within a predefined boundary condition. This allows us to create highly intricate three-dimensional shapes. After distributing the binder, another thin layer of soil is distributed within the boundary condition. Correspondingly, this layer of soil is compressed to adhere to the already placed and compressed soil soaked with a binding agent. The process is repeated until an element is finished. After a drying period, which depends on the humidity of the space, the soil material and binding agent, and the amount, the soil elements can be excavated (Fig. 3). Only the parts where the binder is deposited are hardened out. The remaining areas of loose soil help stabilize the structure while hardening and can be reused for additional elements afterward.

(2) Biodegradable material systems:

The critical feature of Soil 3D printing is to create entirely biodegradable structures. This includes all fabrication aspects, such as the binding agents, granular material, and post-fabrication.

Figure 3: Excavation of the individual 3d printed pieces after a drying period.

Binding agents:

Soil 3D printing tests different biodegradable binding agents such as polysaccharides and biopolymers. These binders adhere to the individual soil layers and in the post-fabrication process to stabilize the overall structure. In condensed form, the binders can increase the compressive and tensile strength of the structure.

Granular material:

As an organic granular material, we use standard soil. The process allows all forms of soil types in correlation with the correct binding agent mixture. The different soil types' mechanical, physical, and chemical properties must be well-balanced with the suitable binding agent composite. As soil is a granular material, especially the parameters of density, compaction, and permeability define the potential of using soil as a functioning building material for complex geometries.

(3) Design process:

We developed a material-driven design approach to associate and define geometry through fabrication and material constraints for this research. These constraints refer to fundamentally different design steps. The first design step discretizes the overall design into individual parts able to be fabricated with the corresponding fabrication setup. The second design step adjusts the geometry of the individual parts according to mass transfer. Especially for the drying process, it is essential to align the center of mass and the center of gravity for each discrete unit.

(4) Robotic Fabrication process:

The fabrication setup of Soil 3D printing includes different robotic setups. „Pahoehoe Beauty" and „Terrestrial Reef" included a robotic multi-move setup including two robotic arms. The tasks of compacting soil and distributing binders were split between those two robots. In „Magic Queen," we used one robotic arm and a transferable robotic end-effector, which was used for both compressing soil and extruding binder. The custom-built end-effector was attached to the robotic arm and autonomously refilled itself periodically. The end-effector was equipped with sensor systems, defining pressure load and adapting to different layer heights. The robotic toolpaths transformed geometrical data into instructions for the robotic arm. In order to establish the perfect balance of fast printing and high precision, several algorithmic filling route densities and patterns were evaluated while considering the expansion of the binding agent on the material and the thickness of the extrusion nozzle.

Magic Queen

Magic Queen is after Pahoehoe Beauty (Ars Electronica, 2018) and Terrestrial Reef (Royal Chelsea Flower Show, 2019), the third iteration of the series „Artificial Ecologies' and proof of concept for the Soil 3D printing technology. The installation was fabricated in situ from March 2021 to May 2021 for the occasion of the Biennale Architettura 2021. In total, 90 tons of soil were used for the structure. For the structure of the Magic Queen, we used ordinary filtered soil (a mixture of sand, silt, and clay) from the on-site location, the mainland area of Mestre (Fig. 4). Two ABB robots were used for fabrication using transferable robotic end-effectors. One robot remained hanging upside down on-site throughout the exhibition period. The task for this robotic gardener was to observe the underlying terrain and to analyze, scan and care for the underlying topography and techno-organic built habitat (Fig. 5). The robotic gardener is equipped with two types of tools and sensors: First, a watering system to garden the seeds of the mushrooms in the soil, and second, a machine vision system to detect and register any changes in the surface texture, such as cracks and shrinkage, and growth of biological entities, such as plants and mushrooms on the structure (Fig. 6). This information was live streamed to a visual interface and an interactive soundscape to inform the visitors about the observations of the robotic gardener. These interfaces allowed visitors to understand and uncover the otherwise invisible stream and interconnectedness of impact and growth. The ambient sound was a mixture of artificially produced and natural tones, continuously influenced and manipulated by the robotic gardener's movements and the physical changes of the Magic Queen. The 3D printed terrain shows the potential of a fully reversible construction process for architectural and landscape components as the soil was fully reused and re-integrated into a garden in mainland Mestre.

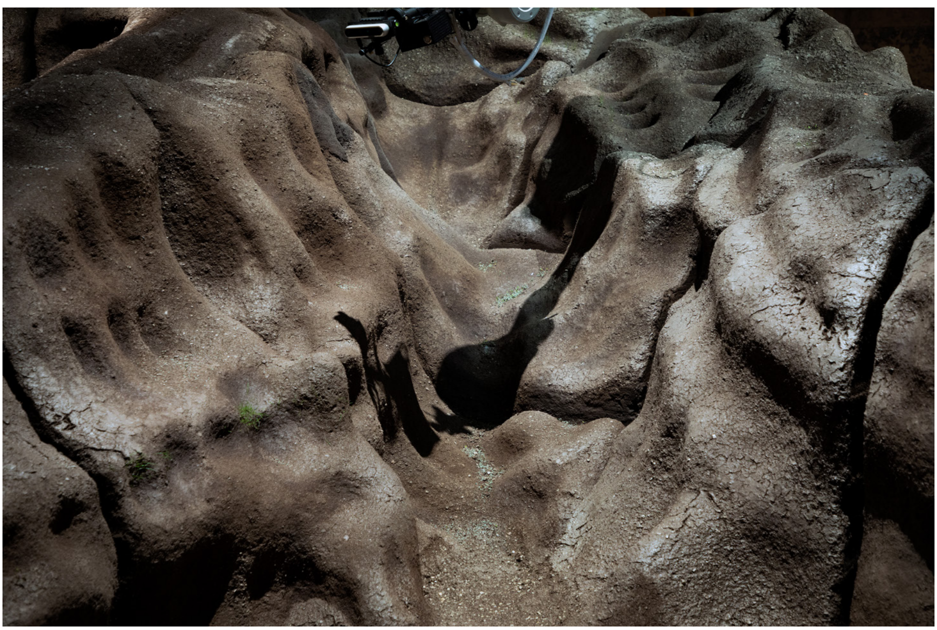

Figure 4: surface and geometric quality of the soil 3d printing process. The structure is cared for by a robotic gardener, scanning and analyzing the earthen construction.

Figure 5: Topview of the Magic Queen. The overall structure is build in individual segments that are assembled after the printing process.

Figure 6: Indoor grass grown on top of the soil 3d printed structure throughout the period of the exhibition

Discussion

The project highlights a novel robotic binder-jetting process for earthen materials and combines bio-based polymeric binders with granular soil substrates. The project shows a fully reversible in-situ biodegradable construction process for architectural and landscape components. It enhances the printability of soil structures for complex geometries and facilitates the integration of different soil compositions or substrates during the printing process. The long-term implications of this research lie in integrating low-carbon and biodegradable materials and evaluating their impacts on digital and robotic fabrication. The potential to fabricate full-scale constructions depends simultaneously on several fabrication parameters, such as biodegradable material research, novel digital additive manufacturing technologies, and robotic fabrication. Simultaneously, those factors indicate the need for greater automatization of tedious tasks while allowing for human-in-the-loop processes of specific fabrication steps. Such a robotic fabrication process requires real-time control of the fabrication process. Developing new earthen-based construction methodologies in contemporary manufacturing also requires the improvement of strategies for modeling the hygrothermal behavior of volatile and organic materials. Integrating continuous feedback on material behavior and predictive modeling approaches may help reduce the need to empirically validate material performance and integrate novel design strategies during the evaluation process. Further work is currently under development by the authors concerning the further characterization of the material composition, evaluation of environmental impact with long-term structural monitoring, improvement of mechanical behavior, and refinement of the fabrication process for in-situ applications.

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Figure 1: Presentation of a final module.

BIOTILES: A SUSTAINABLE INTERIOR WALL PANEL

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Abstract

The present project proposes the use of materials of natural origin in additive manufacturing, with a view to producing new decorative wall tiles. The historical evolution of the Vimaranense house, tells us a narrative that even today is kept intact by the preservation of its memory. It is common to see slate tiles in the city of Guimarães for gable linings, or additions to the roofs of buildings, such as chimneys, skylights, and rooflights. The soletos' or fish scales, are tiles of small dimensions and distinctive shapes, obtained from slate rocks.

Introduction

Contemporary architecture has been seeking new construction practices taking advantage of sustainable' green' materials. The excessive extraction of natural resources and the use of polluting equipment is causing a considerable environmental impact on planet earth. It is necessary to reduce the extraction of these resources and select materials of natural origin and low cost to obtain.

The presented project has the function of reinterpreting the soletos used in the housing construction of Guimarães, replacing the slate rock for materials of natural origin, reusable and biodegradable. The display consists of a set of individual modules, with the same geometry and different finishes, produced with cellulose and chitin – two natural biopolymers very abundant in our planet. Taking advantage of digital design and additive manufacturing techniques, a dynamic pattern was developed with different densities, providing a three-dimensional effect. Individually the modules are all distinct, when assembled they form a continuous pattern.

SEAfood waste

The fishing industry produces tons of seafood waste every year, resulting in large losses due to poor management of marine resources. Shellfish waste, such as seafood shells, fish scales, squid skins and fungal cells, are rich in chitin – the second most abundant natural biopolymer on the planet [3]. Chitin is a monomer structurally similar to cellulose (the most abundant polymer on the planet) and is obtained by a set of chemical processes – demineralisation, deproteinization – from shellfish waste. Chitosan, a polymer also of natural origin, is a derivative of chitin. The application of this biopolymer has led to a high search in the production of new components because it is a natural, non-toxic, low-cost, renewable, sustainable and biodegradable material. [1] The MIT has developed

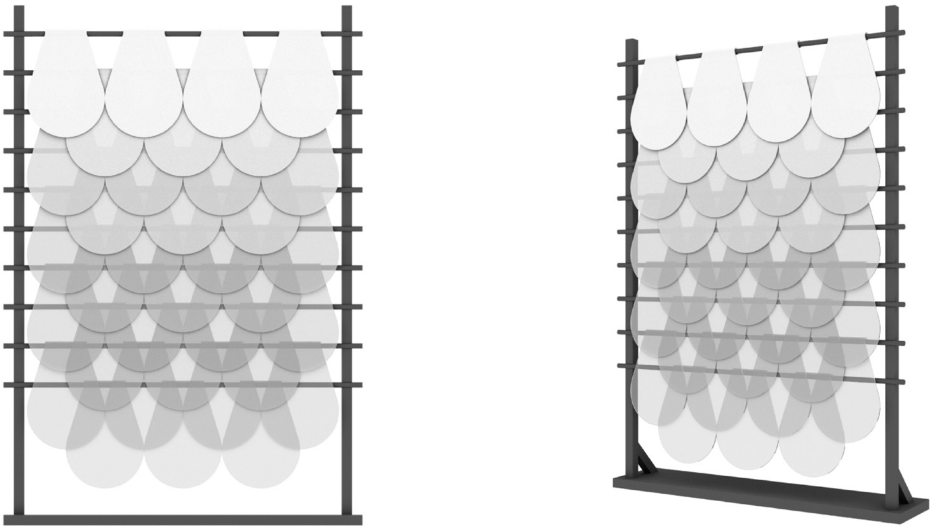


Figure 2: Three-dimensional presentation of the designed exhibitor with the respective modules. Front view (left). Axonometric view (right).

a prototype 'Aquahoja Pavillion' which consists of coating a metal structure using a mixture based on materials of natural origin –cellulose and chitin – for the additive manufacture of highly customised leathers. [5-7] At the University of Singapore, a 100cm high column was designed, using materials of natural origin – cellulose and chitin – inspired by the biological forms of nature. [4] The Shellworks group has developed a set of machines for chitin extraction. The machine prototypes designed have different functions, from the pure extraction of the material, to the transformation of the biopolymer into a marketable, highly sustainable, biodegradable and recyclable product.

BioDESIGN: Exhibitor digital fabrication

As a way of transforming the waste heavily found in the fishing industry and developing an architectural system, a vertical exhibition was proposed, composed of a group of individual modules, the BioTILES. These result from a reinterpretation of the old 'soletos' used in Portuguese historic buildings and aim to develop new decorative wall coverings. The 'soletos' or fish scales, are tiles of small dimensions and distinct shapes, obtained from slate rocks. with thin thicknesses, they overlap each other, fixed on a wooden lath with metal elements.

Developed using three-dimensional modelling software, Rhinoceros and Grasshopper, the proposed exhibition is composed of 35 individual modules, with different shades, textures and shapes (Figure 2). Like the 'soletos', the modules were designed taking into account the shape and fixing system. The geometry was inspired by the silhouette of the sea shells as a representation of nature and the sea.

The exhibitor is composed of a vertical structure – 1000mm height by 700mm width - and 10 horizontal profiles to support the modules and block it. The fixing system consists of the AM (Additive Manufacturing) of a semi-circular piece with a front open grid geometry (Figure 3). The grid functions as an aggregation system, in which the material surrounds the geometry, soaking it up, creating a strong link between them.

Designed the exhibitor and taking advantage of the AM technique PEM – Paste Extrusion Modelling – a pattern was developed to be printed in the modules. The pattern has the function to confer resistance to the module.

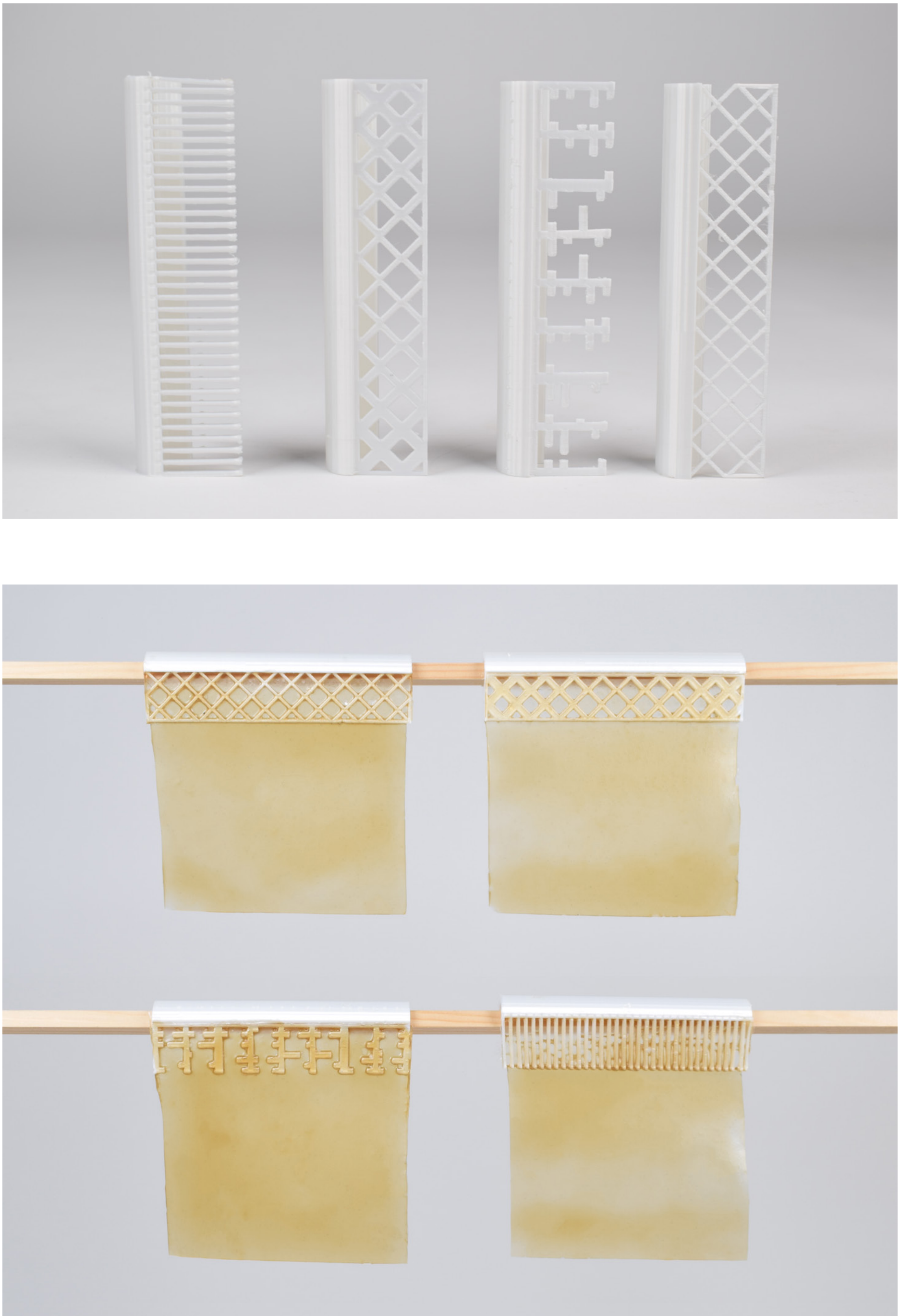
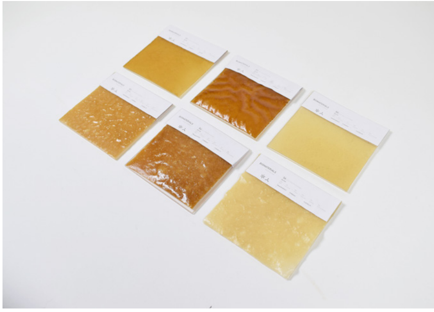


Figure 3: Presentation of the proposed fixing system. Proposal of the designed system (up). Proposed system embedded in the mixture (down).



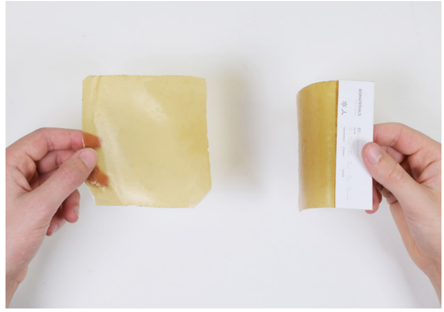


Figure 4: Different material finishes (left). Behaviour of the material with glycerine (right).

BioTILES fabrication

(1) Material Preparation

The material preparation consists of a combination of 80%-90% water (v/v), 4%-8% starch (w/v), 4% glycerine (v/v) and according to the final properties required, 0%-12% cellulose (w/v) is added. After homogenisation of the components, the mixture is heated until it forms a viscous pulp – a water-based hydrogel. Then, as the temperature decreases, 4%-8% chitosan (w/v) and 2%-4% acetic acid (v/v) are added and the material is ready to be used. [3]

(2) Material Properties

The addition of cellulose during the preparation of the material is related to the characteristics intended to be obtained in the final object. The function of this material is to increase the strength, rigidity and durability of the final product. The addition of glycerine is intended to give flexibility to the material, the higher the proportion, more flexible is the product. The chitosan and then the addition of acetic acid aims to transform the water-based hydrogel into a fully viscous and homogeneous pulp. [3] In addition, it has the function of giving colour to the final product, the higher the proportion of chitosan added, the more colourful is the final tone.

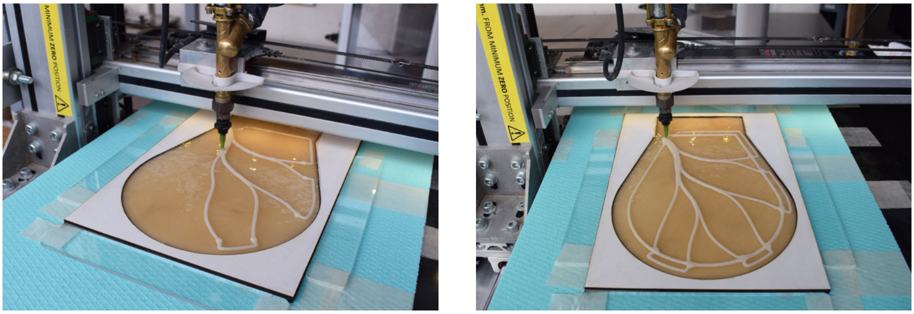


Figure 5: Printing a module using the PEM technique (Paste Extrusion Modelling).

(3) Fabrication

The manufacture of the exhibitor was divided into three work phases:

(1) Manufacture of the vertical and horizontal structure;
(2) Manufacture of the fixing system;
(3) Manufacture of the individual modules.

In a first step, taking into account the previously designed model, the support structure for the individual modules was produced. The structure is composed of 2 solid pine beams (20mmx20mmx1000mm), 10 solid pine slats (10mm (radius)x700mm) and a base in solid pine wood (1040mmx200mmx20mm).

In a second phase of the work, taking advantage of AM techniques, namely FDM - Fused Deposition Modelling - a set of open geometry patterns was studied and the one with the highest capacity to support external forces was adopted.

Once the structure and the fixing system had been developed, in a third phase the production of the 35 individual modules that make up the exhibitor started. The production of the components resulted in the combination of two AM techniques – Moulding and PEM. First the fixing was placed on the edge of the previously made mould. Then, the fluid mixture was introduced inside the mould until the empty space was filled, holding on to the open geometry grid (fixing soaked in the mixture). Finally, using the Lutum® 2.0 Mini printer, the developed pattern was printed on the previously filled mixture.

For the manufacture of the components, two types of mixture were used:

(1) Mixture introduced into the mould, a fluid mixture with a high level of flexibility (water + starch + glycerin + chitosan).
(2) Mixture printed on the mould, a fluid mixture with a high level of resistance (water + starch + cellulose + chitosan).

The combination of these two mixtures allows the module to assume different shapes, with a degree of resistance to possible breaks or tears

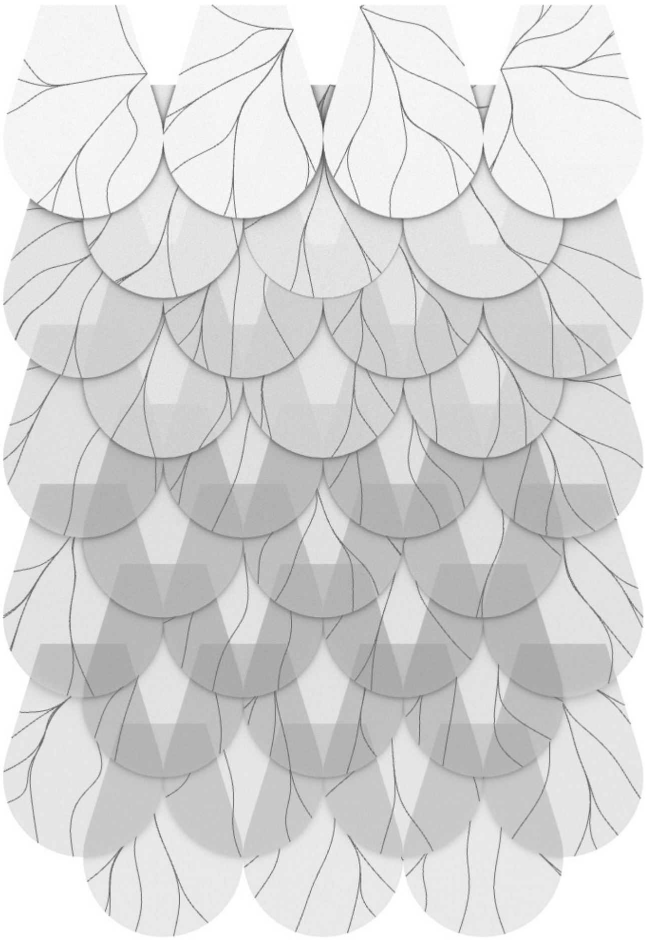


Figure 6: Proposal of the pattern for each module.

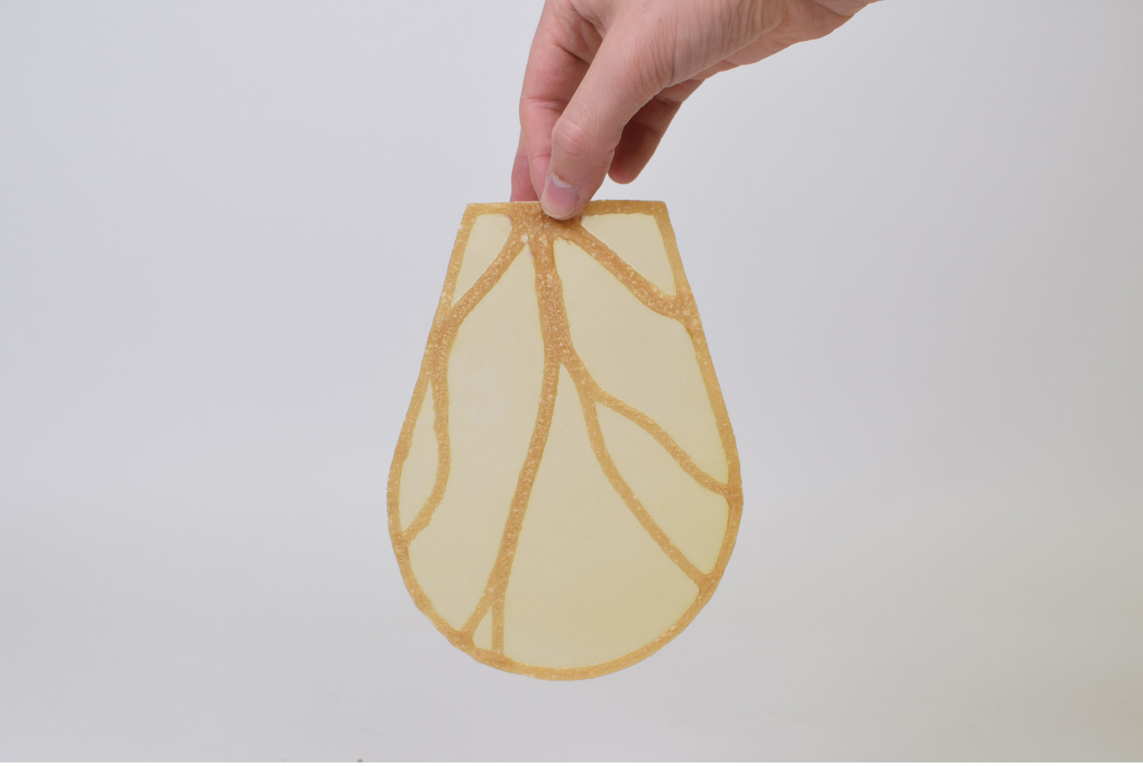


Figure 7: Presentation of a final module.

Conclusion

Motivated by the need to find a new strategy to reduce the continuous accumulation of seafood waste in the fishing industry, we have developed a set of natural, non-toxic, low-cost, renewable, sustainable and biodegradable mixtures. With the use of natural biopolymers, we have developed a new architectural application, the BioTILES, fully customisable. These pieces are a reinterpretation of the history of Vimaranense architecture – the famous Portuguese slate soletos' used in buildings in the historic centre of cities in northern Portugal, namely Guimarães and Porto. The alteration of the proportions of the different mixtures produced, confer different mechanical, physical and aesthetic behaviours. The proportion of chitosan strongly influences the shade of the material; cellulose considerably decreases the transparency; and glycerine provides flexibility and resistance to possible breaks. When combined in different proportions they give the final product different solutions. The exhibitor is composed of a set of options previously thought out, with the aim of creating optical illusions to the observers, due to the differences in colour and texture of the material.

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Figure 1: Detailed view of DED-L node in feature wall construction

TOWARDS ADDITIVELY MANUFACTURED FREEFORM STEEL & GLASS FACADES

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Abstract

AM is explored as a means of producing structural nodes for freeform steel and glass facade construction. Three AM methods are explored: PBF-L; DED-GMA; and DED-L. An overview of the respective fabricated node designs is provided. The novel AM methods are demonstrated in a mock-up and a large feature freeform facade. The mock-up and the feature facade are designed and constructed using a parametric digital workflow. The work presented in this paper is part of the exploratory phase of an on-going product development – a collaboration between Jansen AG, TU Delft, and knippershelbig GmbH.

Introduction

Freeform steel and glass facades are an increasingly popular feature in modern construction. The use of glass is an obvious choice as a means of providing spaces with natural daylight, and the use of steel as a substructure, which has high stiffness and strength, enables large spans and the use of slim members for maximum transparency and elegant facade constructions.

Steel and glass facades are typically constructed using multi-layered systems (Figure 2) where each layer has specific functions. In freeform applications, using straight profiles and planar glass is a common strategy for cost and fabrication efficiency. In these cases the complexity of the system is concentrated at the nodes. Node conditions are particularly challenging because the geometry required to effectively bridge each layer of the assembly without compromising their respective functions is complex, and also because each individual node condition is usually unique. The structural node, which is responsible for the transfer of forces, is the focus of this study.

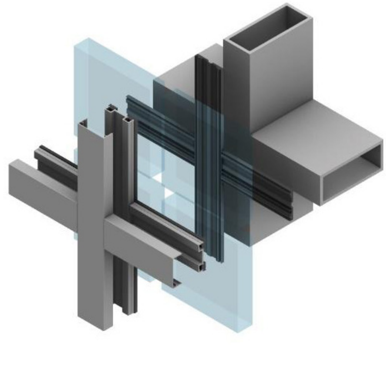


Figure 2: Multi-layer steel-glass construction

Figure 3: Solid CNC-milled Node for Bratislava Shopping Centre (image: Metal Yapi)

The current practice for the fabrication of structural nodes for freeform applications relies heavily on Computer-Aided Manufacturing (CAM). CAM technologies such as laser cutting, laser welding, and Computer Numerical Control (CNC) milling have all been used to create different structural nodes. Existing node solutions generally have key challenges related to fabrication efficiency, material efficiency, and performance. The solid CNC-milled node (Figure 3) is perhaps the most popular contemporary typology of freeform structural node, which enables elegant seemingly continuous grid-shells through the form-freedom afforded by multi-axis CNC milling. This type of component, however, is typically underutilized and materially inefficient. Especially in larger nodes this can add significant loads to the structure.

Additive Manufacturing (AM) enables an unprecedented level of geometrical freedom which allows designers to not only address the aforementioned challenges, but also allows for more design flexibility. This study explores the potential of AM as means of improving freeform steel/glass construction, and to expand the use of a commercial high-performance steel-glass facade system for freeform applications using AM node components. Three different steel AM methods are explored for the development of structural nodes. A full-scale mock-up and feature wall are constructed using the AM components.

A System-Approach to Freeform Construction

A "system approach" in reference to facade construction refers to the development of series of parts within a facade system which can be interchanged and/or adjusted based on the specific requirements of a given project without modifying the technical core of the system. Such an approach allows facade system providers to supply designers with a range of design possibilities for their buildings with a high level of engineering and manufacturing efficiency. The idea of a "system approach" is a key requirement for the development of the AM parts for this study. Standard interfaces are developed for the structural nodes to connect to the Jansen VISS facade system. The node designs should also have a parametrically-driven geometry with set design variables that can be sized based on the spe¬cific applied forces of a given application. In this way, the general shape, consistent with the printing strategy, remains the same within each node type. This comes with a number of key advantages: the fabrication operations and path planning can remain consistent; printing parameters, which can take significant effort to fine-tune for high-quality prints and reduced failed prints, can quite reasonably be standardized; and the engineering process can be made more efficient.

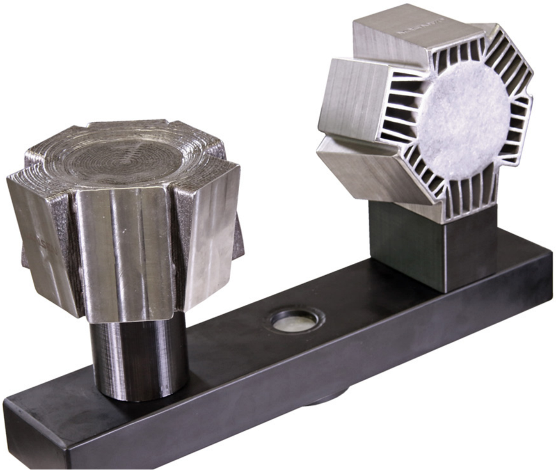
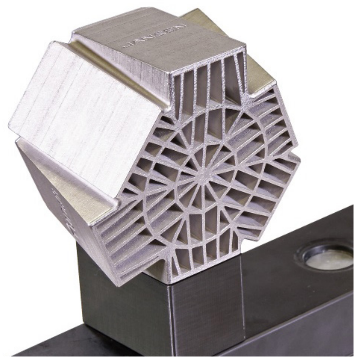


Figure 4: DED-L node design (left) PBF-L node design (right)

Structural Node Development

(1) PBF-L Node Design

The PBF-L node (Figures 5,6) was printed in 316L Stainless Steel. The main geometry of the node consists of a network of walls aligned roughly with the node axis and z-axis of the printer, such their overhangs are well within printing limitations. End faces and side walls make up the main volume of the node, an interior structure of concentric cylindrical walls with varying radii are at the centre, and plates running from each arm end face along the normal force direction of each arm connect the network of walls. Additionally, volumes of solid printed steel are printed around the main features of the end connections. The thus created radially oriented webs of the node arms provide a direct load path for the normal and shear forces as well as bending moments onto the cylinder at the centre of the node. Compression forces are introduced through contact, while tension forces are introduced via the four bolts anchored via the metric threaded blind hole in the thick end plates (not included in picture below). The central cylinder efficiently redistributes these loads predominantly via membrane action through the curved walls to the neighbouring arms and back into the adjacent structural profiles.



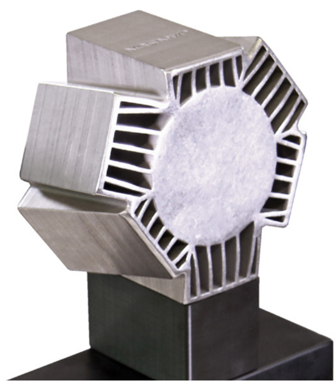


Figure 5: PBF-L node design interior face (up)
Figure 6: PBF-L node design exterior face (down)

Figure 7: : DED-GMA node front view

Figure 8: DED-GMA node interior structure (during printing) (image: MX3D)

Figure 9: Test print for DED-GMA node during CNC-milling

(2) DED-GMA Node Design

The DED-GMA node (Figure 7-9) was printed in 308LSi Stainless Steel. The print sequence and overhang implications of DED-GMA influenced the node design. The node consists of a primary arm that runs through the centre along the main load bearing artery of the node, and secondary and tertiary arms that connect to that one. The hierarchy of arms corresponds to the sequence in which they are printed. Each arm consists of outer plates at the outer-faces of the node, and interior plates running at around 45 degrees from the edges of the outer plates and joining at the centre of the node, gradually decreasing in width. For the end conditions, the plates gradually increase in thickness merging together at the end to form a flat end plate which allows for the standard end conditions. It should be noted that it is possible with more intricate path-planning to achieve flat end faces using less material without the gradual increase in thickness; however, the decision was made to print end conditions in a single plane to contain costs. The end faces and specific end conditions are subsequently CNC-milled to overcome the larger

Figure 10: DED-L node design

tolerances of the DED-GMA printing process.

The structural logic behind the node geometry is based on the principle of intersecting castellated beams. The continuous flanges allow a smooth transfer of in-plane forces from bending and axial forces across the node, while the thick webs connected at the centre transfer shear forces between members. The arm hierarchy is clearly visible in the surface pattern of the printed node. While the other two designs were designed to be as small as possible, the DED-GMA node was allowed to have longer arms so that the interior structure could be clearly visible, a design decision which negatively impacted the fabrication-intensity of the design.

It is also worth noting that while DED-GMA is able to produce objects at this scale, it is at the edge of what is appropriate for this technology. Upon reflection, this design would be more suitable for a larger node, or alternatively, at this scale, a better design would avoid such constricted printing space in the center of the node in order to fully take advantage of the strengths of this technology.

(3) DED-L Node Design

The DED-L Node (Figure 10) was printed in 316L Stainless Steel. The machine a hybrid 5-axis DED-L/ NC-mill. The node is printed radially in a solid volume so there are limited overhang conditions. The end faces and end conditions are subsequently milled to achieve the high required tolerances.

The structural principles for the node build-up and load transfer follow those described for the PBF-L node. The material displays orthotropic behaviour as a result of the directional printing. The latter was assessed by means of physical tests on small samples: the tensile capacity of the material perpendicular to the direction of printing is lower than in the longitudinal direction but still exhibits sufficient strength compared to the base material so that in combination with the force-optimised node geometry, this provides a robust and efficient solution.

Full-Scale Facade Development

(1) Parametric Workflow

The realisation of the AM facade is rooted in a parametric workflow from the design of the overall geometry to the generation of the CAM models. This parametric workflow takes place in five phases summarised in Figure 12 The purpose of compartmentalizing the parametric workflow in this arrangement is to complement the system-approach to the node design, which allows generous flexibility over the course of design exploration through fabrication.

(2) Mock-up Development

In order to demonstrate the novel AM facade system, two full-sized mock-ups were designed, fabricated and assembled at the Jansen HQ in Oberriet. Both use as a base system the VISS facade system, a commercial facade system by Jansen AG, with the AM interventions at the complex connection points – i.e. the nodes.

The first mock-up (Figure 11) incorporated the three nodes produced with the three AM methods during the exploratory phase of the project in a 1.5m x 3m wall section. This phase also included material testing to verify the durability and strength of the materials.

After the first round of node exploration for the mock-up, the decision was made to produce the structural nodes for the feature wall with DED-L technology. The feature wall (Figures 1;14-15) is an approximately 25m^2 facade with an S-shaped plan and constantly variable double curvature. The design aims to showcase as many application cases as possible, incorporating concave, convex and anticlastic conditions across the facade.

The mock-up and feature wall were subjected to a range of global and local structural calculations and simulations to ensure structural stability and the structural capacity of the facade system (Figure 13). During the design and engineering process, a lot of attention was also paid to the development of the connection detail between the structural nodes and the profiles. Several concepts were examined and tested by means of prototypes.

Figure 11: Mock-up wall with 3 trial nodes: DED-GMA (top); PBF-L (middle); and DED-L (bottom)

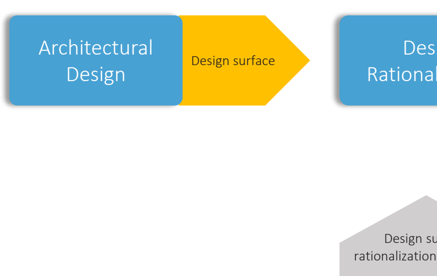


Figure 12: Parametric workflow for mock-up and feature wall development

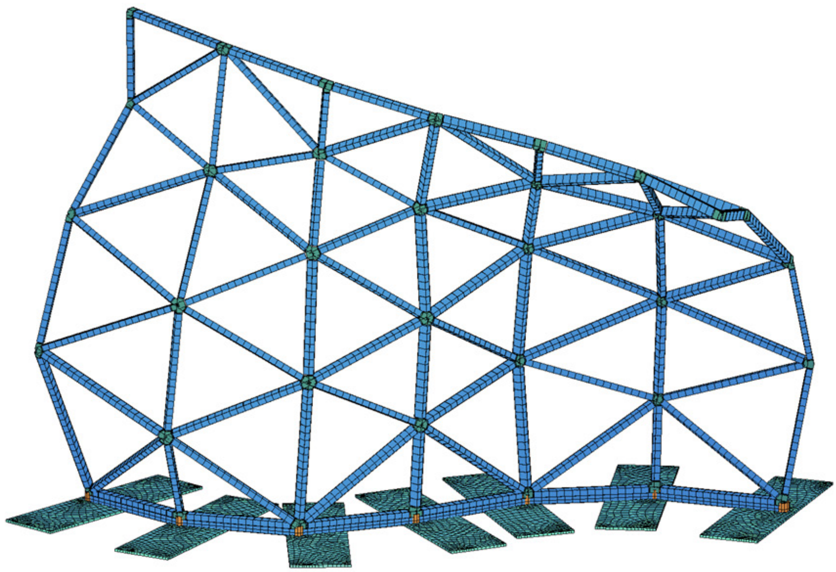


Figure 13: Finite Element Analysis model of feature wall
(image: knippershelbig GmbH)

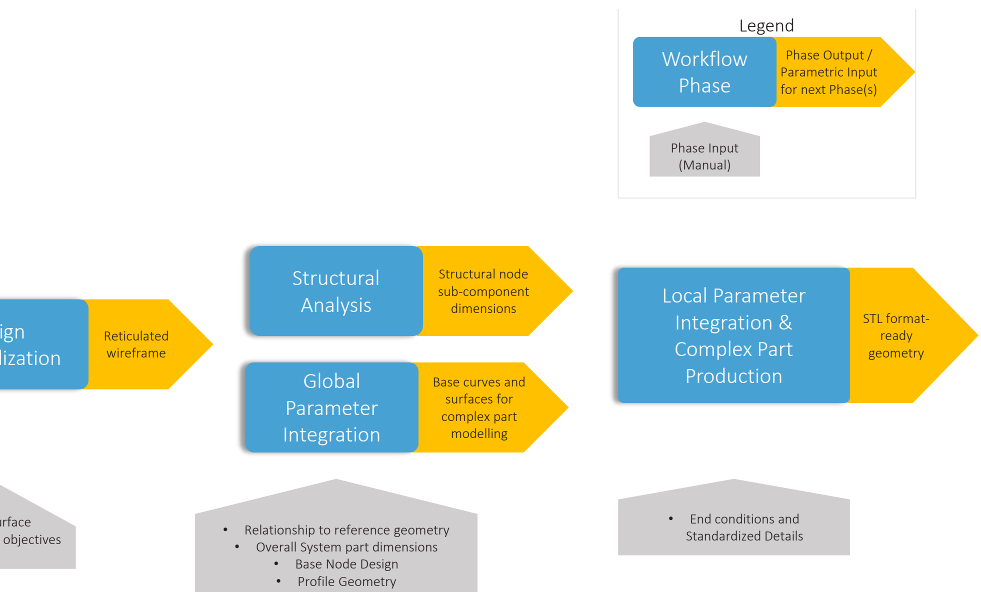


Figure 14: Exterior view of freeform feature wall with AM nodes

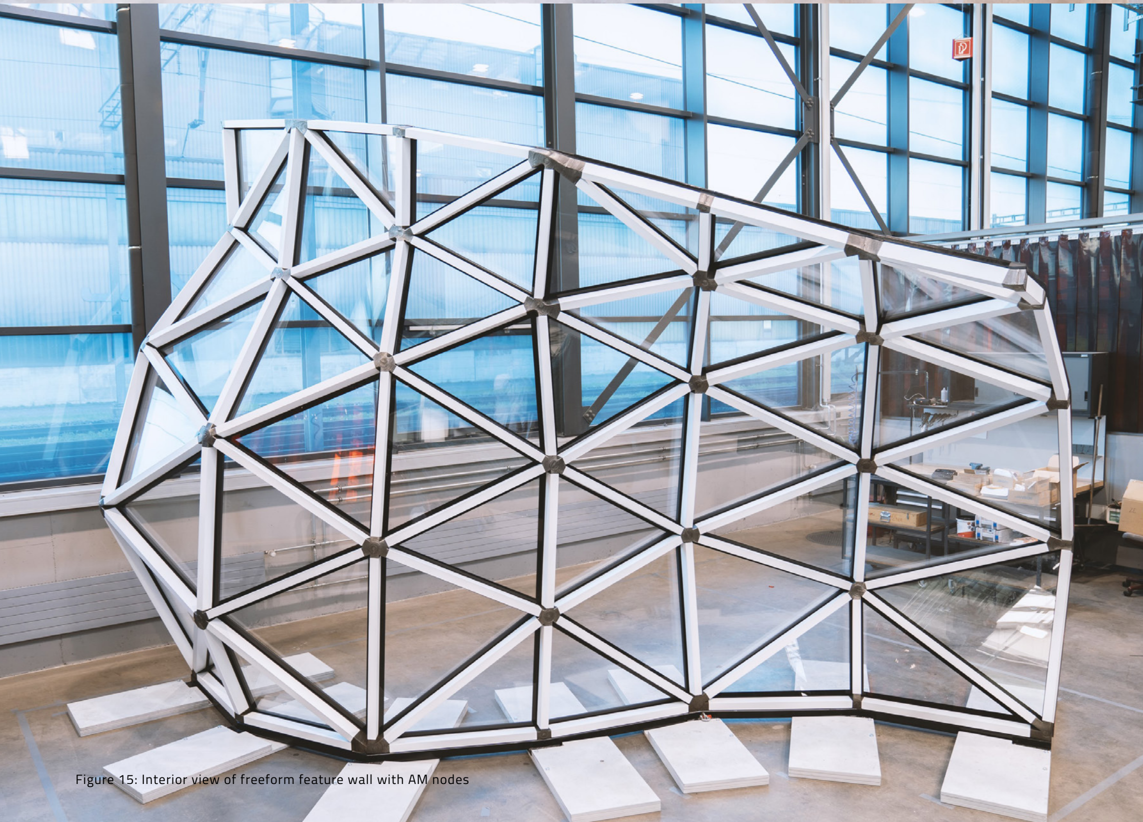


Figure 15: Interior view of freeform feature wall with AM nodes

Conclusion

In this study, three different AM methods and three respective node designs were explored as a means of producing structural nodes for freeform steel-glass facade applications. It should be noted that the node selected for the final construction is not a conclusive assessment of which printing method is more suitable for this type of application. This is because, as mentioned, "this type of application" in itself varies quite significantly and the most suitable printing method for one project may not be the same for another depending on a number of design variables such as size, structural requirements, desired shape and surface quality.

The development of the mock-up and feature wall have highlighted many of the strengths but also the challenges of working with AM. On one hand, each node design brings something to the table that the more traditional designs do not. The DED-GMA node has an organic interior geometry that would near-impossible to produce using other manufacturing methods. The SLM node also has a unique character as is approximately 40% lighter than a solid CNC node. The DED-L Node is also 20% lighter than a solid CNC node and has an intriguing surface finish. The designs were conservatively engineered for this study and there is plenty of room for further material optimization in future development. In addition, the AM nodes have an almost insignificant amount of waste material when compared to that from the solid CNC-milled node, which can have high buy-to-fly ratios. The system-approach to design also provides the groundwork for standardized engineering processes for freeform structures that enables to minimize risks in planning and cost. On the other hand, the integration of CNC milling was necessary to varying degrees for each of the printing methods. This is unlikely to change when high-tolerance, concealed mechanical connections are desired. Also, particularly in cases of DED technology, proper path-planning is an integral part of the process and a big factor in the efficiency of the printing process.

Regardless of the AM method in question, the development of AM structural nodes benefits from multi-disciplinary collaboration. The overall geometry of the freeform facade and its discretization dictates the structural requirements of the assembly and the minimum size of the AM intervention. Further, the geometry of the nodes and manufacturing method selected to fabricate them is inextricably linked to their appearance, their structural performance, and their manufacturability. Each AM method also has its own strengths and limitations which need to be navigated in order to achieve time- and cost-effective AM products. The effective use of AM thus benefits from communication between designers, facade system experts, structural engineers, and experts in the field of AM. This on-going project is a multidisciplinary effort between Jansen, TU Delft and knippershelbig GmbH.

Figure 1: Rendering of a 3D-printed, point-shaped connection of glass facade elements by a spider construction (image: Robert Akerboom)

ADDITIVE MANUFACTURING OF GLASS FOR THE BUILT ENVIRONMENT: POTENTIAL AND CHALLENGES

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Abstract

The rare combination of transparency, strength, durability and recyclability makes the material glass extremely attractive for our built environment. In the building industry glass is commonly used as a flat 2D-Element. The technology additive manufacturing (AM) allows the realization of new structures and free-form applications in the built environment. AM of components made of metals and plastics has experienced severe attention from researchers worldwide over the last years and can be considered as a state of the art technology in several industries. Compared to metals and plastics, AM of glass can still be considered within an embryonic state of research. This paper presents and summarizes the potential applications and the challenges of AM with glass in the field of architectural engineering. The possibilities of reinforcing and local stiffening are addressed, as well as the vision to develop glass connections, directly printed on a glass pane. Glass in the building industry will not always be flat in the future.

Introduction

Because of its unique combination of properties in terms of transparency, strength, durability and recyclability, glass is a unique and indispensable material for architects and engineers in the built environment. Besides a few applications as curved glass, flat glass as soda-lime silicate glass is used for applications in the building industry. The reasons are processing limits in glass industry, especially high requirements for shaping large glass structures in combination with the low quantities and the costs. The technology additive manufacturing allows the realization of new structures and free-form applications in the built environment. In contrast to metals and plastics, research in this area is still in its infancy.

Due to the experience with glass as a flat element, it is evident to apply a 3D structure to the 2D element with the help of AM Glass, thus enabling completely new possibilities in different sectors for individual designs (e. g. building, facades, furniture and automotive). With this substance-to-substance bond homogeneous, transparent and individual glass joints and glass reinforcements on flat glass are imaginable. The requirements to transparency, durability and strength in the building industry means a challenging task for the realization of 3D printed glass structures on flat glass.

A few research projects (see [1], [2], [3], [4], [5]) focus on the additive manufacturing of individual glass components, but they did not address the joining process between the additive manufactured glass and flat glass or other larger glass structures. Furthermore, the largest manufacturing output of AM glass samples are in a range of 200 mm x 200 mm x 200 mm. For the building sector, the processes are thus not suitable in functional applications. For potential applications, AM of glass on flat glass is thus a very promising idea, but challenging. The AM technology fused deposition modelling (FDM) is our research focus because this technology allows high process speed and is ideal for components being printed on flat glass. Preliminary investigations demonstrated the general feasibility of Fused Glass Deposition Modelling (FGDM) on a flat glass plate as a first step towards the additive manufacturing of glass structures on flat glass Seel et al. [6], Seel et al.[7].

Potential

Within the field of architecture, glass plays a key role in both the appearance and the experience of buildings. Not only does it establish a relationship between the in- and outside of a building, but it also transmits light and protects the occupants from external ambient conditions such as rain and wind. Glass is strong enough to be used as a structural barrier and its transparency might offer a clear orientation within the space, which can include visual relations between inside and outside or different rooms.

Additive manufacturing (AM) of glass provides completely new possibilities for individual and optimized glass structures. This enables homogeneous, individual glass and transparent glass joints and glass reinforcements on flat glass without drill holes or adhesives. As a result, material-related thermal bridges and the effects of aging in adhesive joints, e. g. due to solar radiation, can be reduced. For example, one future application is a point-shaped connection of glass facade elements by a metal spider construction (see Figure 3). The transparent point fixings made of glass are printed onto the flat glass. Further examples of applications are line-shaped reinforcements of flat glass, like ribs are shown in Figure 2 and Figure 4. This allows, among other things, an adjustment of the bending stiffness of flat glass according to serviceability requirements. The resulting reduction in flat glass thickness enables savings in resources such as energy and CO_2. This is briefly illustrated by the following example. In consideration of the serviceability limit state (ULS) according to glass design code DIN 18008-2 [8], an uniaxial load-bearing glass plate with a length of 2000 mm (load-bearing direction) and a width of

Construction type	Glass plate	Glass plate with addition AM glass reinforcement
Glass platte - thickness [mm]	12.2	6
Additional linear glass reinforcements - cross section width [mm] x height [mm] (amount reinforcements)	-	14 x 10 (6)
Area of cross-section	12 200	7400
Moment of inertia [mm^4]	151 320	154 380
Deflection [mm]	19.7	19.3

Table 1: Comparison of a flat glass plate to a glass plate with additional reinforcement via AM glass

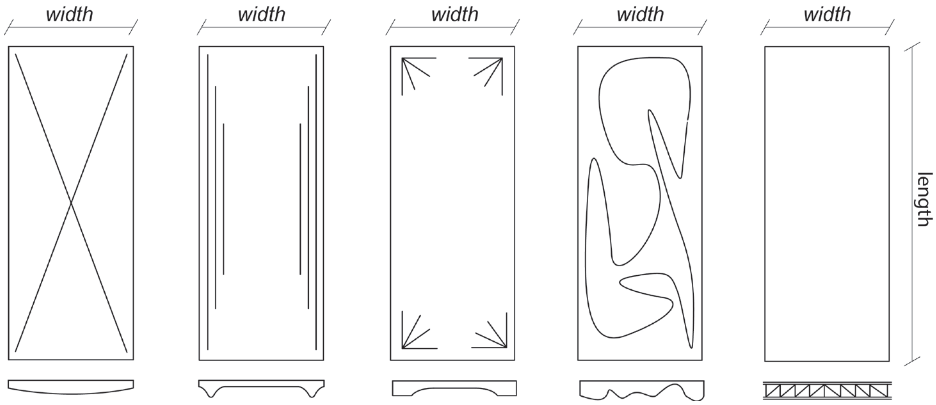

Figure 2: Potential typologies for structural reinforcement of flat glass by AM Glass (iamge: Robert Akerboom)

1000 mm under a surface load of 0.001 N/mm² requires a glass thickness of more than 12 mm. In contrast, if a 6 mm thick glass plate is reinforced with 10 ribs in the dimensions of 14 mm in height and 10 mm in width, then 39% of weight can be saved. The corresponding results between the two design types of a 2000 mm long are shown in Table 1. A further application are line-shaped glass consoles for the load transfer of a transparent staircase (see Figure 5).

In addition to a structural improvement of glass constructions, architecturally attractive designs can be implemented in a facade. Individual and colored structures can be created. Figure 4 shows such colored reinforcements on flat glass. In general, waste glass can be used for the printing process (FDM). Our vision is to realize 3D printed glass on flat glass in the dimensions of 3.25 m x 20 m.

Figure 3: Rendering of a 3D-printed, point-shaped connection of glass façade elements by a spider construction (image: Robert Akerboom)

Challenges

The printing process via FDM on flat glass in large dimensions is sophisticated due to the high process temperatures (T > 1000°C), the development of non-uniform residual stresses in combination with the brittle material behavior of glass as well as the shape conservation of the flat glass plate. During the joining process between the molten glass layers and flat glass (joining area), the glass is to be heated to a temperature in the range of the working point (1030°C for soda-lime silicate glass) with a viscocity of 10^4dPas. On the one hand, the low viscosities or high temperatures are necessary for the joining process and the durable joining of glass. On the other hand, they lead to unintended changes in shape of the desired structure, if the glass remains too long in a state of low viscosity. The temperature of the glass outside of the joining areas of a glass component should be in the range of the glass transformation temperature (525°C for soda-lime silicate glass) in order to maintain the geometrical shape of the structure, to avoid residual stress and cracks. In addition to cracks and unintended changes in shape, bubble formation and crystallization areas can also occur if temperature management is inadequate.

A successful joining process of glasses is primarily dependent on the glass viscosity, the joining time and the temperature settings during heating, joining and cooling phase. Further parameters are the ratio of heat quantities and the geometry of the joining partners, the thermal expansion behaviour of glasses to be joined as well as the residual stresses generated during heating and cooling. Furthermore, the temperature dependence of the material properties (e.g. thermal expansion coefficient, strength and viscosity) of the glass both for fusing as well as providing the flat glass to be printed on (glass base plate) have to be considered during the joining process. In the ideal case, the resulting glass structures are homogeneous and reproducible. Homogeneous glass joint implies that the interface between the joining partners is undetectable (visually), free of cracks, crystallization, bubbles and residual stresses. Furthermore, there are no differences in mechanical properties, such as strength and Young's

Figure 4: Reinforced glass plate via colored glass ribs


Figure 5: Rendering of a future console (3D-printed) envisaged for a staircase (image: Robert Akerboom)

moduls, in the joining area.

For the realization of these ideas, there was no machine available to implement these ideas, so we designed and built our own lab-scale glass 3D printer within an interdisciplinary team at the Glass Competence Center of TU Darmstadt. This printer is designed for the fundamental analysis of the process-structure-properties of the integrated joining process between fused layered glass (printed glass object) on flat glass and the optimization of this manufacturing process. The extreme high process temperatures in combination with molten glass and the ambient atmosphere in the building chamber or melting chamber require special high-temperature materials, which do not degrade in this mentioned environment.

The additive manufacturing with glass is quite complex, but feasible.

Conclusion

This article presents and summarizes the potential and the challenges of AM glass structures on flat glass in the built environment. The additive manufacturing of glass structures is complex and sophisticated due to the high process temperatures, the occurrence of residual stresses, the brittle material behavior of glass and the large amount of process parameters. An own lab-scale glass 3D printer is under development for investigating the resulting glass components and optimizing the manufacturing process. In following papers more results of printed samples will be shown. In a further step, this lab setup is to be scaled up to larger glass formats together with an industrial partner, so that a system is created that is capable of printing on flat glass in dimensions of 500 mm by more than 1000 mm. Further aspects such as pre-stressing and laminating the resulting structures as well as the development of a design concept for a safe and durable usage in the building sector are on our scope.

As a vision for the built environment, we foresee facade glazing with dimensions in the range of 3.25 m x 20 m which can be connected to a substructure using 3D printed glass joints on flat glass for the connections and locally reinforcing the flat glass perpendicular to its surface. AM is a possibility to created 3D and free-form glass structures without molds, thus glass structures in the building industry will not just be flat in the future.

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Figure 1: Completed building in august 2021 (image: PERI)

DIGITAL FABRICATION IN 3D CONCRETE PRINTING

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Abstract

MENSE-KORTE ingenieure+architekten, owned by Ulrich Mense and Waldemar Korte, is an architecture and engineering company based in Beckum, Germany, with a tradition of over sixty years of planning residential buildings, industrial properties, schools and offices. In 2020 MENSE-KORTE designed and engineered the first 3D printed residential building in Germany. With the construction of that house, this new manufacturing technology was successfully used for the first time in this country for the production of a residential house, thus laying the foundation for the successful introduction of the 3D concrete printing process into practice in the German construction industry.

Introduction

The idea to realise Germany's first printed residential building was raised from a Beckum dry construction company. Inspired by the idea, the main task was to transfer the technology, which had already been developed on a smaller scale, into practice, so that a real building could be created that met all the building code requirements of the German state of North Rhine-Westphalia. Since small printed building structures (pavilions) already existed in the surrounding European area, the challenge should be increased. Therefore, it had to be a building of a size and complexity equivalent to a high-quality detached residential building with two storeys. Starting with a fairly simple building structure in the initial design, it quickly became apparent that it would be essential to design a building that should optimise constructional, design and process challenges of today's building industry (Figure 2).

Figure 2: Animation first 3D-printed building in Germany (image: MENSE-KORTE)

Design process

The initial design process for printed building structures is largely similar to that of conventional construction methods. The designer and the client jointly define the requirement profile for the building use, the building size and the architectural design. In terms of building architecture, concrete printing can already show its advantages for the first time. The planners are no longer limited in the realisation of their own ideas by cost-efficient, rectangular floor plan geometries, but can give free rein to their design ideas (Figure 3). In 3D concrete printing, free floor plan shapes can be realised without affecting costs or construction time compared to stringent shapes. Thus it was possible to design the building in Beckum completely freely in terms of floor plan, in order to demonstrate the potential of the printing technology. However, in order to also serve practical purposes like e. g. the ability to mount cupboards or pictures on a wall and use standard furniture, a certain number of straight walls was included. With 3D printing, the design process takes place early on the digital building model, so that effects of planning changes become directly visible and provide planning security for all project participants.

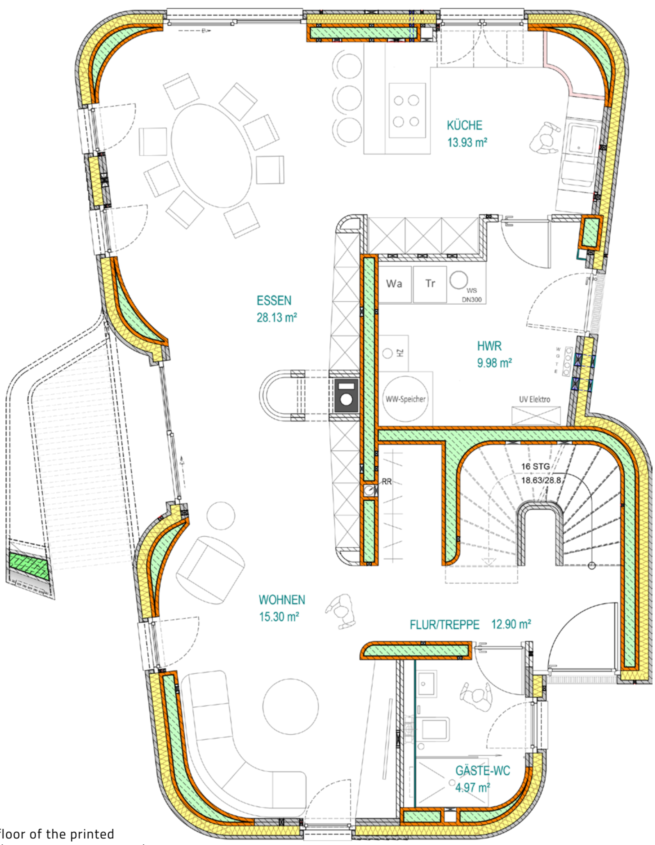

Figure 3: Groundfloor of the printed home in Beckum (image: MENSE-KORTE)

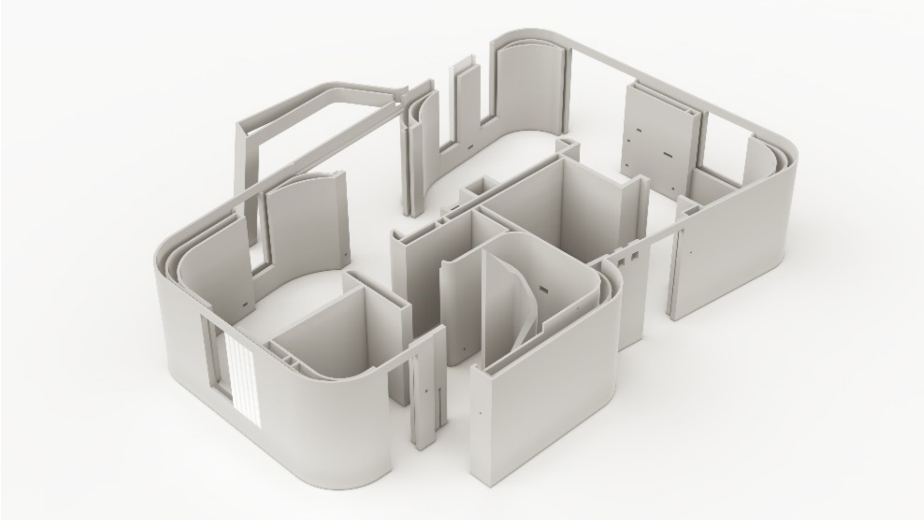

Figure 4: BIM model of the printed house (image: MENSE-KORTE)

Special features in the design of 3D-printed houses

The BIM-based building model is an essential part of the project management of concrete-printed buildings. On the one hand, planning with a 3D model means generating a great depth of planning at an early stage, but on the other hand it requires the project team of building planners, structural engineers and TGA planners to work together much earlier than it is the case with conventional construction projects. With additive manufacturing of buildings, wall recesses and slots for supply lines can already be planned in the 3D building model and precisely produced on site by the machine. In the Beckum project, for example, cut-outs for the electrical junction boxes and slots as well as risers for the sewage pipes could be integrated in the printed structure and then manually fitted with junction boxes or sewage pipes directly during printing (Figure 4).

This largely eliminated the need for subsequent rough installation by the building services trades. The functionality of a seamless digital process chain has proven to be an important element in the planning and local realisation of printed buildings.

Figure 5: Printed groundfloor with cavity walls (image: MENSE-KORTE)

Construction concept

The residential building in Beckum was designed as a solid construction with multi-layered wall structures. Through the interaction of the different wall shells with individual widths of 60 mm, it was possible to generate cavities which, on the one hand, could accommodate the thermal insulation as fill-in insulation and, on the other hand, were used as a lost formwork for locally casted unreinforced concrete for statically highly loaded parts of the building. All vertical wall components were constructed without reinforcement. The horizontal components such as ceilings and the floor slab were conventionally reinforced, partly as partially prefabricated concrete elements laid on site on the printed wall panels and subsequently concreted on with ready-mixed concrete (Figure 5).

The facade consists of a 60 mm wide strand of printing mortar and was connected to the load-bearing printed exterior wall structure with wall anchors made of stainless steel.

Figure 6: Completed building in august 2021 (image: PERI)

Conclusion

The construction of the first 3D-printed residential building in Germany in Beckum shows that additive manufacturing processes are a real alternative to conventional construction methods. In addition to the ecological and manufacturing advantages, a new design language can be applied to the architectural drafts and multifunctional components can be realised (Figure 6).

Lessons learned during the project majorly revolve around the overall construction process. While once the printer was running the actual print process was very smooth, however the preparations for the print were time consuming. Due to some slight deformations in the 3D printed structures, the elevations of the printed object did in the reality not equate to the model. Hence, regular adjustments to the model were needed to achieve e. g. level window sills around the whole building. This can be avoided in the future with the help of laser scanning during the printing process

Figure 7: Completed building, interior design (image: PERI)

Figure 1: Representation of the infilled diagrid column fabricated at TU Braunschweig.

WAAMGRID: DIGITAL DESIGN AND FABRICATION FRAMEWORK FOR WIRE-AND-ARC ADDITIVE MANUFACTURED DIAGRID LATTICE STRUCTURES

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Abstract

The digitalization of the construction sector could potentially produce more efficient structures, reduce material waste and increase work safety. Current strategies for the realization of automated steel constructions see the application of metal 3D printing processes (and in particular Wire-and-Arc Additive Manufacturing) as an opportunity to build a new generation of efficient steel structures with reduced material use. This, though, requires advanced multidisciplinary knowledge in manufacturing, metallurgy, structural engineering and computational design. Lattice structures are adopted at different scales and applications for their high efficiency in terms of high stiffness and minimized material use, however with strong limitations in the scalability for the assemblage of the single elements. The WAAMGRID project proposes a comprehensive digital design and fabrication framework for a new generation of steel 3D printed lattice diagrid structural elements for various applications in Architecture, Engineering and Construction (AEC). The idea comes from the preliminary results achieved in terms of new structural optimization theories, fabrication of large-scale lattice elements with WAAM and structural verification of first prototypes of WAAM diagrid columns. The project aims at increasing the application of 3D printing in construction, through a new generation of metal 3D-printed efficient structures.

Introduction

The digitalization of the construction sector could potentially produce more efficient structures, reduce material waste and increase work safety [1,2]. In particular, the application of additive manufacturing (AM) has proved to support the Circular Economy by (i) offering new raw material options, (ii) increasing the efficiency of the fabricated designs thus reducing the in-production waste and (iii) simplifying the resource recapture, hence supporting composting and recycling [3]. Among different AM processes, Wire-and-Arc Additive Manufacturing (WAAM) appears the most suitable for large metal structural elements with 50% reduction in CO2 emissions [4]. Moreover, breakthrough design tools for modern architecture as algorithm-aided design could be used to increase the structural efficiency and thus reduce the environmental impact of the construction industry. However, high-skilled professionals are needed to fully apply automation in construction. In order to efficiently apply WAAM in construction through innovative computational design tools, several challenges and drawbacks need to be faced.

The use in recent decades of computational design technologies resulted in the development of new structures with formal freedom and ideally infinite complexity, often designed to aim for structural efficiency. Nonetheless, current building production still does not allow for such freedom. Hence, the application of advanced tools for free-form design is often limited to few explorations in pioneering architectural applications.

Slender structural systems, as the ones commonly adopted for tall buildings, are based on stiffness-based design criteria. For this reason, diagrid structural systems have been widely used for tall buildings (with high slenderness) over the last century [5]. The pioneer of optimal lattice structures for towers was Vladimir Shukhov, who first introduced the hyperbolic gridshell structure [6]. However, the main drawback laid on the customized connections of straight elements forming the lattice structure, which increased their complexity and construction cost.

Specific considerations must be made when dealing with WAAM elements: (i) the inherent surface roughness, which could influence the mechanical properties [7,8], (ii) the marked mechanical anisotropy due to the specific microstructure [9–11], (iii) the influence of process parameters in both geometrical and mechanical response [12]. Hence, specific knowledge in advanced manufacturing technology should be combined with structural design competences to efficiently fabricate high-strength WAAM elements.

The structural behavior of WAAM systems is strongly governed by the specific geometrical and mechanical features. One possibility to directly account for these issues is to follow a "design by advanced analysis" approach resulting in a "digital twin" of the structure, as recently proposed by Gardner et al. for the MX3D Bridge [13]. Nevertheless, such advanced simulation tools require high computational skills beyond the capabilities of professional structural engineers.

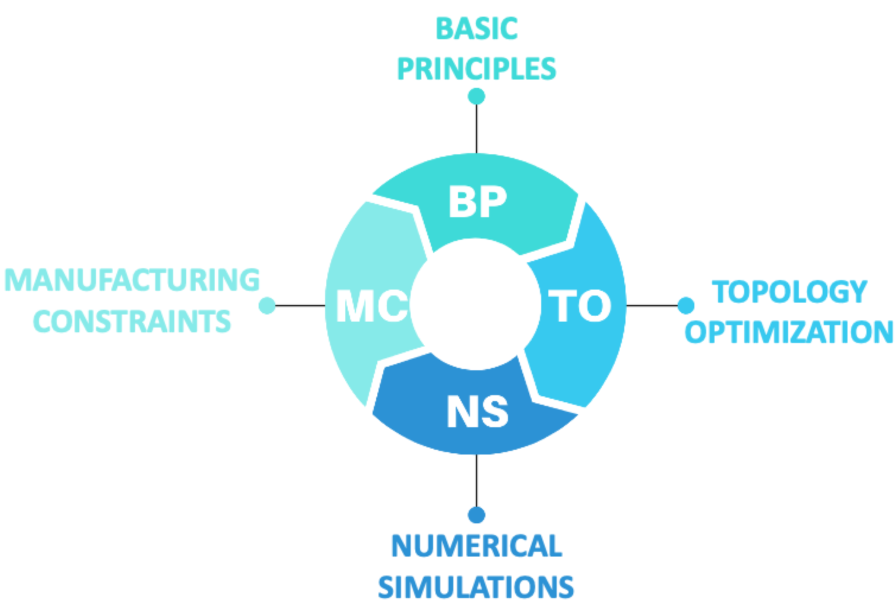

Figure 2: Fundamental aspects of the blended structural optimization approach. Adapted from [14].

Preliminary studies

Preliminary studies on the WAAMGRID project were developed to assess (i) the computational design tool for WAAM, (ii) the fabrication of large-scale WAAM lattice elements, (iii) the structural verification of WAAM diagrid elements for construction applications.

"Blended" structural optimization

With the aim of integrating the capabilities of optimization procedures in terms of new structural shapes with the current limitations of WAAM technology (i.e. manufacturing constraints, printing precision and material properties) together with the robustness and reliability of structural design verifications, a so-called "blended" structural optimization approach was proposed (see [14]). Indeed, the approach is intended to "blend" a stiffness-based topology optimization approach (suitably tailored for WAAM stainless steel, see e.g. [15]) with basic principles of structural design in terms of conceptual design and structural solutions to conceive an initial design, together with concepts of robustness and reliability to guide the designer from the purely mathematically optimized solutions towards the final design. A "blended" structural optimization approach may be conveniently used to investigate effective solutions in an efficient way. The fundamental aspects of the blended design approach are the basic principles, the manufacturing constraints, the algorithms for topology optimization, the numerical simulations to verify the structural performances (Figure 2). Detailed information on the approach can be found in [14].

Figure 3: WAAM diagrid column fabricated at MX3D (left) and representation of a real-case scenario (right). Adapted from [18].

Fabrication of WAAM infilled lattice column

A joint research collaboration with TU Braunschweig in Germany was assessed to study the fabrication process to realize large-scale lattice columns produced with WAAM. The technology consists in the production of a series of bars intersected to each other fabricated with the so-called "dot-by-dot" printing strategy, as also studied in [16,17]. The final outcome resulted in the first 60 cm high fully infilled steel lattice column, representing the base of a 12 m high pillar (see Figure 1).

Structural verification of WAAM diagrid column

The first study on WAAM diagrid lattice structures was performed on a half-scaled diagrid column designed by the author and fabricated at MX3D facilities in Amsterdam in 2018. The design was also recently awarded with the "Special Mention by Autodesk" in the Construction category of 3D Pioneers Challenge 2021.

The research presented an overarching design process from the concept to the fabrication of a diagrid column realized using WAAM. It represented an example of a fully-engineered structure based on the circular integration of information coming from material characterization and manufacturing technology, architectural shapes and computational structural design and analysis. The final design was then verified through numerical simulations with finite element models and its effectiveness has been assessed in terms of weight ratio and utilization ratio considering a uniform cylindrical column as a benchmark solution, confirming its good performances. Further information can be found in [18].

The WAAMGRID project

The WAAMGRID project aims at creating a new computational design tool for the design and fabrication of WAAM diagrid structural elements for various applications in Architecture, Engineering and Construction (AEC) (see Figure 4). Below are reported the steps forming the proposed framework.

(1) definition of the computational design protocol

In order to adopt algorithm-aided design techniques for WAAM and integrate structural design requirements for the construction industry, a new computational design protocol for WAAM lattice structural elements is proposed. The computational design protocol will combine: (i) specific features proper of WAAM process (such as manufacturing constraints, specific mechanical properties and geometrical tolerances), (ii) structural design requirements from Eurocodes based on the specific AEC applications, and (iii) topology optimization algorithms for efficient designs. The protocol is based on new analytical derivation of efficient lattice poles based on slenderness and inertia equivalency currently under patent protection.

(2) creation of a catalogue of WAAM lattice structures

Based on the current state-of-art, a comprehensive catalogue of WAAM diagrid lattice structures for efficient design is proposed. Literature review on gridshell structures, diagrid systems and lattice towers will be thoroughly studied focusing on specific aspects, e.g. (i) the structural design procedure adopted, (ii) the structural stiffness-over-strength ratio and (iii) the construction procedure. The catalogue will be implemented in the computational design protocol and used to select the designs to be then fabricated.

(3) fabrication process

From the developed catalogue, selected WAAM diagrid lattice structures for different applications in AEC will be proposed for fabrication. The envisaged applications are, among others: (i) aluminum pole systems for street lighting, (ii) stainless steel pillars for high architectural appealing buildings, (iii) carbon steel reinforcement grid for shotcrete 3D printed (SC3DP) free-form concrete systems, (iv) carbon steel grid as retrofitting system for existing reinforced-concrete columns.

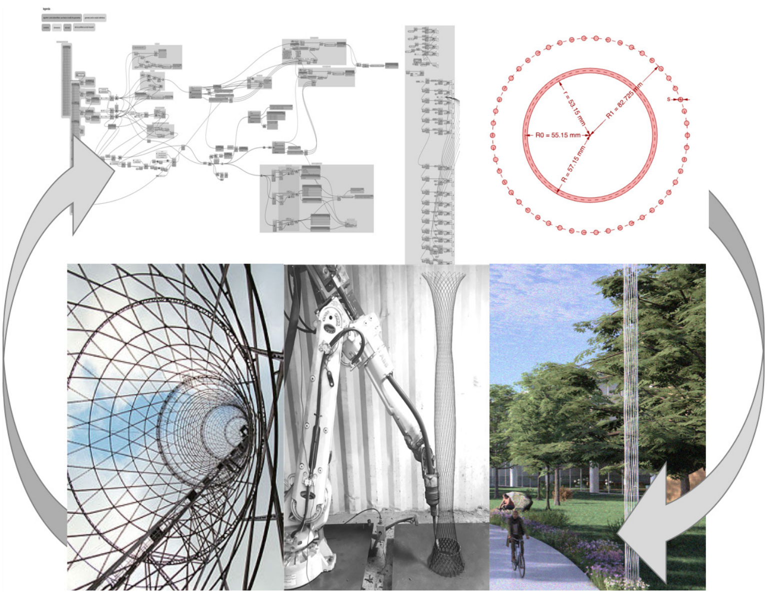

Figure 4: Overview of the WAAMGRID project.

(4) structural verification process

From the fabrication of the design solutions for different applications, a specific testing and verification procedure for WAAM diagrid lattice structures is proposed. First, ad-hoc testing procedure will be formulated, accounting for the mechanical anisotropy and geometrical irregularities proper of WAAM process. For this aim, ad-hoc mechanical and geometrical characterization will be carried out on small elements. The test results will be compared with the outcomes from structural verification through finite element (FE) modelling.

Conclusion

The work presents an ambitious project (called WAAMGRID) for the development of a computational design and fabrication framework for WAAM lattice diagrid structures.

WAAM technology, and in particular the so-called “dot-by-dot” strategy, allows to produce diagrid lattice elements with high structural efficiency, reduced material use and high impact in the construction field. Preliminary studies were carried out on (i) computational design tools aimed to realize WAAM structural elements, (ii) fabrication of large-scale WAAM lattice structures and (iii) structural verification of first examples of WAAM diagrid column.

The project aims at facilitating the development of metal 3D printing technique in the construction sector, by creating a new generation of high-efficiency structural elements following the basic principles of lattice structures (from Shukhov’s studies) combined with advanced computational design tools and fabrication techniques.

Acknowledgements

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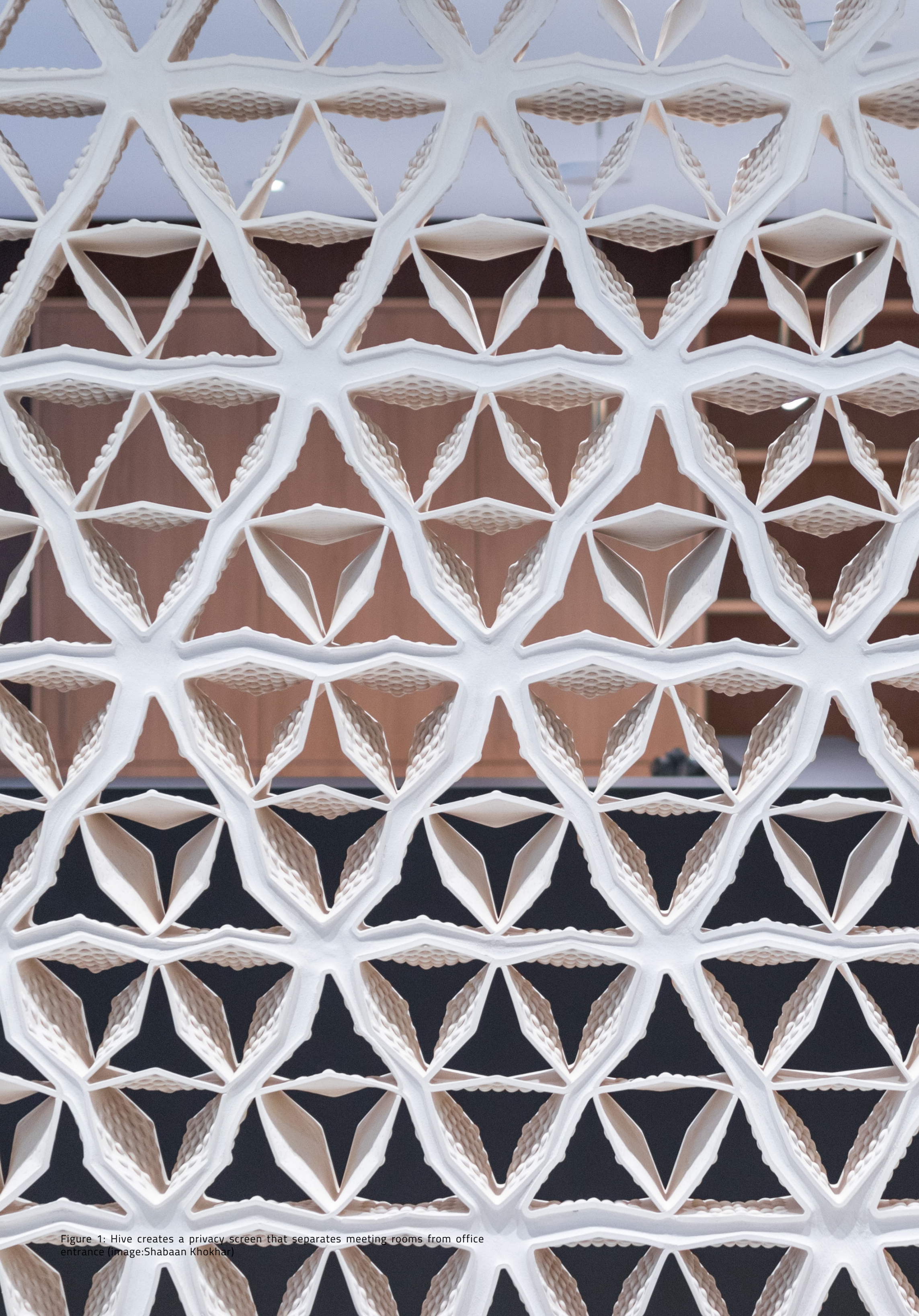

Figure 1: Hive creates a privacy screen that separates meeting rooms from office entrance (image:Shabaan Khokhar)

3D PRINTED CERAMIC SCREENS: LEVERAGING TOOL PATH DESIGN IN FUNCTIONALLY GRADED ADDITIVE MANUFACTURING

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Abstract

This paper presents two projects that challenge the prioritization of regularized performance attributes in contemporary ceramic material systems. Both projects utilize Functionality Graded Additive Manufacturing at different scales to alter material performance attributes. Custom tool path generation is leveraged to control material deposition over the volume of the printed part and create apertures that capitalize on the viscoelastic properties of clay.

The first project, Oil Lamp 2, is a unitary light screen that forms apertures on a meso-scale by prioritizing sectional performance over form generation. Apertures utilize controlled deformation to grade illumination across the surface of the light screen. The second project, Hive, is a masonry wall that forms apertures on a macro-scale by utilizing the form definition of masonry components as the principal mode of regulating performance. Hive is constructed from an aggregation of 175 unique units that form variable hexagonal apertures. Each aperture expands or contracts to create a gradient of porosity that regulates views through the wall

Figure 2: Oil Lamp 2 on display at the Canadian Clay and Glass Gallery

Oil Lamp 2

Oil Lamp 2 is a ceramic light screen that utilizes tool path design to generate apertures in the wall section. In this research, an individual opening in the light screen section is referred to as an aperture. These openings are functionally graded in scale to generate light diffusion effects and regulate illumination. The tool path of this light screen generates unsupported overhangs that create sagging coils, an aesthetic feature that is commonly utilized to create ornamental 'looping' in 3D printing clay artifacts. While the deformation of 'looping' or 'woven' textures in 3D printed ceramics is often regarded as an unnecessary aesthetic feature in the development of structural applications, they can be harnessed to address alternative performance characteristics.

The functional gradation of the apertures is achieved in the section profile of Oil Lamp 2 by creating a repeating cycle of deformation and re-stabilization in the print layers. The tool path is designed to prioritize the performance attribute of controlled plastic deformation at the scale of a single print layer over contributing to a global geometry. The printed tool paths in this light screen are designed to deviate significantly from one another. Clay is deliberately directed into unsupported areas, creating porosity in the section profile (see Figure 4).

Print coil deformation is utilized in Oil Lamp 2 at the scale of a single print layer to form a dense, multilayered sectional condition that creates multidirectional light diffusion. A pattern of three vertically repeating print layers forms the multilayered apertures in this light screen.

The first (A) and third layers (C) in this sequence act as a homogenous substructure. The second layer (B) regulates the amplitude of the apertures by sagging away from the substructure to produce a gradient of

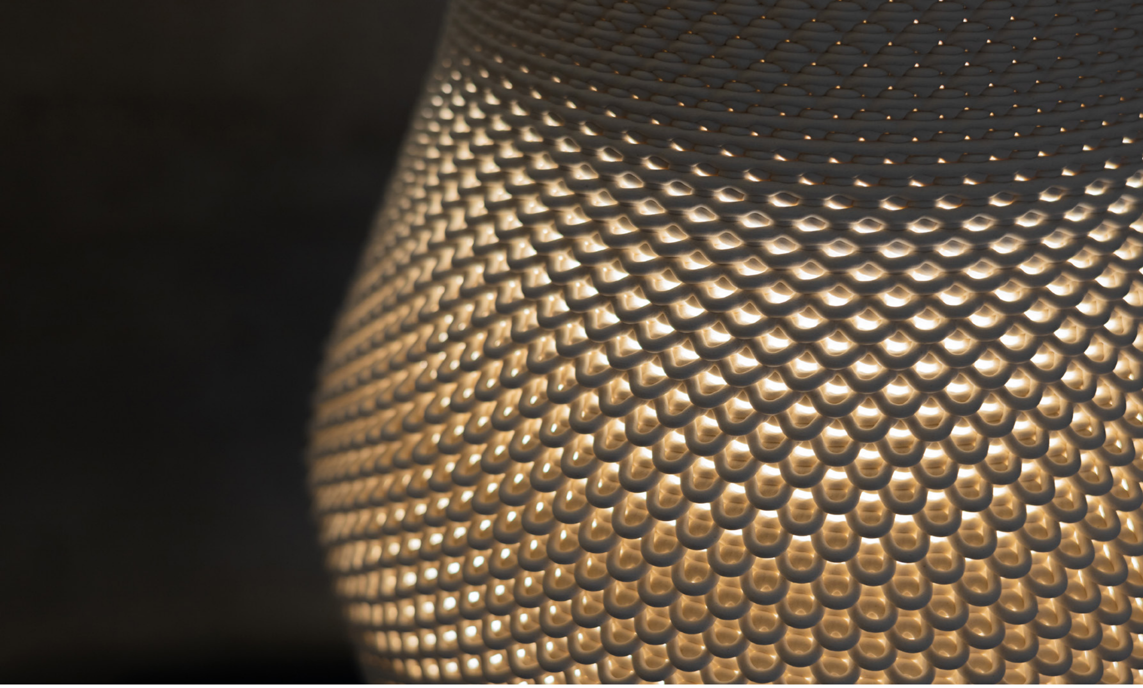

Figure 3: Oil Lamp 2 detail

sectional conditions that range from a high level of light diffusion to nearly opaque.

Brightness in this light screen is controlled by the relative location of the light-regulating layer (B) to the substructure layer (A and C). Oil Lamp 2 has the largest openings in the apertures when the light-regulating layer (B) is displaced to the exterior of the substructure and held in place by the viscid properties of the clay. The light-regulating layer (B) creates an opaque condition when stacked with the substructure to create a condition of full adhesion (see figure 4).

Oil Lamp 2 leverages custom tool path design and clay's viscoelastic characteristics to intentionally regulate the print coil's sagging behaviour in relation to targeted light scattering effects. The presented methodology manipulates light scattering behaviours by controlling deformation through a multilayered section profile.

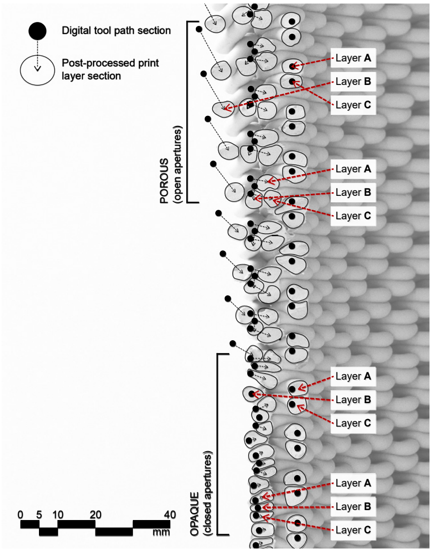

Figure 4: Deformation of tool path mapped onto physical print

Hive

Hive is a masonry wall comprising 175 unique 3D-printed clay units. The project combines traditional masonry construction techniques with smart geometry and robotic precision. The stoneware units in Hive consist of four interwoven hexagonal apertures. Apertures have different degrees of opening based on the global design of the wall, making each 3D-printed masonry unit unique (see Figure 6). The geometry of each aperture impacts the way units fit with their surrounding neighbours. Variable aperture openings add visual interest to the space while acting as a privacy screen between a reception area and meeting room. The hexagonal units break the conventional rectilinear structure of a masonry wall while providing a strong and materially efficient structure.

The design of the masonry units and the overall wall design was made possible by a highly iterative design and fabrication process. The early design iterations of Hive were composed of individual hexagonal apertures. The custom tool path design of the multi-aperture masonry units leverages coplanar toolpath intersections that bond four apertures into one continuous and efficient print path that does not require pauses in extrusion. The interwoven aperture design reduces the clay required to print the wall by 25% and mortar joints by 50% compared to printing individual apertures. Each masonry unit is scaled to use precisely one full 3600cc clay cartridge on the Potterbot SLX-1.

The installation is conceived of as a traditional bonded masonry system with units adhered together using mortar and later grouted. The development process of Hive involved working back and forth between digital and analogue models through an integrative computational design process directly tied with the 3DP fabrication. In order to respond to the dynamic material qualities of wet clay and formulate clay mixes suitable for 3D printing, new computational design and fabrication tools, extensive material testing, and multiple assembly mock-ups were required. This approach embraces the spirit of traditional ceramic craft with robotic precision, offering new avenues for material expression and geometric complexity within this field.

The capacity of these nascent technologies to quickly produce large prints offers an exciting and economically feasible intersection for 3D printing and architecture. While clay's messy and unstable nature presents technical challenges in practical applications, these attributes also create opportunities to explore unique aesthetic and functional possibilities not available to other materials.

Figure 5: Comparison of Hive masonry unit apertures at opposing ends of the gradient, open (left) and closed (right)

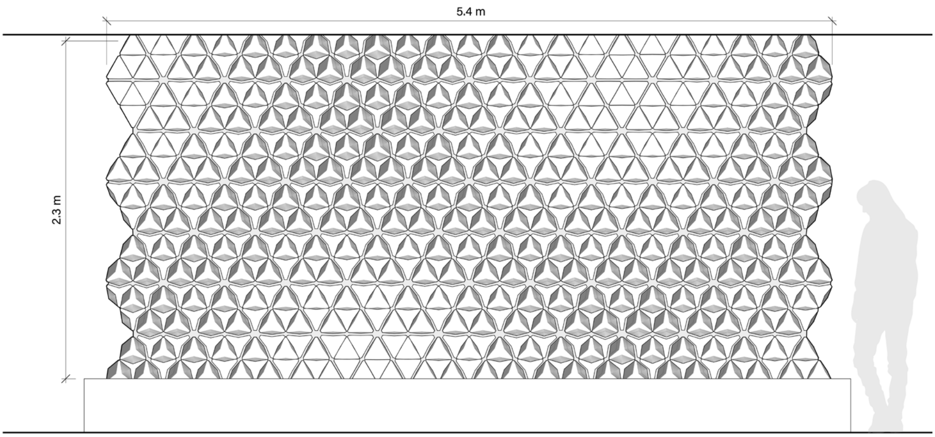

Figure 6: Hive masonry wall elevation

Acknowledgements

Oil Lamp 2 builds on research initiated at the University of Waterloo School of Architecture by Adjunct Professors Isabel Ochoa and James Clarke-Hicks as part of their Master's thesis, supervised by Associate Professor David Correa. Oil Lamp 2 is part of Isabel Ochoa and James Clarke-Hicks' larger ongoing body of work entitled 'Grading Light.' 'Grading Light' explores how designing custom digital tool paths, not otherwise possible through slicer software, can capitalize on the way that print layers deform to create porous geometries that alter light-scattering behaviour.

Hive was designed and developed by Ye Sul E. Cho, Ji Shi, Meghan Taylor, James Clarke-Hicks, Isabel Ochoa and David Correa. The project was made possible through a research partnership between the University of Waterloo and Investment Management Corporation of Ontario (IMCO). The project was commissioned by SDI Interior Design. Technical and financial support for 3DP masonry research was provided by the Masonry Works Council of Ontario.

Figure 7: Hive final installation (image: Shabaan Khokhar)

Figure 1: Semper's Bekleidungsprinzip opens up questions as to how structure is concealed and revealed

HOW TO DRESS A COLUMN: 3D PRINTED CERAMICS FOR ARCHITECTURAL CLADDING SYSTEMS

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Abstract

Through additive manufacturing architects are presented with new ways of forming clay and the ability to create new tectonic solutions for ceramic clad buildings. Preceding this technological evolution is a rich history of ceramics in architecture as a decorative and performative material to draw from, as well as more theoretical questions in what it actually means to clad a structure. This article presents an approach to designing with 3D printed ceramics that tries to answer a central yet complex question– how do you dress a column?

Introduction

One of Gottfied Semper's central theories is that architecture begins with dressing; a point he illustrated by tracing the metamorphosis of textile wares into the tectonics of walls and other enclosing architectural surfaces. The 'Bekleidungsprinzip'[1] has become an enduring theme and its influence can be interpreted through the tectonics of many ceramic and concrete clad structures from the past 200 years. What is attractive about Semper's theories is that they have been able to evolve with changing building technologies as well as more conceptual ideas about how structure is either concealed or revealed. In the contemporary digital environment, architects can re-interpret them in a new light as new tools offer new possibilities to shape clay and other paste-based materials.

Informed by Semper's theory, and the rich historical precedent of buildings by architects like Louis Sullivan, Frank Lloyd Wright, this article presents 2 conceptual prototypes that draw on the new possibilities of 3D printed ceramics as a cladding material. The aim of these works is to consider theoretical and artistic approaches for architects working with additive manufacturing as an alternative to computational methods that dominate the field.

> *"the principle of dressing seeks to focus attention not on ornament, but on that layer in the order of things which architecture spreads out between the outside world and the skin: a texture produced by human intelligence and work, which gives pleasure to both the eyes and the hand". [2] – Ákos Moravánsky 2017*

Figure 2: Interlocking ceramic cladding for structural steel

Figure 2: Textile Column

The Historicist and the Algorithm

The ornamented column is a 3D printed ceramic architectural folly that was assembled at the Glyptotek museum in Copenhagen. It is an experimental work that was undertaken to test a design method that explored the aesthetic and tectonic possibilities of 3D printed clay informed by the architectural language of an existing site. The catalyst for the project was a series of criticisms on the expression of digitally designed and fabricated architecture that has in some cases lacked sensitivity to context [3] and has the potential to lead to a sense of estrangement when details are too complex. [4] The aim of the prototype was to develop a design method that would result in a piece that had a formal dialogue with the existing building and broaden the existing scope of design methodologies in the field of additive manufacturing.

The approach was based on adopting selected details within the architectural fabric museum building as a point of departure and consider how they could be translated into 3D printed ceramic pieces that would make up the column. The Glyptotek museum is built in a historicist style and inspired by the Venetian Renaissance therefore the surfaces of the building are eclectic mix of relief's, classical details and ornate panels which presented a rich variety of forms and motifs to work with.

A series of vegetal tiles were registered, developed into digital models, and then designed as print paths for the printer at a resolution that would both make them readable as motifs as well as appropriate to the width of material extrusion and structure of the pieces. Through working with the patterns and weaving an internal structure with the external decorative layer it was possible to use the motifs as a mediator between the language of the building, the structural logic of the column elements as well as the language of the printed clay.

The prototype invokes Sempers 'knot' as the most significant basic tectonic element [5] and considers the fusion between 2 layers at any point in the structure as a representation of this notion. Furthermore, it considers

Figure 10: Interlocking and dry stacking column elements

Figure 5: Ornamented 3D printed ceramic column (image: Jakob Gate)

the individual motifs not just as interpretation of the vegetal patterns, but also as integrated woven details much like Louis Sullivan's ideas about ceramic cladding alluding to tapestry-like patterns on the Guarantee Building in the USA. Where it differs from Sullivan's approach is that the articulation of the clay is more than skin deep, and the way it is woven into the internal structure shows the possibility of the clay acting both decoratively and structurally through the precise deposition of material only possible through additive manufacturing techniques.

The piece is 220cm in height, 30cm at its widest point and is made up of 24 dry stacked ceramic elements that interlock in the vertical and horizontal plane. The elements are assembled around a hollow steel section for support but are not structurally dependent on it. In its current iteration, this work is to be considered a prototype that explores both architectural and theoretical ideas about surface, context, ornament, and tectonics but it is not intended to be evaluated for its performance as a technical solution as either a loadbearing column or a cladding system.

Textile Column

Textile Column is the next prototype in the series that represents a more refined cladding system where the joints between discrete 3D printed ceramic elements are articulated as bespoke interlocking parts held in place using dry-fix steel ties. The aim of this experiment was to work in a direct way with Semper's theory that walls and cladding are informed by both textiles and dressing, [6] and to try and translate aspects of garment design including seams and embellishment into a tectonic solution for how to fix, lock and articulate joints. The project also re-imagines ceramic cladding as a decorative and fire-resistant skin for structural steel through additive manufacturing, which references Sullivan and other architects of the Chicago Schools' use of terracotta to clad steel framed buildings at the end of the 19th century.

When printing with clay, it is possible to design and fabricate highly complex, extruded geometries but if these forms are not able to split apart and be satisfactorily reassembled, they become useless as part of a cladding system as they cannot wrap around

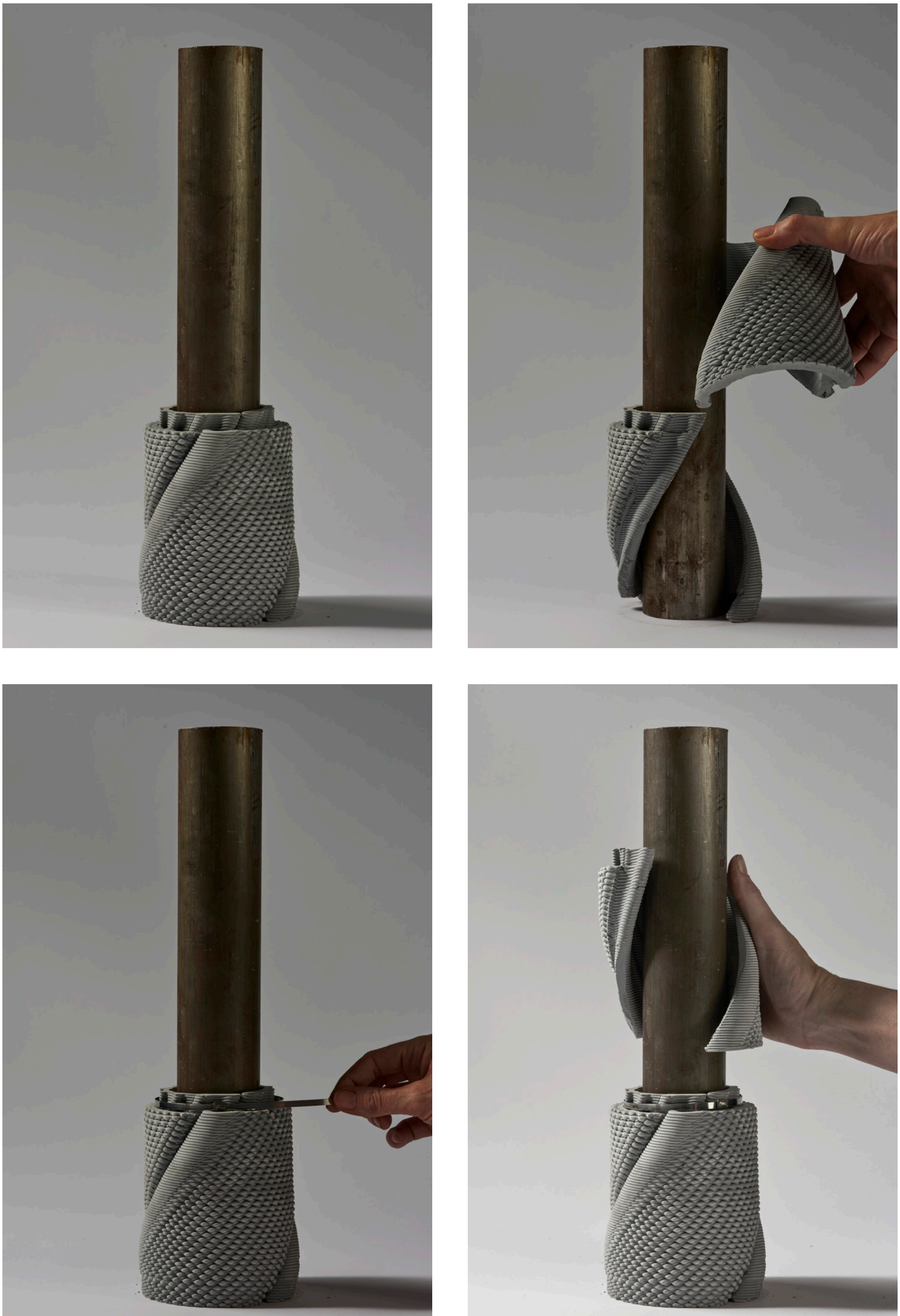

Figure 6: Interlocking and dry fixing system minimising use of mortar and adhesives

or dress an existing structure. Thinking about Sullivan's ornamental cladding where joints and junctions in the building are celebrated with ornament, the vertical seam along the ceramic tiles is considered a place of expression and articulation as well as a functional joint. The seam is amplified where the two tiles wrapped around each other and interlock, and by expressing the joint as a spiral that was more tightly coiled at the bottom and released towards the top, it was possible to play on both the idea of wrapping, cloth and the embellished seam as well as suggest a feeling of weight and increasing pressure as well as sense of movement in the column.

> *"The seam is an expedient that was invented to join pieces of a homogeneous nature – namely, surfaces – into a whole. Originally used in clothing and coverings, it has through an ancient association with ideas and even through linguistic usage become the universal analogy for any joining of originally discrete surfaces into a tight connection." [7] – Gottfried Semper – Der Stil 1860*

The articulation of the vertical seam as a spiral also had advantages from the perspective of fabrication as by printing each pair in their final interlocking position, each piece was able to support each other like formwork throughout the printing process. Through trial and error, it was possible to plan the print paths at the correct adjacency so the pieces could be gently cracked apart when leather hard and reassembled when fired with a very tight and bespoke connection to each pair.

The prototype offers a new interpretation of Semper's ideas, that are not just about dressing or tracing a structural skeleton, or about the articulation of the architectural layer between buildings and humans. It takes the metaphor of textiles a step further and attempts to interpret the physical movement of the 3D printer as a weaving or sewing instrument that constructs architectural garments for the use of cladding.

Figure 7: The motifs on the column were developed from vegetal patterns in the existing fabric of the museum

Outlook

These prototypes provide examples of a method of approaching additive manufacturing technology that are distinctly 'low tech' in nature. They are examples of a method that is informed by historical precedent as well as Semper's ideas on the textile origins of walls and other cladding surfaces. On one hand they offer new ways of interpreting Semper's theory in the digital age, and on the other they question what the model should be for how architects approach the aesthetic potential and new architectural languages possible through additive manufacturing.

Acknowledgements

This work was undertaken with the assistance of Ee Pin Choo, Nitsan Bartov and Jack Young from CITA, and under the guidance of Professor Peter Thule Kristensen and Associate Professor Flemming Tvede Hansen who are all based at the Royal Danish Academy.

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[7] Ibid.

Figure 1: Aectual acoustic panels in Immersive Design Lab

INTERVIEW: HEDWIG HEINSMAN

HEDWIG HEINSMAN

AECTUAL

CO-FOUNDER, CHIEF COMMERCIAL OFFICER AND CREATIVE DIRECTOR

HEDWIG@AECTUAL.COM

Hedwig, you are working on circular architecture. We are designing buildings to last for longer than 50 years or even 100 years. Why do we need a circular process?

I believe in a sort of metabolic architecture. I believe in architecture with structures that stand for centuries, but with a flexible infill. So that the skin, what is inside, and all the surfaces, are flexible, and that they can change over time. That is what we facilitate with Aectual.

Are you advocating modular architecture?

Not so much modular, but more like smart prefabricated 3D printed building systems that are flexible and can adapt over time so that you can meet changing needs. For a smart high-rise, you do need certain standardized structures like steel beams or concrete elements that are so optimized that it makes sense to work with those or, of course even better, with wood. But those work well combined with flexible systems that can change over time.

How does Aectual fit in this picture?

Aectual is a spin-off of an architecture firm that, 10 or even 15 years ago, became very interested in 3d printing as a new means to democratize architecture when combined with new digital design tools. In that sense, we envisioned a sort of Spotify for architecture. And although reality proves to be a bit harder, I am proud that we now established a platform with an array of architectural products and systems, primarily on the interior level but expanding into outdoor solutions. Next year we intend to launch facade cladding, for instance. All the items that we offer are fully customizable by the users, who are primarily designers and architects. Within the parameters, there is a great level of design freedom. And what is interesting about 3d printing is the recyclability of materials, it is really like the holy grail of circular thinking. Because you can create something, then afterwards we take it back, it is shredded mechanically, which does not require a lot of energy, and then it is reprinted into something new. Because this is all a digital, data-driven process, we have more and more data about the designs, so with every material cycle we can make the designs smarter. There is a continuous material feedback loop and a data-driven design feedback loop. This fascinates us tremendously, and we are motivated to make this big and share all opportunities of this technology with the world.

When you talk about shredding used materials, what kind of materials are you thinking about?

We choose our materials, and material partners, based on recyclability, global availability, and reliability. We work with several materials, but primarily with three main materials. One is a material we developed in collaboration with Henkel, a German multinational chemical and consumer goods company. This is a plant-based material, which is both very beautiful but also very easy to recycle. It keeps a high quality for several design cycles. Another material is called PolyAl, which is a polymer-aluminum mixture. It is a waste material of drink cartons. There are roughly 200 billion drink cartons produced annually. Each carton consists of approx. 75% cardboard and 25% of this aluminum-polymer mix. With a whole ecosystem of partners, we are now able to create high-quality products out of that 25%, while the cardboard is re-used conventionally. The third material is recycled polypropylene, which is also a waste plastic. We work a lot with waste plastics, which perhaps not has the most positive connotation. But there is so much waste plastic around that we think now is an opportunity to give it a better purpose. And then, we will gradually expand our material portfolio into renewable materials.

Are you taking waste material from other material streams and then make it into architectural products? Or do you use a truly circular resource system that recycles its own waste?

Both. A lot of our material is already used in true circular cycles. We have several workplace and retail clients who use material that is already in its 2nd or even 3rd cycle. Initially, we did all the recycling ourselves. But now we partner with other big companies to guarantee global supply, global quality, and recycling in large quantities. We have a free take-back service where we take back materials from clients. It is great for them because it is always a hassle to dispose of waste, and it is great for us because it is free material. Our partners then take care of the recycling, and we receive it back as pellets, which we then 3d print again.

How do you address the need for a broader scale industrialization of your technology? Do you have a picture of how this can become mainstream?

I am not going to give away all our secrets! But we see that the technology gets better and better. More and more 3d print manufacturers start to emerge. And to grow, we partner with those companies, who like to work with us because we have a lot of knowledge about design, product development, and regulations such as UV resistance or fire retardancy. We have such data about all our products. That is what makes us an interesting partner to those manufacturers. On the product level, we continuously optimize our products. Our calculations show that this can sometimes be even 200% and, for instance, hides in things like downtime, optimizing between print runs, how many robots one operator can operate, etcetera. There are still many buttons that we can tweak that will lead to more affordable products.

Figure 2: Aectual Dutch Parliament Zecc

Figure 3: Aectual UAE pavillion Floriade 2022

The established notion of additive manufacturing is that it is quite expensive. You are offering to make cheaper products.

We have done over 100 commercial projects for big clients ranging from Nike to Disney to CBRE. And although these are still quite high-end clients, we now start to have more and more mainstream clients, too, which is something that we are very excited about as this marks the start of making the technology available to everyone. That is also why we do not print everything. We have a strict focus on certain items, thereby being able to continuously make them more affordable and better suited for our users. But that does not mean that we do not have big ambitions to broaden our product offering.

Looking 30 years ahead, what is your vision for the industry in terms of design, manufacturing, and the entire workflow?

Aectual is now officially 5 years old, and its foundations were laid some 10 years ago by imagining a Spotify for architecture. I think that this is still where we see this technology going. In a way that anyone can create custom playlists, be a creator and make tailored environments. That does not mean that we do not believe in the role of architects and architectural design. But I do think that our platform technology will evolve, offering a lot of new design and economic models for people in the industry. Architects already now can make additional revenue, by selling their designs over the platform. I am looking forward to exchanging thoughts about this at the BE-AM symposium, because there are so many great ideas being developed at universities that never really make their way into the real world, and we could bring those to fruition with Aectual. And lastly, I really believe that our circular service, or material-as-a-service, will become mainstream. People will be able to subscribe to a certain number of kilos of material, and a few design iterations over time. For now, we offer this already to business-to-business clients, but 30 years from now, this definitely will be common for everyone.

Thanks a lot for the interview!

You are welcome!

Interview: Philipp Rosendahl and Hedwig Heinsman

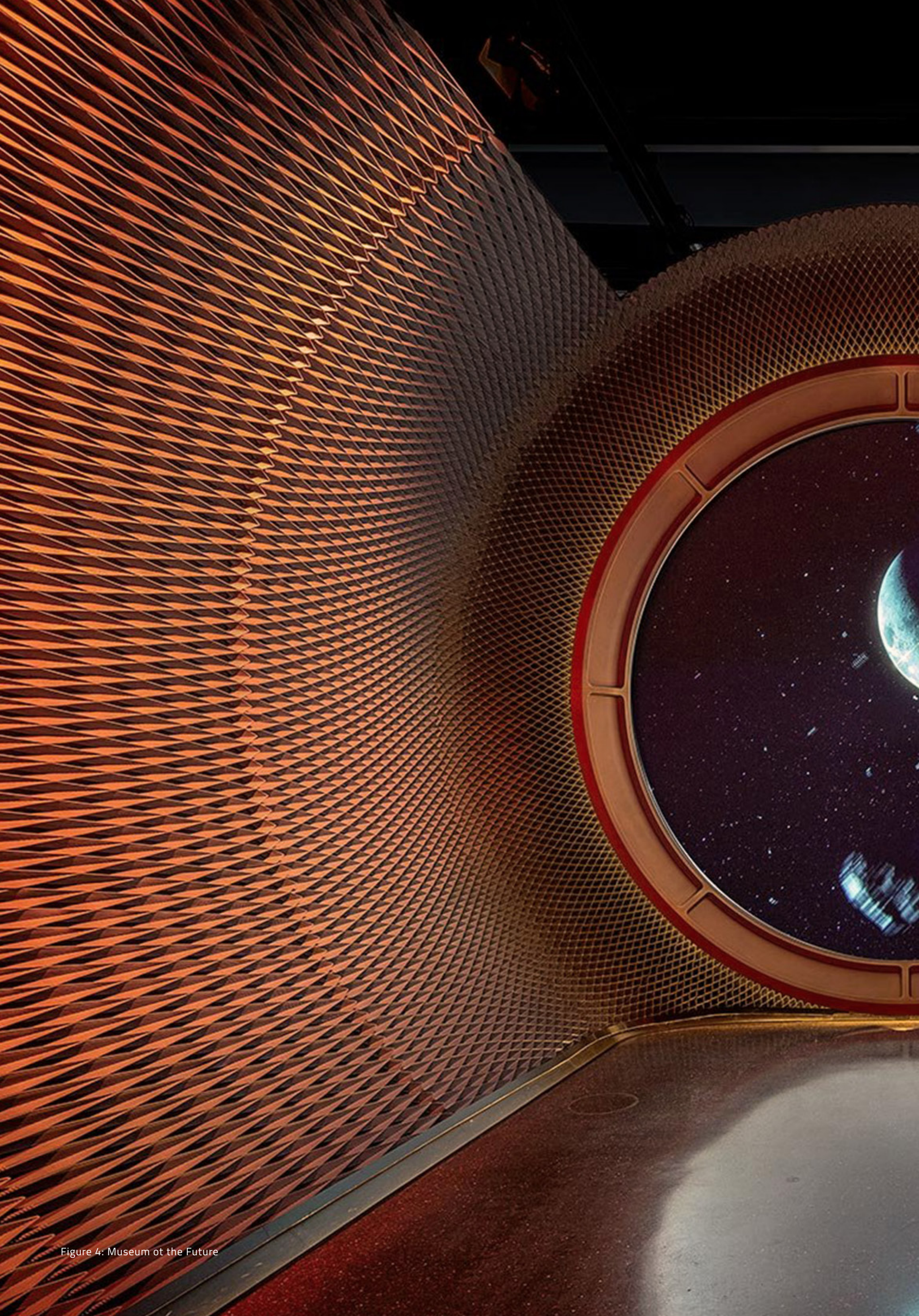
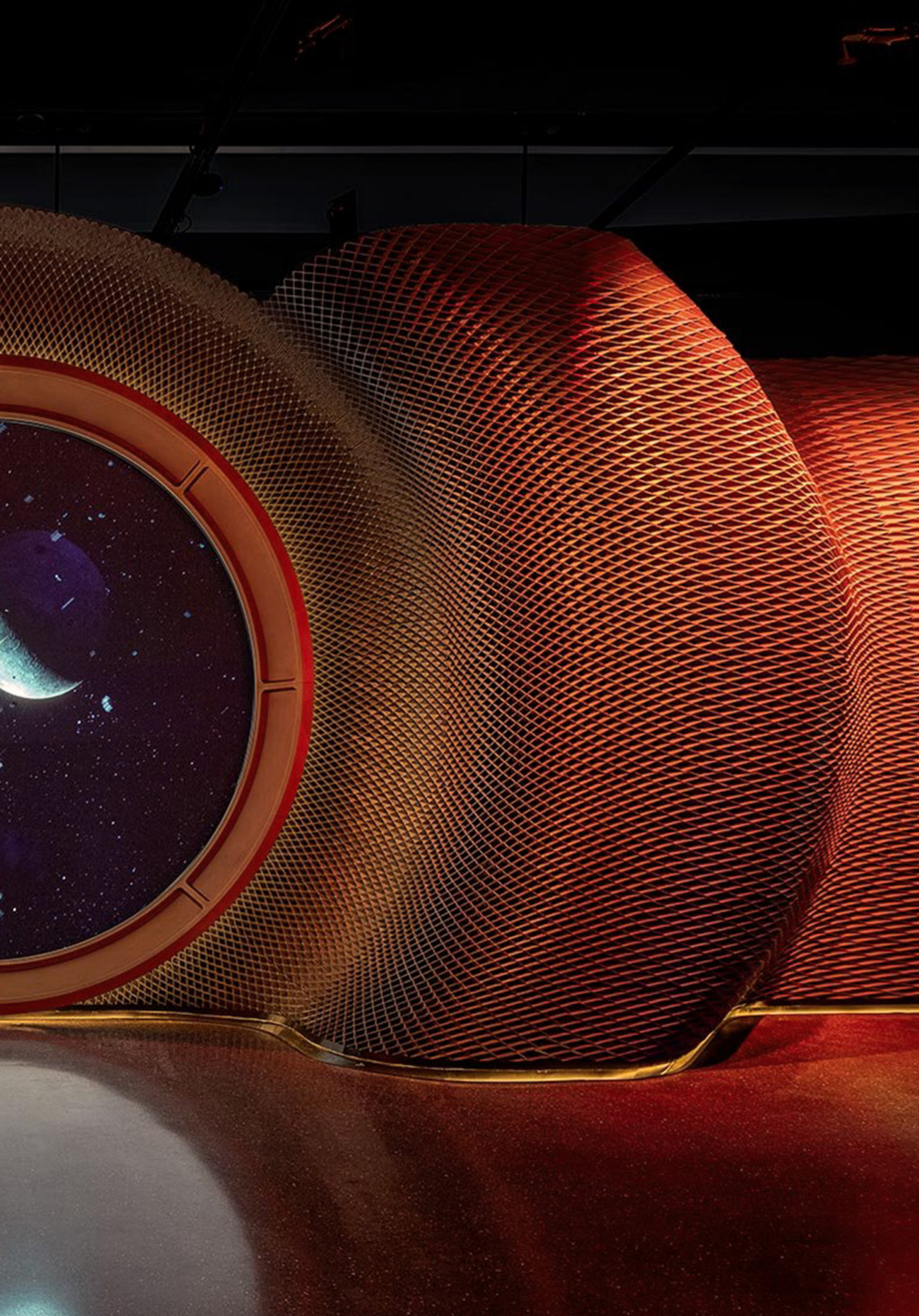


Figure 4: Museum ot the Future



PROJECTS

KUSUDAMA WALL

University of Minho, School of Architecture, Arts and Design
Tatiana Campos, Paulo J.S. Cruz; Bruno Figueiredo

Currently, there is a great interest in seeking or manufacturing objects that comply with more sustainable concepts. Natural biopolymers, such as cellulose, are widely abundant in nature and exhibit extraordinary mechanical properties, especially when combined with organic and inorganic substances, such as corn starch. Cellulose is a natural biopolymer found in the plant kingdom and consists of a long chain of linked sugar molecules that give wood its stiffness. It is also the major structural component of plant cell walls and a building block for textiles. Our goal is to develop a set of natural mixtures and design a modular wall. All the work presented aims to identify the materials – natural biopolymers that are abundant on earth – and the possibility of combining them for subsequent application in additive manufacturing (AM) of more complex, sustainable, and biodegradable architectural building systems. Kusudama is a self-supporting modular wall structure, produced using materials of natural origin – cellulose, starch, and clay – made up of a set of independent components, which can assume different configurations. By exploring different combinations of natural materials, it is possible to map their behavior by studying a set of parameters such as shrinkage, cracking, deformation, delamination, curing time, color change, flexibility, among others.



TEXTILE COLUMNS: DRAWING AND WEAVING WITH 3D PRINTED CLAY

The Royal Danish Academy, Institute for Architecture and Design
Suzi Pain, Ee Pin Choo, Nitsan Bartov, Jack Young

Textile Columns are a pair of 3D printed ceramic columns that explore the decorative and functional potential of additive manufacturing for architectural cladding.

The elements represent dry fixing and interlocking systems that capitalise on the geometric freedom and precision when printing with clay, as well question the historic relationship between the ornamented and the bearing.

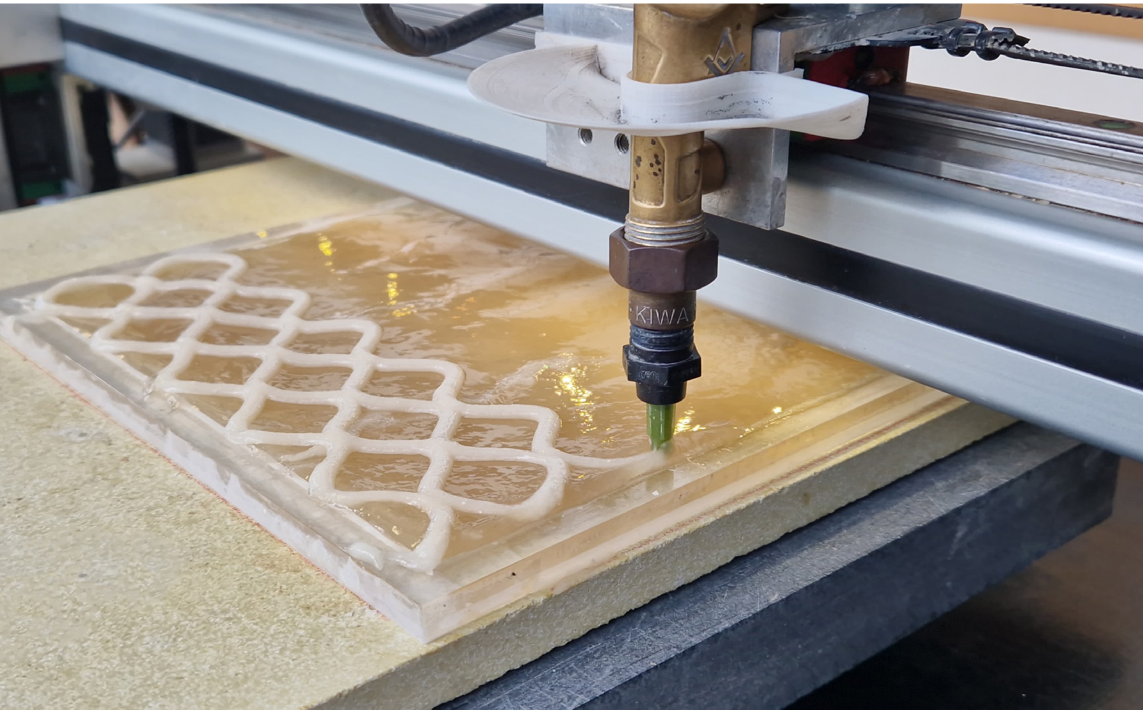
The columns represent an approach that offers an alternative to the complex computational design methods that dominate the field of additive manufacturing with greater focus on architectural theory and craft-based thinking. The aim of these prototypes is to question how we design using paste-based additive manufacturing technologies from an architectural perspective and explore 3D printed ceramics for their ornamental and fire-resistant qualities.

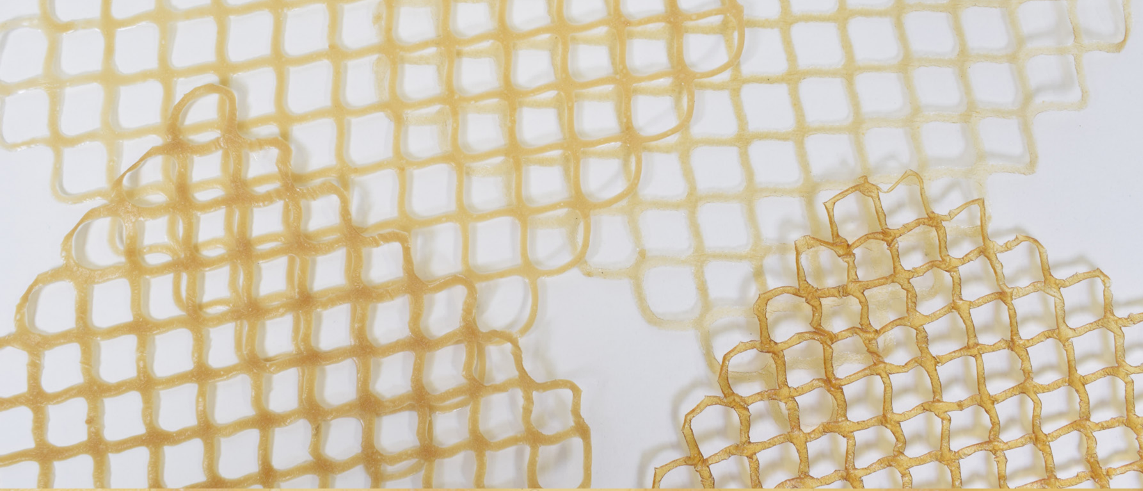
BIOTILES: A SUSTAINABLE NEW INTERIOR WALL PANELS

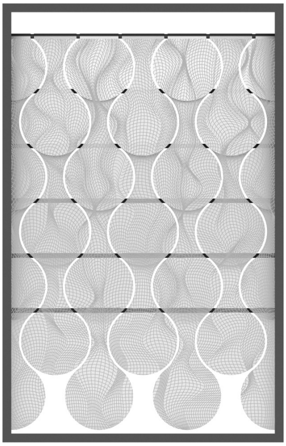
University of Minho, School of Architecture and Arts
Tatiana Campos, Paulo J.S. Cruz, Bruno Figueiredo

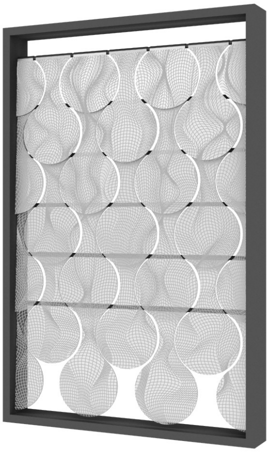
The project proposes the use of materials of natural origin in additive manufacturing, in order to produce new interior wall panels. The historical evolution of the Vimaranense house, tells us a narrative that even today is kept intact by the preservation of its memory. It is common to see slate soletos' in the city of Guimarães for gable linings, or additions to the roofs of buildings, such as chimneys, skylights, and attic roofs. The soletos' or fish scales, are tiles of small dimensions and distinctive shapes obtained from slate rocks. Thinly laid, they overlap one another, fixed on a wooden lath with metal elements

The project aims to reinterpret the soletos' used in the housing construction of Guimarães, replacing the slate rock by materials of natural origin, reusable, and biodegradable. The display consists of a set of individual tiles, with the same geometry and different finishes, produced with cellulose and chitin - two natural biopolymers very abundant on our planet. Taking advantage of additive manufacturing techniques, a dynamic cellulose grid was developed, with different densities, thus providing a three-dimensional effect. The purpose of the cellulose grid is to give the tiles strength and give them their identity. Individually, the tiles are all distinct, when assembled they form a pattern by fitting them. In each tile, a fixing system was placed in the mixture to position the pieces in the exhibitor.







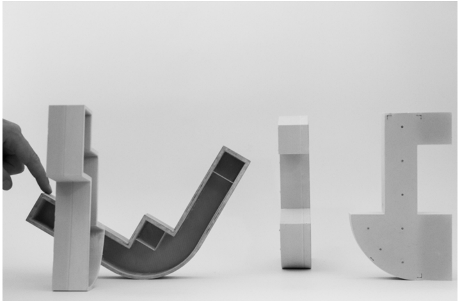


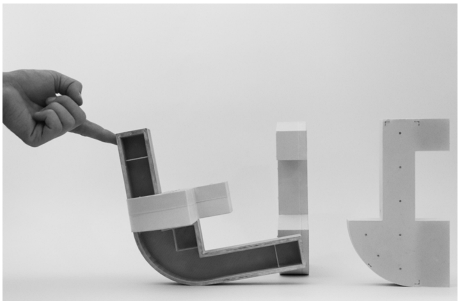
LEVEL-UP

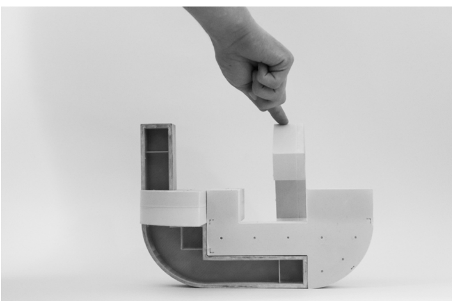
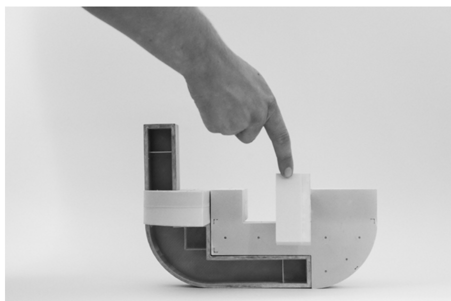
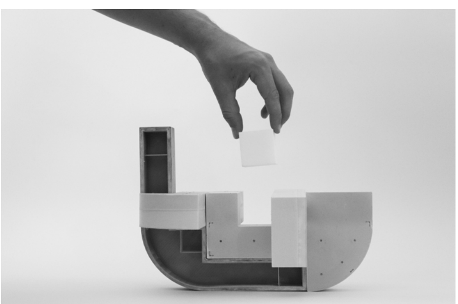
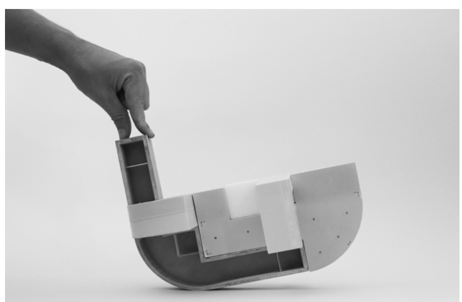
Technical University of Darmstadt, Digital Design Unit
Daniel Schinkels, Ye Hong, Luke Schüßler; supervised by Samim Mehdizadeh, Oliver Tessmann

Level-up is a design-research study as a part of research trajectory animate concrete. The project Level Up consists of a series of elements made from thin-layered 3D-printed permanent formwork to be filled with a water-based acrylic resin polymer. The lightweight elements can be assembled, dis-assembled, and re-assembled into versatile constructions and spatial configurations. Level Up seeks to contribute to a more circular approach in architecture and construction through dry-joint and interlocking construction systems. Its elements can exceed the lifespan of a single building and allow for reuse in novel configurations in future buildings. Their inner cavity is partly filled leading to a counter-intuitive position of its center of mass. Like a tumbler toy they roll, wobble and rock into permanently changing aggregations.

This series of prototypes are build with the PET 3d printed formwork and casted concrete.



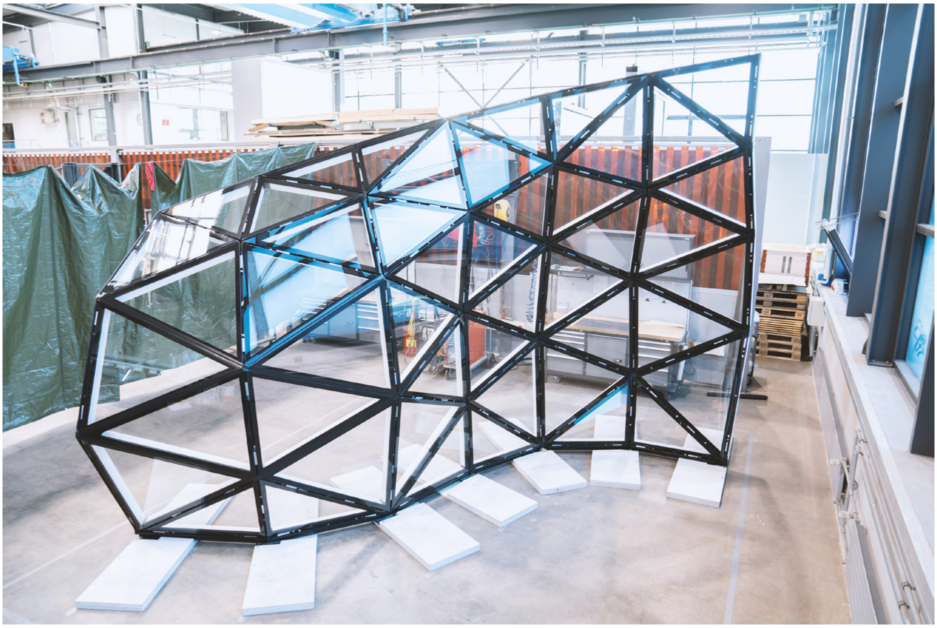


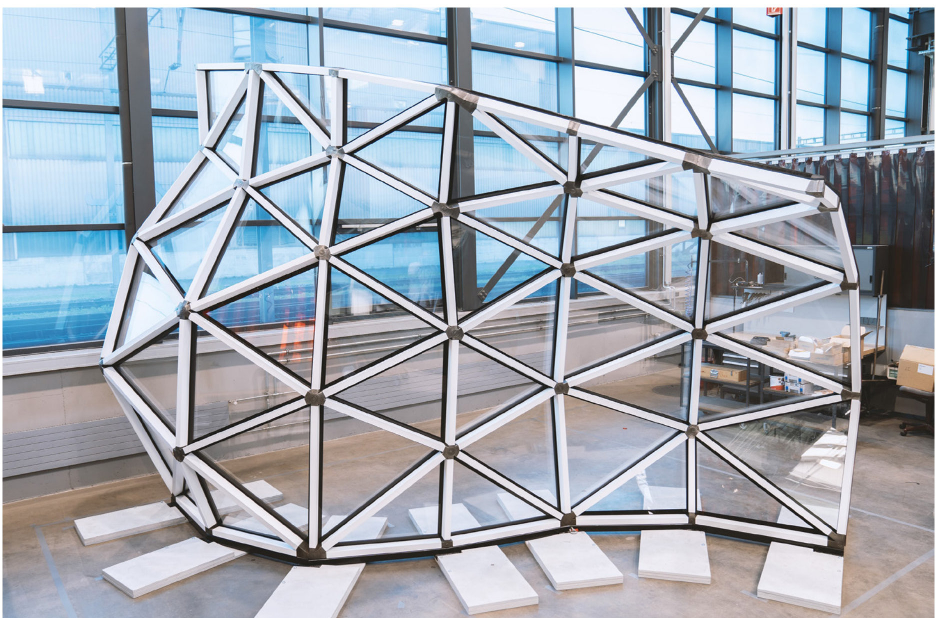





JANSEN VISS³

Jansen AG

Stainless steel nodes combined with slim VISS system profiles form the ideal basis for large glass panels that ensure the transparency of facades. Thanks to 3D-printing technology, there is a sense of freedom in designing the facades, as the nodes can be individually designed to have multiple arms and be positioned at different angles. An additional substructure is unnecessary. The single-layer interior drainage is made continuous by using 3D printed gasket nodes. The nodes and the profile can be connected easily and without the need for any special tools. At the same time, the concealed connection guarantees a uniform visible surface. We would like to thank our cooperation partners – Delft University of Technology, knippershelbig, Glas Trösch and MG Metalltechnik.





„PLASTOCRETEY" - A MATERIAL SYSTEM FOR DIGITAL COMPOSITE MATTER

Technical University of Darmstadt, Digital Design Unit
Nastassia Sysoyeva; supervised by Samim Mehdizadeh, Oliver Tessmann

„Plastocrety" is a material system focusing on „Digital Composite Matters" (DCM) in architecture. This project focuses on designing strategies for composite building elements with individual material deployments in 3D printing building elements, that can be ab-cycled into modules and reused. This research investigates the opportunities of digital composites with a series of artifacts made with very thin 3D-printed PET envelopes and robotic casted concrete inside them. The digital design-simulation framework allows for precise, selective material positioning within a continuous hybrid fabrication framework.

WOOD-BASED 3D PRINTING: POTENTIAL & LIMITATION TO 3D PRINT BUILDING ELEMENTS WITH CELLULOSE & LIGNIN

Technical University of Delft, Architecture, Urbanism and Building Sciences
Christopher Bierach, Alexsander Alberts Coelho

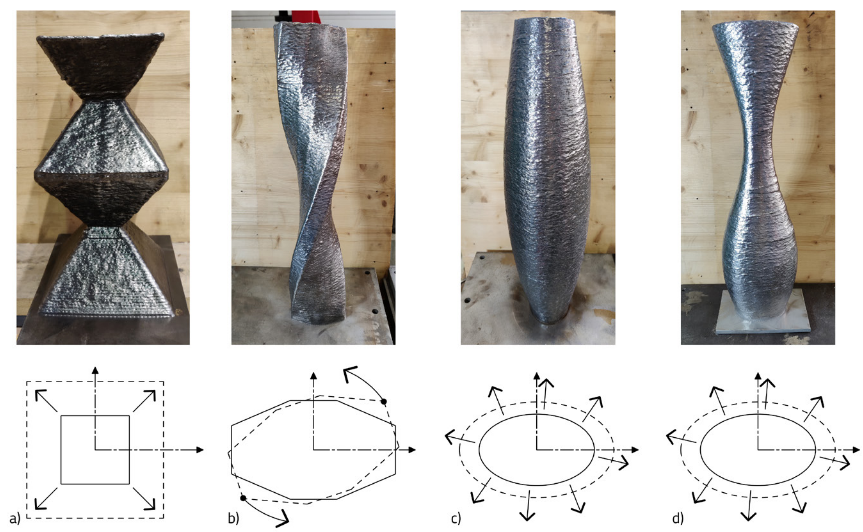
Lignin and cellulose are the most abundant biopolymers on earth and produce a lot of waste by ending up burnt or in landfills. Coming from the pulping and paper industry, lignin waste could be implemented using an additive manufacturing process to reduce or avoid the necessity to cut trees. Thus, the aim of this research is to promote wood waste as an ecological contributor to the building industry. Cellulose and lignin were studied, analyzed, and manipulated before mixing them with a vast selection of binding agents and additives. From a universe of twelve mixes and numerous iterations for each recipe, four alternatives were picked for further characterization and determination of their mechanical properties. In parallel, the printability of the material considered the most promising mix was explored through the extrusion of a sequence of simple geometries and shapes designed to understand and define the most adequate printing parameters. After understanding the explored limits and possibilities of 3D printing with a wholly bio-based material regarding mechanical and printability properties, a window frame, and a structural node were designed and printed as a proof of concept. The final results have shown the potential to 3D print building elements in a cold extrusion process with lignin and cellulose in combination with water and methylcellulose.

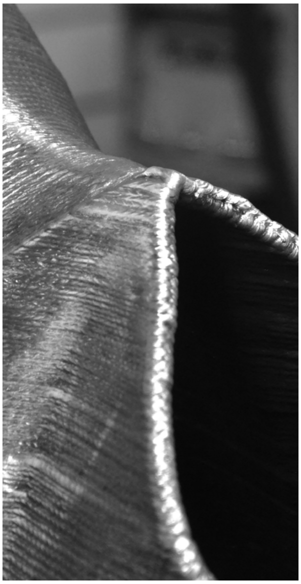
WELDING AND MILLING

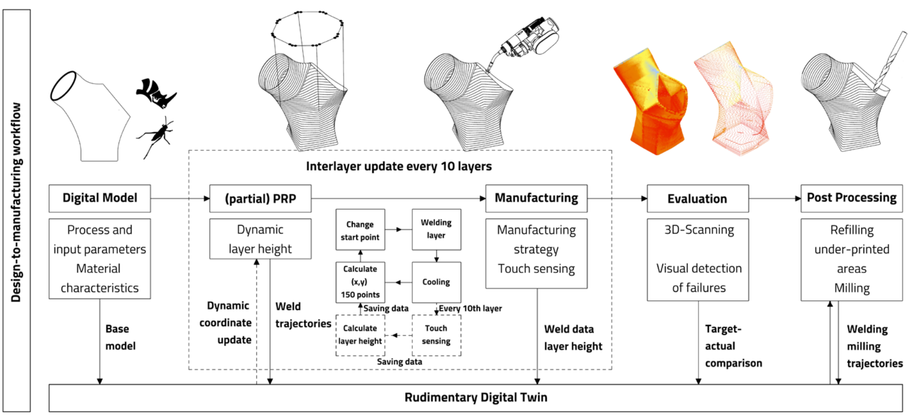
Technical University of Darmstadt, Institute for Steel Construction and Materials Mechanics
Benedikt Waldschmitt, Jörg Lange, Christopher Borg Costanzi, Ulrich Knaack, Thomas Engel, Jan Müller

Many buildings not only have to serve functional requirements but also have representative purposes. Their construction and design calls for a non-standardized approach, making use of highly individualized structures in addition to standard elements. Al¬though today's steel fabricators are already able to produce rather individualized columns and connections the manufacturing process is still very elaborate, expensive, and time-consuming.

The research project "Welding and Milling" aims to achieve an automated process for the inline surface finish of structures, which were formerly manufactured with the Wire Arc Additive Manufacturing (WAAM). WAAM is a robot supported additive manufacturing process based on gas shielded metal arc welding (GMAW), in which a welding wire serves as the printing material.







Design-to-manufacturing workflow
Interlayer update every 10 layers
Digital Model
Process and input parameters
Material characteristics
Base model
(partial) PRP
Dynamic layer height
Dynamic coordinate update
Weld trajectories
Change start point
Welding layer
Calculate (x,y) 150 points
Cooling
Saving data
Every 10th layer
Calculate layer height
Touch sensing
Saving data
Manufacturing
Manufacturing strategy
Touch sensing
Weld data layer height
Evaluation
3D-Scanning
Visual detection of failures
Target-actual comparison
Post Processing
Refilling under-printed areas
Milling
Welding milling trajectories
Rudimentary Digital Twin

BISTRO TABLE SWING

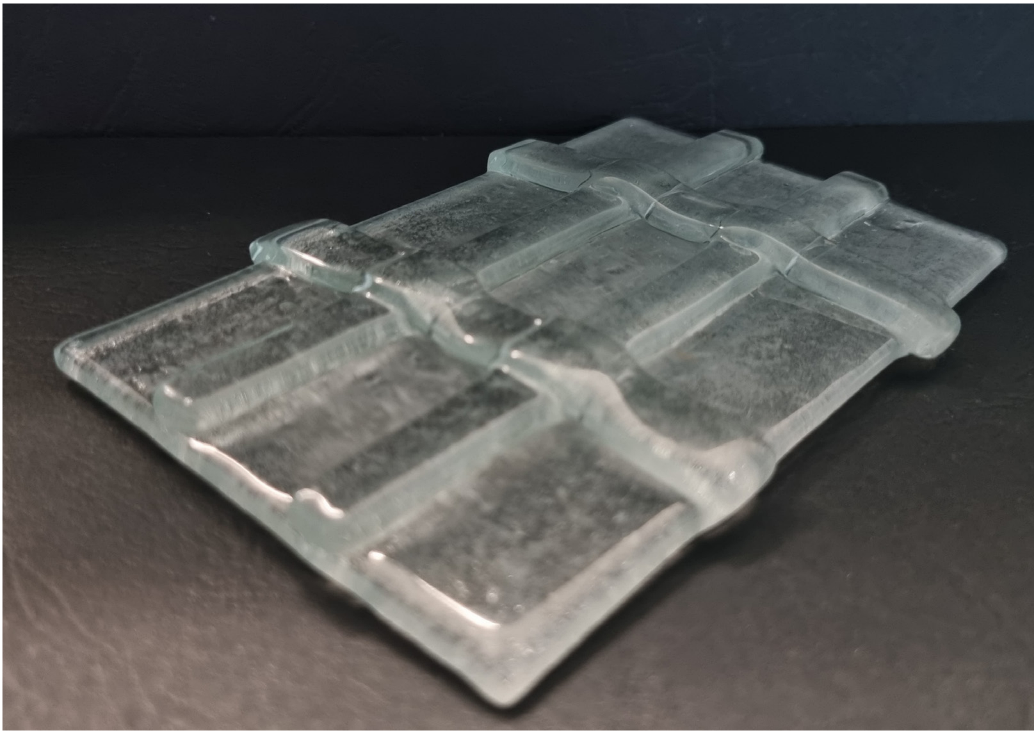
Röser GmbH, Röser 4

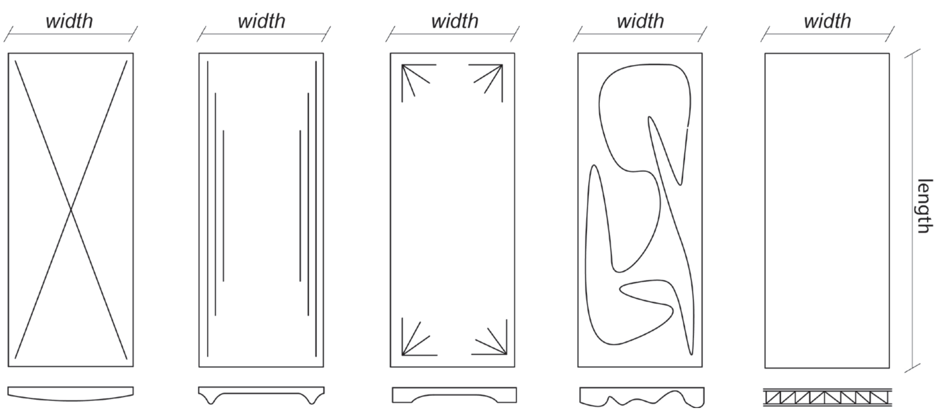
After last year's premiere of Röser GmbH with the 3D Printed Concrete Seating Set, we again demonstrate the possibilities of 3D printed prefabricated concrete elements with our bistro table SWING. The special feature of this demonstrator from the concrete printing manufactory in Laupheim, Germany is the curved base and the incorporated tile for the table surface of this unique model. The project SWING is intended to show once again what is possible with 3D concrete printing: formwork-independent constructions! Thanks to computer-controlled printing technology, the advantages of concrete printing are particularly evident in the field of open space planning, such as concrete sculptures, large outdoor furniture or even garden houses. There are no limitations to your creativity!

AM OF GLASS FOR THE BUILT ENVIRONMENT: STRUCTURAL REINFORCEMENT AND POINT FIXINGS OF FLAT GLASS

Technical University of Darmstadt, Institute of Structural Mechanics and Design
Matthias Seel, Amir Chhadeh, Khodor Sleiman, Kerstin Thiele, Robert Akerboom, Ulrich Knaack

Additive manufacturing of glass provides completely new possibilities for individual glass structures. The focus of our research is the additive manufacturing process FDM with fused glass, which is deposited onto existing flat glass. This enables homogeneous, transparent and individual glass joints for a load transfer and glass reinforcements on flat glass. There was no machine available to implement these ideas, so we designed and built our own lab-scale 3D glass printer within an interdisciplinary team at the Glass Competence Center of TU Darmstadt. This printer is designed for the fundamental analysis of the integrated joining process between fused layered glass (printed glass object) on flat glass and the optimization of this manufacturing process. The next step is to scale up this lab setup to larger glass dimensions together with an industrial partner, so that a system is created that is capable for printing on flat glass in dimensions of 0.5 m × > 1 m. Our focus is on soda-lime silicate glass and borosilicate glass. Glass waste can also be used as printing material if the glass is the same type with the similar material properties. Our vision as a part of the ZIM innovation network amglass+ is to realize 3D printed glass on flat glass in the dimensions 3.25 m × 20 m. This new technology of additive manufacturing of glass enables the development and implementation of completely new glass facades.

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THERMALLY ENHANCED AM LIGHTWEIGHT CONCRETE WALL ELEMENT WITH INTERNAL CLOSED-CELL STRUCTURES

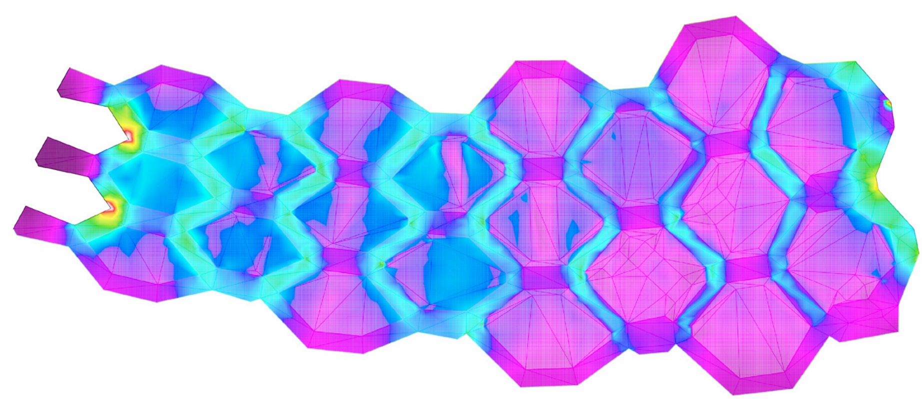
Technical University of Munich, TUM School of Engineering and Design
David Briels

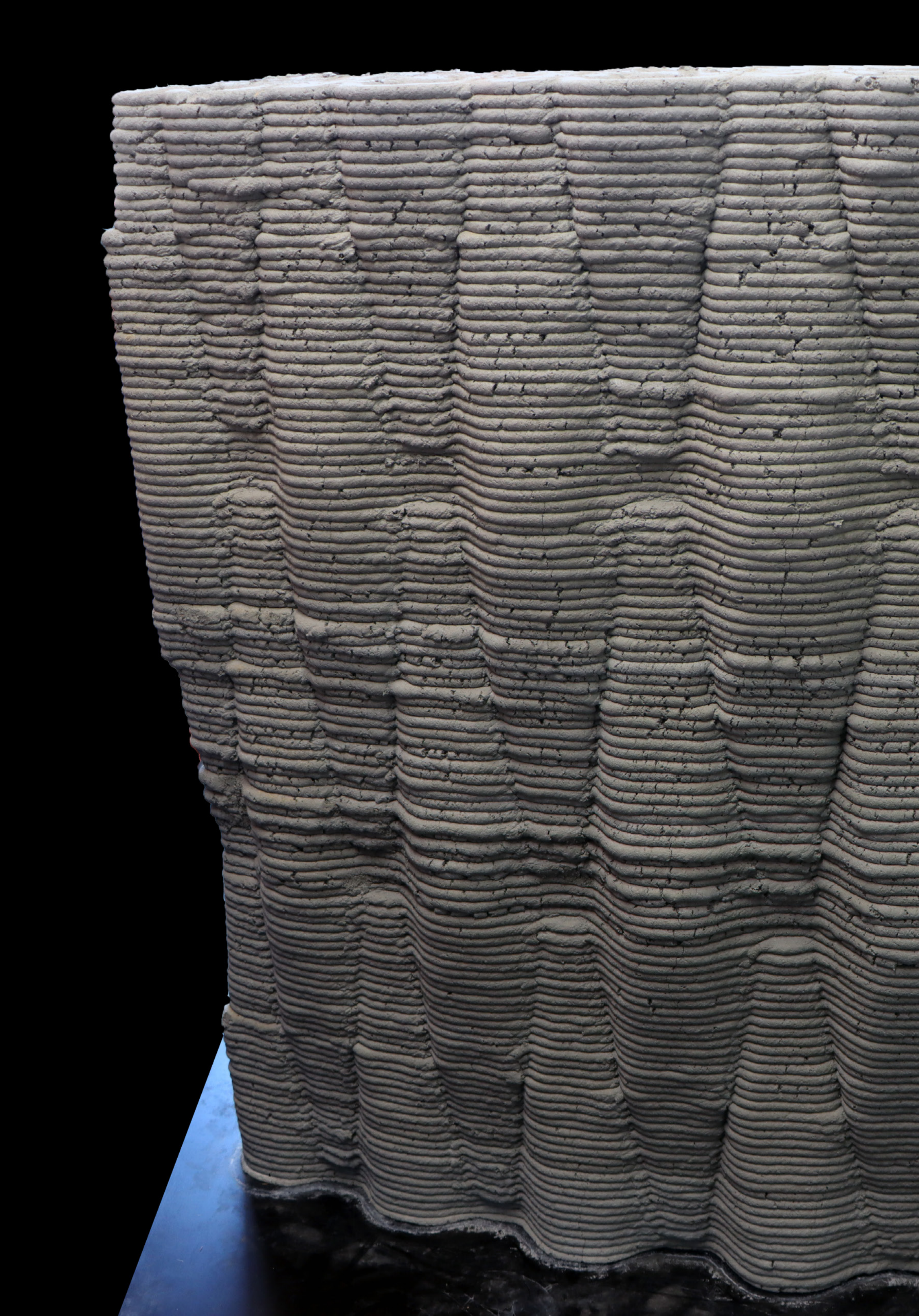
Combining the AM (additive manufacturing) method of extrusion with lightweight concrete, and optimizing their inner structure, monolithic building elements are possible, achieving an enhanced thermal performance at a low resource consumption.

As part of a BBSR-funded Zukunft Bau project, process-related and material characteristics were elaborated in order to enable an automated construction process for freeform lightweight concrete elements without formwork.

A parametric design tool for a closed-cell geometry was developed within Rhino and Grasshopper, using specifically developed Python code, integrating production constraints and a thermal performance feedback.

Within the framework of the DFG-funded TRR277 – AMC, the thermal optimization of AM lightweight concrete wall elements with internal closed-cell structure was driven forward. The thermal performance was investigated using 2D and 3D heat transfer simulations and a parametric optimization was carried out. The existing prototype was used to examine in-situ heat flux measurements and the results were used to validate the analytical approaches. The U-value of the existing prototype was found to be 0.75 – 0.77 W/m^2K (as designed), whereas the measurements show a deviation for the as-built performance by +25% . The optimization led to further improvement of up to 24%, reaching 0.58 W/m^2K.

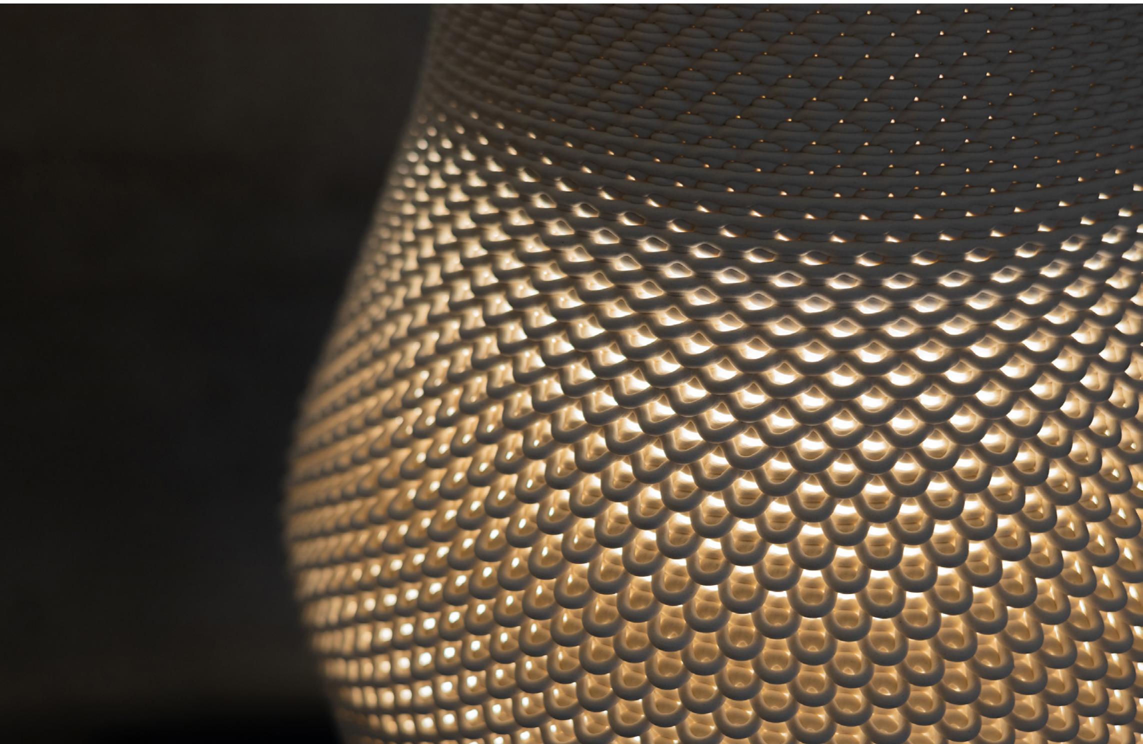




OIL LAMP

University of Waterloo, School of Architecture
Isabel Ochoa, James Clarke-Hicks, David Correa

Oil Lamp is a robotically fabricated porcelain light screen that grades illumination by harnessing the viscoelastic properties of clay during 3D printing. Oil Lamp utilizes additive manufacturing to create highly customized ways of altering light scattering behaviour not easily reproduced through alternative ceramic fabrication techniques. The control of plastic deformation during 3D printing is used to mediate the direction of incident light through Oil Lamp's porous, multi-layered wall section. Strategic material deposition enables the design of targeted material performance characteristics across the body of the light screen. Oil Lamp is part of a larger ongoing body of research by Isabel Ochoa and James Clarke-Hicks entitled Grading Light. Grading Light explores how designing custom design-to-production workflows in additive manufacturing can capitalize on clay's working properties and fired ceramic traits to alter light-scattering behaviour. The research prototypes produced, such as Oil Lamp, focus on mediating light at the level of single pores, or 'apertures,' across 3D printed patterns. The prototypes can thus be adapted and scaled to a range of architectural applications such as masonry units, light fixtures, privacy screens etc. Grading Light aims to investigate how challenges imposed by material behaviour can generate novel approaches to digital craft.



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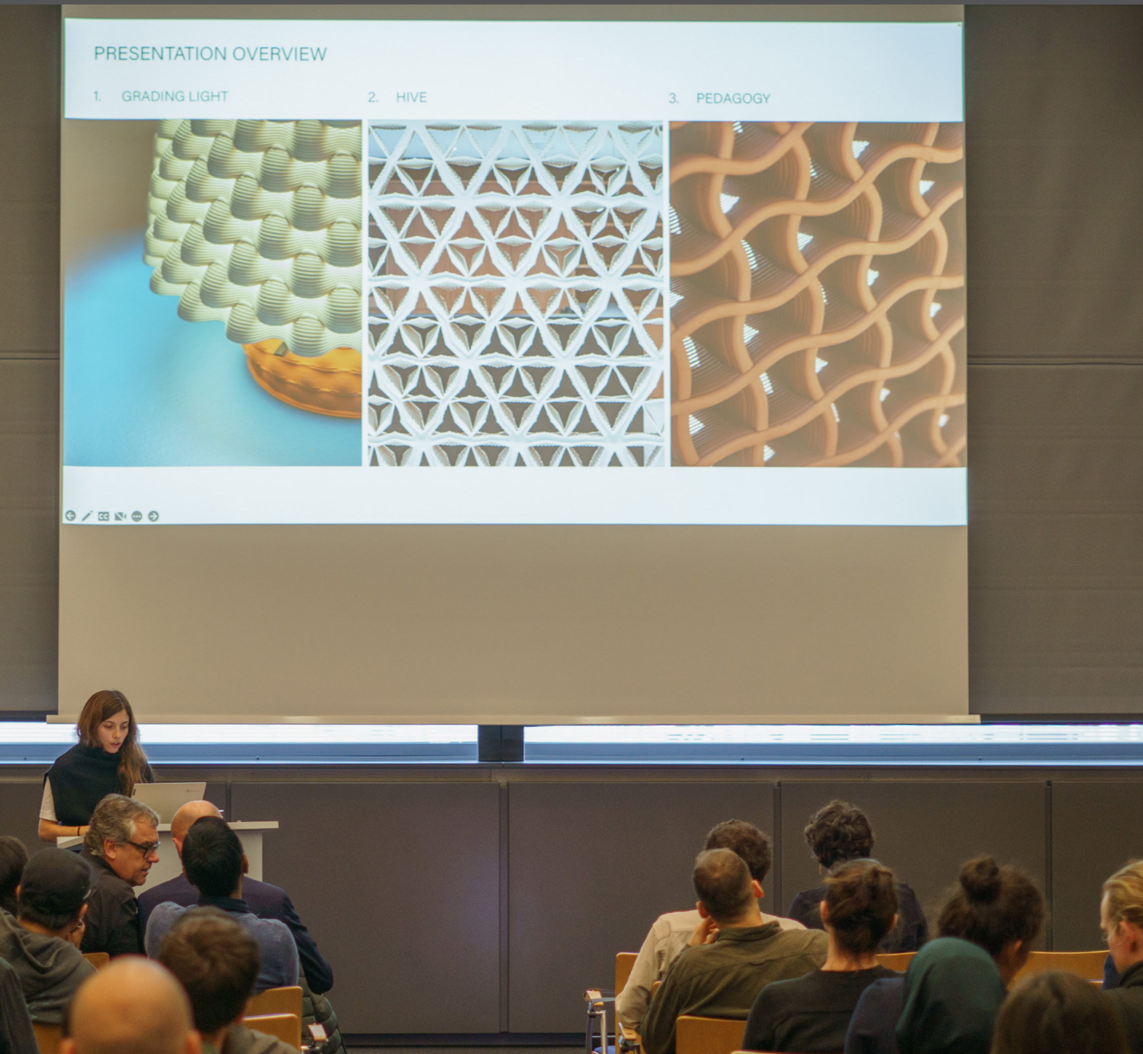
PRESENTATION OVERVIEW
1. GRADING LIGHT
2. HIVE
3. PEDAGOGY


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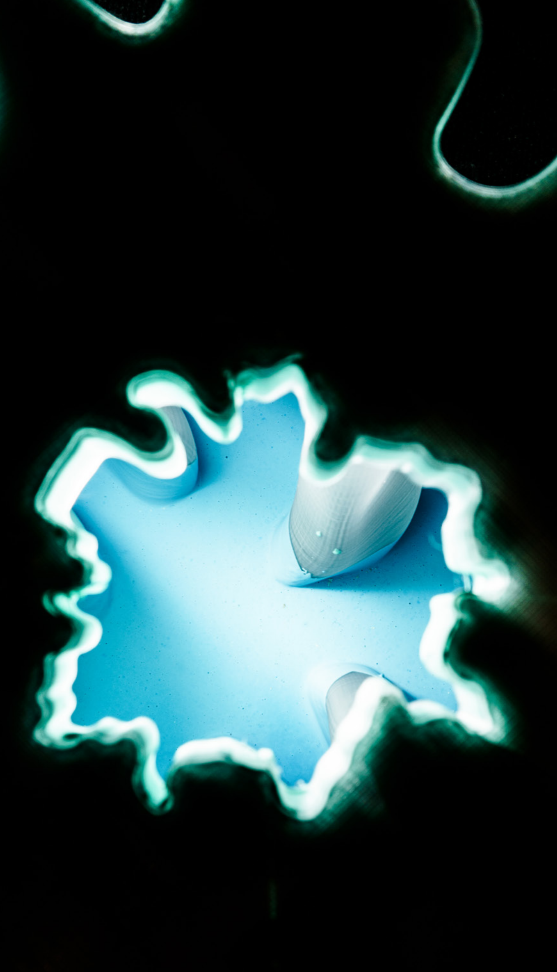



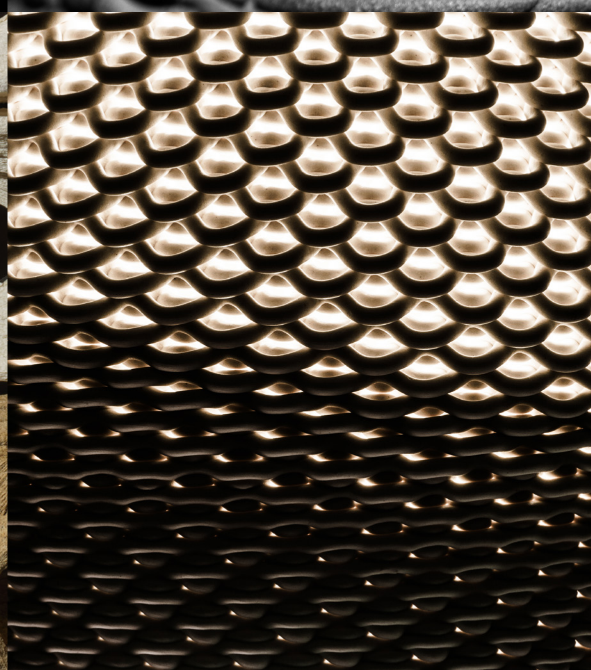

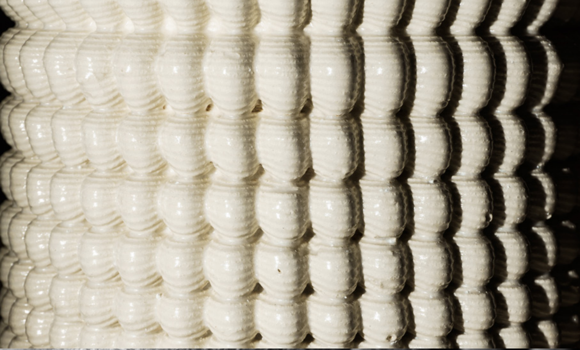

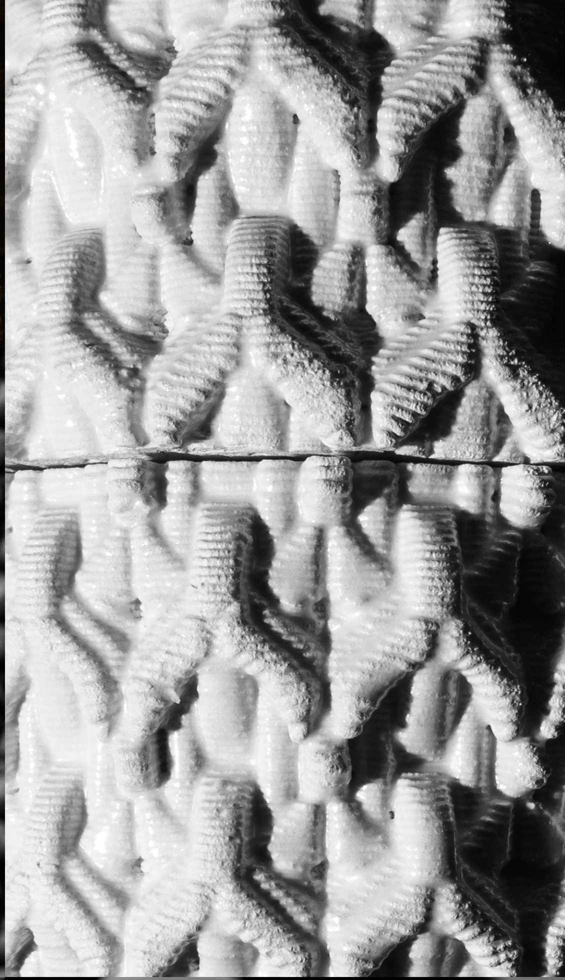

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Institut für Statik und Konstruktion

xchange for innovation

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