

BE-AM

BUILT ENVIRONMENT

ADDITIVE MANUFACTURING

2024

BE-AM 2024 SYMPOSIUM



TECHNISCHE
UNIVERSITÄT
DARMSTADT

DDU

Digital Design Unit — Digitales Gestalten

ISM+D

Institute of Structural Mechanics and Design
Institut für Statik und Konstruktion

xchange
for innovation



Generative
Design
Lab

DFG

Deutsche
Forschungsgemeinschaft
German Research Foundation

formnext

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INTRODUCTION

PREFACE

The 9th edition of the exhibition and symposium, BE-AM 2024 presents work from 7 well-known companies in the industry, 11 universities and 2 research institutes. As a now well established network, BE-AM reflects in this the state of additive manufacturing in the AEC industry, furthering research and development every year. Never has the exhibition featured more large-scale elements, demonstrating new structural systems and new aesthetics for the field, and never has the symposium featured such rich and cutting-edge research, as much by senior as by junior researchers.

Beyond the structural and aesthetical systems it presents, BE-AM 2024 also offers a focus into Artificial Intelligence (AI), or more exactly the integration of AI-based tools in AEC workflows, examining the role played by these tools and the changes they bring about in our design practices. Contributions to BE-AM offer here a precise outlook into how AI can be not just explored for itself, but become a support for architectural design and construction.

Finally, BE-AM 2024 is also the occasion of furthering our venture into sustainable manufacturing and new materials: wood, but also fast growing crops providing alternative streams of resources. Together with the AEC industry, we tackle issues of circular economy, looking at waste streams and how to transform them into renewed, valuable components for the built environment. Extrusion-based processes, but also additive manufacturing beyond 3d-printing provide the means to form these new materials, leveraging the potential of digital manufacturing to process non-standard resources and allow for the use of more sustainable material flows in novel architectural applications.

Nadja Gaudillière-Jami and Alexander Wolf

ESSAYS



BioMat.

MATERIALS AS A DESIGN TOOL.

BioMat aims to explore innovative solutions for better sustainable architecture, using materials as a design tool. This research is driven by the significant global impact of the construction industry, which accounts for 25% of global carbon emissions. The main idea behind BioMat is to explore natural and climate-friendly ways to improve building materials and construction processes.

BioMat takes a bottom-up approach to research by merging material research, architecture, design, and digital fabrication. This approach leverages the unique properties of materials to design solutions for long-term and ecological building. The goal is to create a sustainable and resilient building material that can be used in a wide range of applications, from interior design to exterior architecture. The research is driven by collaboration with architects and artists, exploring the potential of natural materials in a digital context. The goal is to create a sustainable and resilient building material that can be used in a wide range of applications, from interior design to exterior architecture.

The exhibition BioMat at the Venice Architecture Biennale 2023 is a research project for the production of a sustainable building material. The project is a collaboration between architects and artists, exploring the potential of natural materials in a digital context. The goal is to create a sustainable and resilient building material that can be used in a wide range of applications, from interior design to exterior architecture.

Fig. 1: LignoPrint Column exhibited at the Venice Architecture Biennale 2023. ©BioMat@Stuttgart, Photo by ReportArch / Andrea Ferro Photography

FROM FILAMENT TO STRUCTURE: 3D PRINTING OF NATURAL FIBRE FILAMENTS FOR ARCHITECTURE

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Abstract

This essay investigates the potential of fibre-reinforced polymers (FRPs) in the construction industry, emphasizing the role of additive manufacturing in advancing sustainable practices. By leveraging 3D printing technology, fibre filaments can be produced in a streamlined process, allowing for the creation of complex forms with reduced material use. The focus of this study is on both short and long fibre-reinforced filaments, particularly those incorporating natural and bio-based fibres, offering an alternative to traditional petrochemical-based materials. The study evaluates material properties of short-fibre PLA filaments reinforced with wood fibres, demonstrating their suitability for compressive structural elements. Long fibre filaments, produced with natural fibres like rayon, were also examined, with challenges identified around moisture sensitivity and filament consistency. Through an iterative design process, digital fabrication techniques were applied to optimize structural components such as columns and beams, leading to efficient material usage and improved performance in architectural applications. This research highlights the viability of integrating natural fibres into construction materials, promoting both material efficiency and environmental sustainability. However, further advancements are necessary to overcome technical challenges such as moisture absorption and mechanical limitations, particularly for large-scale applications. Continued development in multi-material deposition processes and fibre integration strategies is expected to enhance the potential of FRPs for broader architectural use, bridging the gap between innovative material science and practical construction techniques.

Introduction

Fibre-reinforced polymers (FRPs) offer an alternative material approach in the construction industry, providing opportunities for more efficient material use [1]. FRPs and their additive manufacturing techniques allow for strategic material placement, reducing the quantity of material required for both primary and subsidiary structures [2]. Additionally, the application of bio-based FRPs presents the potential to reduce reliance on fossil fuels, supporting more sustainable construction

practices [3]. However, traditional FRP manufacturing involves several complex processes and steps, leading to significant labour and energy demands [4]. In contrast, 3D printing of fibre filaments simplifies the process by combining fibre impregnation, deposition, and curing into a single step. This allows for the creation of complex geometries and the use of multi-material deposition [4].

While polymers like polylactic acid (PLA) are popular in 3D printing due to their low melting point, cost-efficiency,

and flexibility, their limited mechanical properties restrict their application to smaller-scale designs, such as interior elements and furniture [5]. Although large-scale Fusion Filament Fabrication (FFF) has been investigated in a few research projects [6], it remains largely underexplored, particularly in the context of fibre-reinforced filaments [7]. Current research focuses on increasing fibre content in PLA filaments, such as by incorporating agricultural residue fibres, to improve mechanical properties [8]. This suggests that increased fibre content could strengthen these materials while maintaining their ability to be extruded. In addition, the use of form-finding methods to optimise geometry may help address the mechanical limitations of these materials. Adopting a bottom-up methodology could help apply the material to structural typologies for which it is most suitable, maximising its structural potential in larger-scale applications.

This essay presents the research project 3DNaturDruck [9,10], which examined the architectural application of 3D-printed fibre-reinforced filaments, in both short and long fibre formats. For short-fibre filaments, fine wood fibres (≤ 1 mm) were added to PLA with a high mass fraction ($\geq 20\%$) to evaluate material properties. For long-fibre filaments, flax or rayon was combined with a PLA matrix, enabling the production of components made entirely from long-fibre bio composites. The project included material testing and simulations integrated into the digital design and manufacturing process, enabling early verification of the material's suitability for architectural applications, which informed the development of several demonstrators. This project highlights the potential for integrating natural fibres from renewable resources into architectural components, contributing to environmental sustainability in construction through the use of bio-based FRPs and advanced digital fabrication techniques.

Materials and Methods

The project's investigation was conducted on two fronts: short fibre filament and long fibre filament. Using a bottom-up design methodology, the filaments were produced, and their printability and mechanical properties were tested. Based on the results, a series of demonstrators was designed, taking in consideration

each material's performance. The demonstrators were designed with a digital workflow that involved form finding, FEM analysis and optimisation of material usage and printing parameters.

The short fibre filament was produced from wood flour, derived from ground wood, combined with PLA (polylactic acid), PBAT (polybutylene adipate terephthalate) and additives. Different percentages of fibre filler were tested. During the extrusion process, surface quality and dimensional consistency of the filament were key challenges due to the high filler content. A nozzle geometry was iteratively developed to reduce a problem known as „bearding,“ where polymer compound residues build up at the nozzle exit, creating defects in the filament. Additionally, because the filament absorbed significant moisture during cooling, a drying method was devised to prevent issues during 3D printing. The initial compounds containing high percentages ($> 40\%$) of wood flour were found to be brittle and prone to breaking. Consequently, new compounds with reduced wood flour content were formulated. A compound containing 20% wood flour was successfully printed, while the 30% wood flour compound remained too brittle for reliable processing. Mechanical tests, including tensile strength, density, and impact resistance, revealed that lowering the wood flour content improved printability and performance, making the material suitable for further 3D printing applications.

For the long fibre filament, various natural fibres (including hemp, flax, linen, and rayon) were tested, but most failed to produce consistent filament quality due to irregularities. Rayon was chosen for its smooth surface, high tensile strength, and stable diameter, although its hygroscopic nature (moisture absorption) posed significant challenges during extrusion and 3D printing, often leading to bubbles in the filament. Proper drying of the fibres was critical, as even brief exposure to humid air introduced bubbles that weakened the filament.

The long fibre filaments (Figure 2) were produced using a twin-screw extruder equipped with a coating die, where pre-dried natural fibres were coated with pre-dried PLA, resulting in filaments with a consistent 2.85 mm diameter. Laser measurement was used to monitor and adjust the

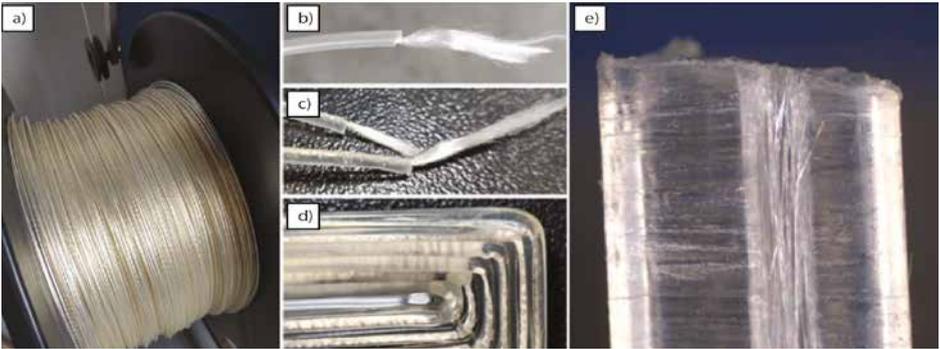


Fig. 2: Images of the long fibre filament. a) Filament on the spool, b) Before printing, c) After printing, d) Printed test specimen, e) Cross-section of the filament. Photo: Fraunhofer WKI

filament diameter as needed. Cooling also presented difficulties, as traditional water cooling distorted the filament. To address this, an air-cooling system was developed to ensure controlled cooling without disturbing the fibre's position in the filament. Ensuring the fibre remained at the centre of the filament was another significant challenge. A custom guiding system, using a PTFE-lined brass tube, was designed to keep the fibre in place and prevent polymer backflow. Another challenge was controlling the flow of polymer around the fibre, as polymer backflow led to clogging. Various solutions, including seals, cooling, and heating, were tested, but the problem was ultimately resolved by redesigning the fibre feed system. Additionally, maintaining consistent fibre tension was crucial for the filament's performance during 3D printing, so tension devices were introduced to

stabilize the fibre throughout the development process. After extrusion, the filaments were deposited on a conveyor belt and wound onto spools, with their visual quality carefully assessed for uniformity and defects. The tensile properties of the filaments were determined, revealing that fibre reinforcement improved tensile strength.

Short Fibre Filament Applications

Following the mechanical characterization, it was observed that the short fibre filament exhibited superior compression properties compared to its performance in tension. This finding underscores its potential suitability for structural typologies characterised by predominant compressive forces, such as shells, columns, arches, domes, and vaults. To practically demonstrate this

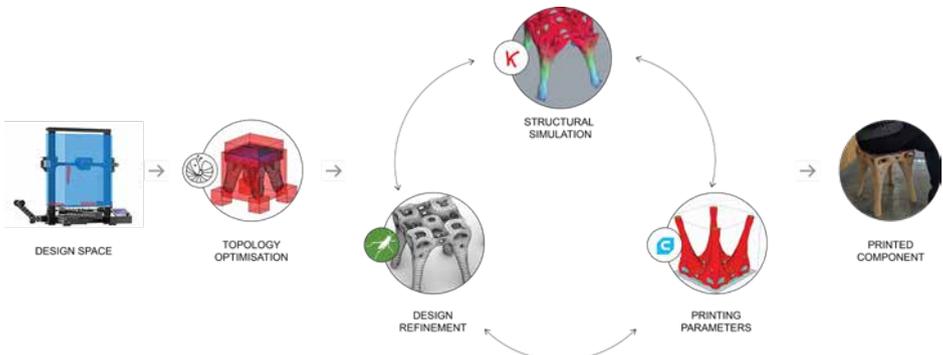


Fig. 3: Workflow implemented for the short fibre demonstrators, exemplified with a furniture scale case study.



Fig. 4: Topologically optimised stool 3D printed with the short fibre filament. The stool weighs 1.3 kg and is capable of supporting loads of 80kg without structural damages. Photo: David Schadwill

material's structural potential, a stool was designed as a small-scale functional prototype. This prototype not only highlights the material's performance in a tangible structural application but also established a digital design-to-production workflow scalable to larger components. The developed workflow (Figure 3) incorporated topology optimization of the total printer volume, accompanied by an iterative process of design refinement, structural simulation, and calibration of printing parameters. The outcome was a lightweight stool (1.3 kg) capable of supporting a person weighing 80 kg.

Based on these results, the system was scaled up for a larger architectural application. Specifically, a funicular shell structure was developed, leading to the design of the LignoPrint column. This column, which forms part of a larger structure, showcases the versatility of short fibre filaments beyond traditional shell construction. Through form-finding techniques, the optimal shape was determined, ensuring both material efficiency and structural stability. The surface geometry was divided into discrete components that fit the printer's working area. Initial simulations using ABAQUS indicated that

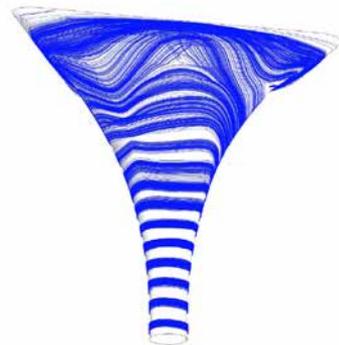
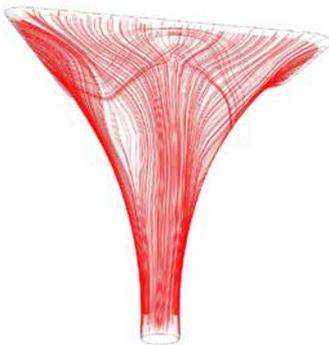


Fig. 5: Main stress diagrams from the column demonstrator. The tensile stress is shown in red, the compressive stress in blue.



Fig. 6: Image of the finished column, exhibited at the Venice Architecture Biennale 2023.
 ©BioMat@Stuttgart, Photo by ReportArch / Andrea Ferro Photography

the column's optimal average thickness was 30 mm. However, to further optimise material distribution, the components were further refined with variable thickness. By analysing the principal stress diagrams (Figure 5), compression rings were identified within the column.

This insight led to the development of a reinforcement strategy, wherein additional material was applied to the connection zones of each component, forming structural „ribs“ (Figure 7). These ribs not only enhanced structural performance but also improved the printability of the components by providing a stable base and eliminating

the need for support structures, thereby reducing both production time and material usage. Additionally, the ribbed detailing facilitated the assembly process, as the bolted connections required greater thickness than the simulated structural thickness. The LignoPrint Column (Figure 6) was successfully assembled over two days by a small team at the 2023 Venice Architecture Biennale, without requiring any scaffolding. The lightweight components and streamlined assembly and disassembly underscore the design's efficiency and highlight its practical potential for a wide range of architectural applications.

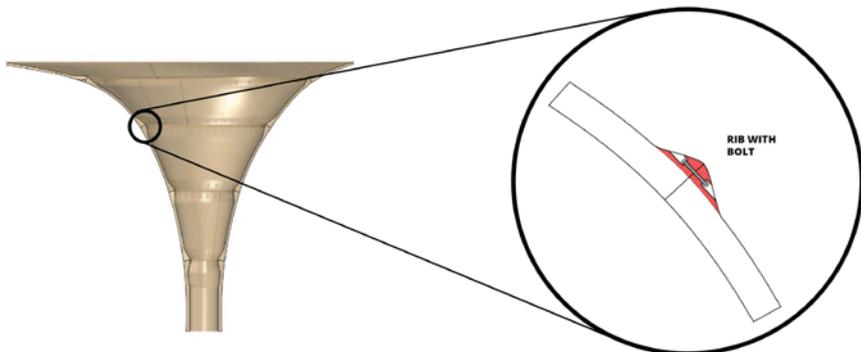


Fig. 7: Rib detail on the demonstrator and detail of the bolt connection



Fig. 9: beam demonstrator for the long fibre filament. component of beam 3D printed with long fibres. Photo: LZH

Long Fibre Filament Applications

A critical aspect of integrating long fibre filaments into large-scale 3D printing is the ability to print and cut them both during and after deposition. The design of the print head (Figure 8) was therefore crucial to this process. The development of a cutting mechanism for processing long fibre-reinforced filaments involved extensive testing and optimisation. Initial trials aimed to synchronise material feed and deposition speeds, with a nozzle slightly smaller than the filament diameter proving effective. Early cutting methods, including a cold-state cutting mechanism and a magnetic actuator, encountered challenges related to sealing and power. However, the final prototype incorporated a high-force

linear actuator with a 90° cutting angle, achieving a 100% success rate in filament cuts. Further improvements, such as enhanced heat dissipation and increased structural stability, ensured reliable performance, making the mechanism suitable for industrial-scale applications. In parallel, the Beam Demonstrator (Figure 9, 10) was designed to illustrate the potential of long fibre filaments for horizontal structural elements. Initially conceived as a 3-meter beam, the design was scaled down to reflect the current state of long fibre integration and production, requiring careful consideration of dimensions and material use. The final design comprises two components, each approximately 50 cm in length, connected by M6 screws in a simple yet effective manner. The design of the beam followed a workflow similar to that of the short fibre

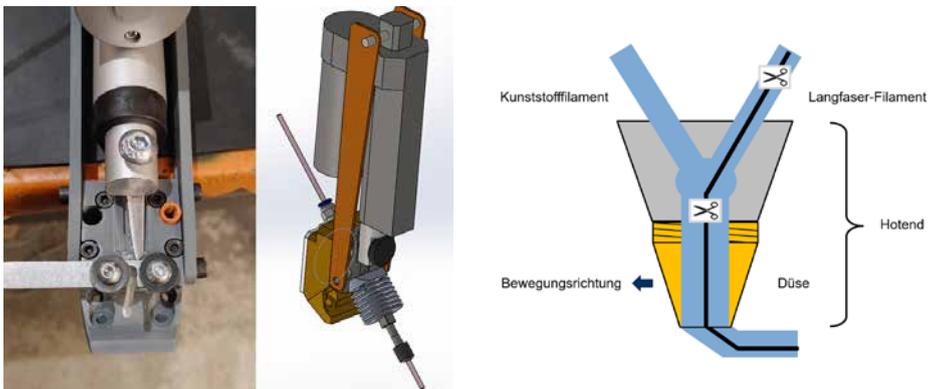


Fig. 8: Final prototype of the cutting unit. Left: Test setup, middle: CAD drawing, right: Diagram of cutting concept, Images: ATMAT and LZH



Fig. 10: beam demonstrator for the long fibre filament. 3D model of assembled beam

demonstrators, incorporating topological optimisation. This process resulted in a convex shape that enhances the beam's resistance to bending moments. The convex design ensures more efficient material distribution, allowing the beam to better withstand these forces. Moreover, aligning the diagonals with the force flow improves load transfer and enhances overall structural integrity.

Another investigation explored the potential of using long fibres in the connection elements between short fibre components, given their superior mechanical properties. This approach could eliminate the need for bolted connections, leading to even more streamlined, efficient structures (Figure 11).

Research was also conducted on a multi-material deposition process, where the base component consisted of short fibres, reinforced with long fibres strategically placed to follow the stress flow across the surface (Figure 12, 13). This approach involved the deposition of multiple material layers, controlled by a custom G-code slicer. Initial tests focused on non-planar slicing and printing on individual curved surfaces. The process underwent several iterations to resolve issues within the slicing script and to refine print quality through additional test prints. While these preliminary tests were successful, the process has not yet been scaled up to trials using the actual materials intended for final application. However, the slicer logic was designed to be adaptable, allowing its use with other 3D printers for future large-scale fabrication.



Fig. 11: Small multi-material demonstrated created in two separate processes, short fiber printing and long fiber printing. Dimension: 180 x 200 x 30 mm, Photo: LZH

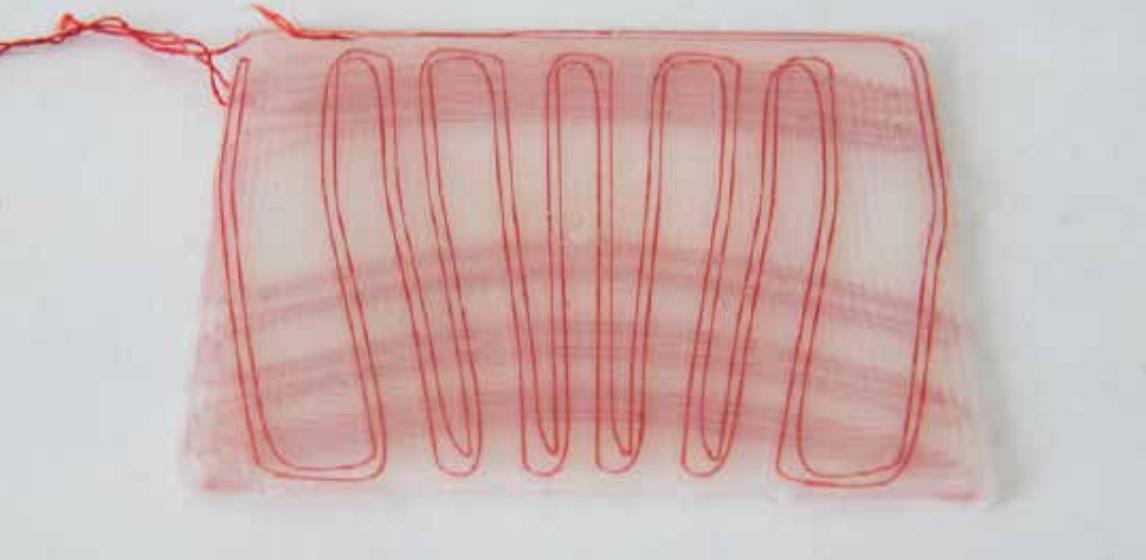


Fig. 12, 13: Test prints of a component for multi-material deposition. Colored lines represent the long fiber filaments printed on the components in the direction of force flow. (Photo: Daniel Pauli)

Further testing needs to be done to fully realize the benefits of continuous fibre printing in this context. Continuous fibre printing represents a significant advancement in manufacturing technology, offering the ability to produce highly efficient, structurally optimized components. By pushing the boundaries of material properties and design integration, this approach opens up new possibilities for future applications in construction and other industries that demand lightweight, high-performance structures.

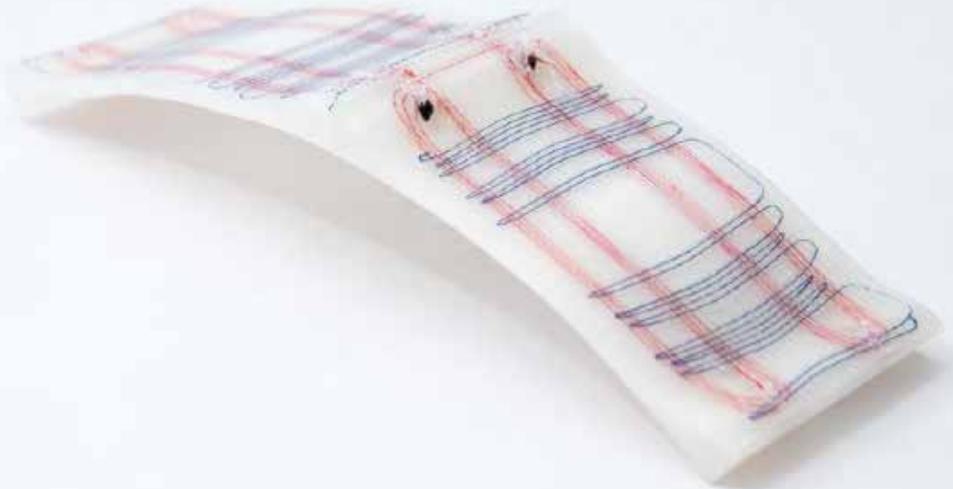
Conclusions and Outlook

This essay explores the potential of 3D printing with fibre-reinforced filaments as a solution for enhancing material efficiency and performance in the construction industry. A key advantage of this technology is the accessibility of fibre-reinforced filaments, which can be used not only in large-scale industrial applications but also in smaller, privately accessible 3D printers. This accessibility broadens the scope for design and

fabrication, enabling individuals and smaller firms to create structurally optimised components with reduced material usage. Furthermore, the ability to use bio-based materials in these filaments supports more sustainable construction practices, making advanced material technologies available to a wider range of users.

The 3DNaturDruck project demonstrates the practical application of fibre-reinforced filaments in architectural components. In the case of short fibre filaments, the LignoPrint column's development and successful assembly demonstrate its potential for applications beyond furniture scale applications. The ribbed reinforcement strategy proved effective in enhancing both structural performance and printability.

Simultaneously, research into long fibre filaments demonstrated the feasibility of producing continuous fibre filaments for horizontal structural elements, exemplified by the Beam Demonstrator. Despite challenges such as moisture absorption and filament consistency, the research provides a foundation for advancing continuous



fibre 3D printing. Additionally, the exploration of long fibres in connection elements between short fibre components suggests the potential for eliminating bolted connections, improving structural efficiency.

While the findings are encouraging, several challenges remain. Further research is required to enhance the mechanical performance of bio-based polymers and fibres, as well as to test the durability of these materials under real-world conditions, which is essential for their broader architectural and structural applications. Furthermore, the integration of fibre-reinforced polymers into complex, load-bearing structures will require continued advancements in multi-material deposition techniques. With further refinement, the combination of short fibre components reinforced with continuous fibre holds significant potential for creating efficient, lightweight, and structurally optimised components. The sustainability benefits, combined with advances in digital manufacturing, present a promising direction for innovation in construction, bridging traditional methods with emerging material technologies.

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The LignoPrint Column was exhibited at the Venice Architecture Biennale 2023 at ECC Pallazzo Mora and was shortlisted for the 2023 ECC-ITA Design Awards.

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Fig. 1: 3D print with wood particles

3D PRINTING WITH WOOD WASTE

Development of reusable printing material based on waste wood particles and its digital manufacturing process for wall constructions in architecture

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Abstract

Due to changes in the Renewable Energy Sources Act (2017), several million tonnes of waste wood are generated in Germany every year. This research focuses on adding value to this waste by developing a sustainable, recyclable 3D-printing material made from shredded waste wood, secondary raw materials and environmentally friendly additives. This material is processed using robotic extrusion 3D printing to produce CO₂-neutral, circular constructions.

The aim of the project is to develop a complement and alternative to 3D concrete printing that exploits the synergy effects inherent in the material utilisation of residuals, the use of alternatives to harmful materials, recycling, waste reduction, cascading use and the creation of a closed material cycle.

Introduction

Germany produces 9 million tonnes of waste wood every year, including industrial and sawmill waste, construction demolition wood, furniture that can no longer be reused, packaging and waste wood from outdoor areas every year. Two recycling strategies are currently used: material recycling, which involves the production of chipboard, and thermal recycling, which generates heat and electricity. Nevertheless, only 17% is currently recycled as material [4]. In consequence of amendments to the Renewable Energy Sources Act (EEG 2017), thermal utilisation is no longer subsidised. However, thermal and material recycling remain of equal importance in the industry. This is set to change with an upcoming reform in favour of material recycling, which will further exacerbate

the problem of waste wood recycling. [8]. In Germany, waste wood is classified into four categories. Category A1 comprises natural or merely mechanically processed wood. Category A2 includes painted or treated wood. Category A3 is distinguished by the use of organohalogen compounds in the coating. If wood preservatives have been used, the wood is categorised as A4. Fig. 2 illustrates examples of each category, both before and after shredding at a recycling facility.

Additive manufacturing in architecture is currently predominantly developed in concrete and clay 3D printing. PERI is one of the largest international manufacturers and suppliers of formwork and scaffolding systems. In June 2021, after an eight-month construction period, the



Fig. 2: Overview of the Waste Wood Categories (A1-A4) with the shredded output

first printed two-storey detached house with approx. 80 square metres of living space was completed in Germany (Beckum). Using extrusion technology, the flowable fresh concrete is transported to the print head, which is located on a gantry robot (COBOD BOD2), and pressed out in layers [7].

In the same year, WASP and the architecture firm Mario Cucinella Architects collaborated to create the 'Tecla House', a prototype of a 3D-printed clay house. It was printed using components from local soil, water, rice husk fibres and an unspecified binder. At the start of construction, the earth was excavated and analysed for components, and additives were added according to its composition. WASP's own 3D printing technology, CraneWASP, was used for production. From 2021, this was operated by a stationary unit and two synchronised printing arms, each capable of printing an area of up to 50 m³ simultaneously. The approximately 60 m³ house consists of modules up to 4.2 m high and could be printed within 200 hours. [5, p330]

Research on 3D printing with wood particles focuses either on material (small scale) or technology application (M 1:1). In 2017 Michael Rosenthal used a mix of wood particles and methylcellulose to extrude a small tower with the dimensions of approx. 40 x 40 mm [6]. In a kind

of binder jetting process, Klaudius Henke used wood, gypsum, methyl cellulose, sodium silicate and cement. Water was sprayed between the individual layers to activate the adhesive effect [2]. The research project at BOKU Vienna is pursuing a similar approach, which uses starch and lignin to apply individual adhesive layers. By adding water and thermal activation, the individual layers stick together [3]. Composite filaments made of wood and PLA or PP are widely used in combination with FDM printers.

This research project aims to combine the two issues of material use of waste wood and wall construction with robotic digital fabrication to create a sustainable alternative. A largely unexplored area of research is the process of direct extrusion and waste wood particles paste using a robot arm with ecological binders in a layering process. The research aims to develop a new digitally supported process using robotic arms and extrusion technology for the production of sustainable monolithic wall structures.

Our process focuses on residual materials, promises 100% recyclability and reuse and is aimed at industrial applications. The construction industry lacks sustainable strategies without harmful additives and consistent recycling concepts. The project examines the feasibility by

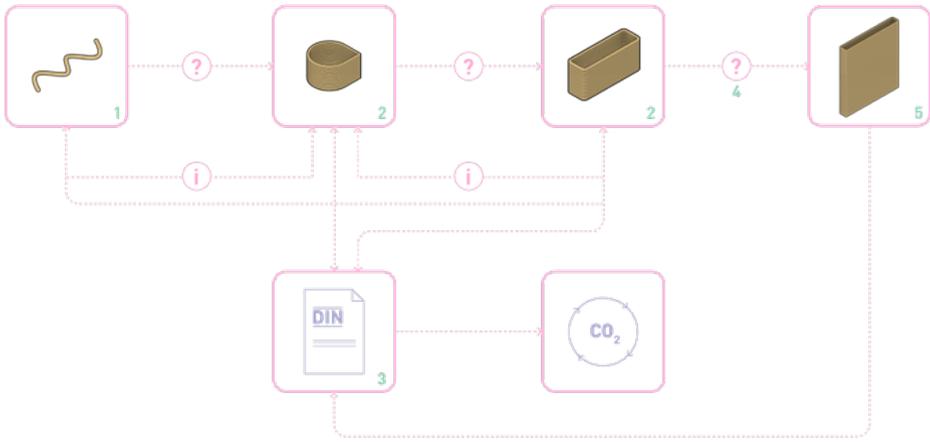


Fig. 3: Schematic diagram of the methodology for material development

scaling up test bodies with the help of industrial partners and compares tangential processes from science and technology.

In Section 3, the methodology of material development based on residual waste wood, manufacturing and testing methods are explained. Section 4 summarises the results and section 5 gives an outlook on the future architectural application scenarios for scalable wall structures with integrated functionality.

Methodology

In order to evaluate individual parameters and their interactions, the following series of research studies were carried out (see Fig. 3):

- (1) development of printable material formulations
- (2) Benchmark test prints in different scales,
- (3) test methods
- (4) component design/development
- (5) production of a 1:1 wall structure.

Material development

The base material consists of wood particles and has no binding function of its own, which is why it is dependent on the mediating effect of a binder system. This is necessary in order to withstand the forces to which the resulting components are exposed during digital production, transport and handling. In addition to the properties of the particle material, the binder and its application (e.g. solids content) also have a major influence on the mechanical properties of the subsequent material. The properties of the printing paste can be adapted through the binder and the use of additional additives - such as protection against moisture, mould growth or an increase in fire protection.

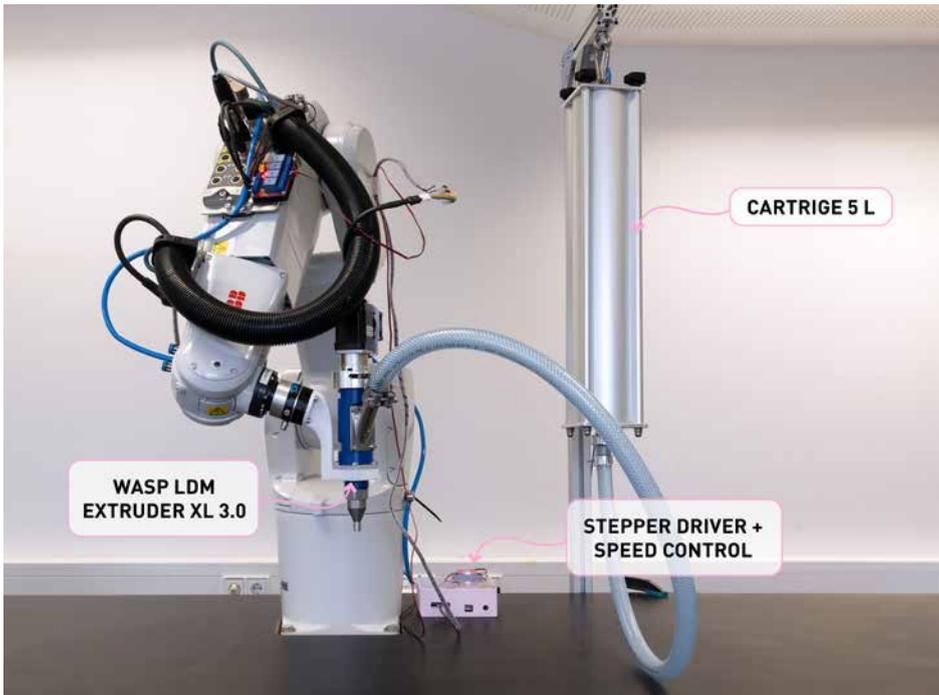
The wood fiber materials were sourced from the company JELU-WERK J. Ehrler' and are classified as A1 waste wood [1]. To make the coarse heterogeneous fibers usable for the process, the wood sticks were shredded into fine powder (75 µm). To bind the resulting and loose wood particles into a collective and generate a flowable printing paste, various sustainable binders based on residual materials were tested as follows: (1) cold-swelling (modified starch) and warm-swelling (cooked starch) starches based on potatoes, corn, waxy

maize, and wheat, (2) chitosan hydrogel, and (3) cellulose ether. To adjust the printing and component parameters, additional sustainable additives can be added to the base formulation. These additives can enhance properties such as flowability, stability, drying speed, and mold prevention. Examples include electric gypsum, polycarboxylates, calcium sulfate, calcium chloride, sodium chloride, and guar gum. As a mold inhibitor, the preservative XF Superfine from ADDCON was used in low dosages.

A variety of different material formulations and print settings were investigated on a small scale with the aim of developing a promising material formulation for the M 1:1. The print path of the test bodies is constructed in a teardrop shape with the dimensions 75 x 180 x 100 mm (W x L x H). The next step was to scale up a selection

of potential formulations by developing small wall and column structures with dimensions of around 1000 x 1000 x 500 (W x H x D in mm). The focus here was on the geometry itself, taking into account the parameters of the layer height, number of wall lines, filling, pattern of the filling and the nozzle geometry. The collaboration with the industrial partner „RUPP Gebäudedruck“ enabled promising formulations to be tested on a 1:1 industrial scale using demonstrators in their technical facility, utilizing established mixing, pumping and printing techniques. This is the final scaling stage, which forms the basis for the design and manufacture of a large-scale prototype. Once the results have been categorized (see Fig. 5) using various test procedures, it is possible to switch agilely between the different scales.

Fig. 4: Photo of the printing setup: ABB Robot with a screw extruder



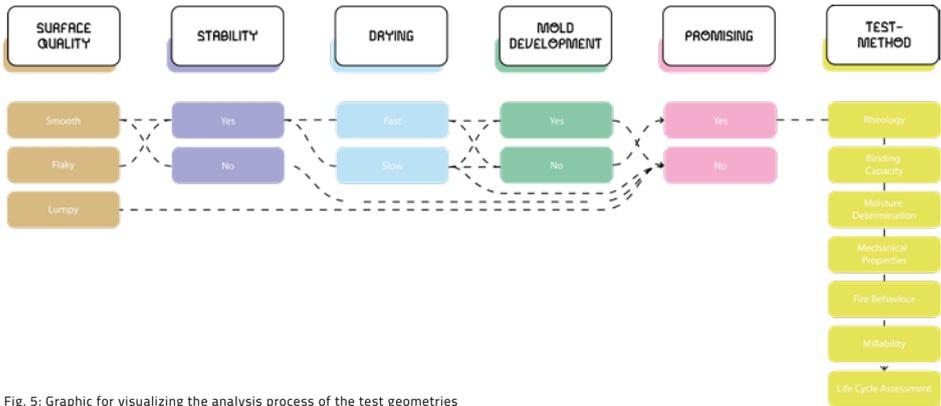


Fig. 5: Graphic for visualizing the analysis process of the test geometries

Manufacturing process

The manufacturing process consists of (1) material preparation, (2) 3D-Printing and (3) drying.

In order to create a homogeneous mixture and ensure an even distribution of all substances, dry ingredients such as wood particles and powdery moulding binders and, if necessary, other dry additives were first added to a mixer water and, if necessary, fluid binders and/or additives were added in a next step and mixed for 30 seconds. For robot-guided 3D printing, the extruder was mounted on the robot using a 3D-printed adapter, while the cartridge is located next to the robot on a movable holder (see Fig. 4). The material was fed into the extruder via a PVC hose with compressed air (4-6 bar). The extruder was controlled via a digital signal sent by the robot and the speed of the screw can be adjusted during printing, which made it possible to adapt the revolutions per minute of the screw to the material to be printed. The robot code was generated by Grasshopper and the 'Robot Components' plug-in. In the final stage of production, the printed samples were stored on a grid in an open environment to allow the

evaporation of moisture and the possible formation of mould. During this stage, the weight loss due to the above processes could be monitored by weighing the samples over a period of time.

Test Methods

The dried samples were analysed after the production process. Figure 5 shows a visualisation of the process. Each sample was evaluated for surface quality, stability, drying time and mould development. If a positive result was obtained for all four points, the sample was considered promising. The best samples were then analysed at regular intervals using various test methods. Firstly, an insulation test was carried out to determine the general insulation properties of the material. Five different samples of the material were analysed, both printed and as bricks. Further samples were produced following this test. Test specimens are currently being prepared for a compression test.

Results

To date, we have conducted over 70 formulation tests in the course of our research (see Fig. 6). The results of the material and component tests show that the materials have favourable insulating properties with values ranging from 0.059 W/mK to 0.079 W/mK. A combined analysis of the initial test results with the material behaviour of the formulations during printing indicates that the following additives have the most potential: chitosan gel, bentonite, talcum and electrical plaster. The slow drying process of the samples remains a major challenge. This will need to be monitored and, if necessary, further drying strategies will need to be found to prevent the formation of mould on the larger geometries and to allow the process to proceed quickly.



Fig. 7: Photo of a small 1:1 sample print

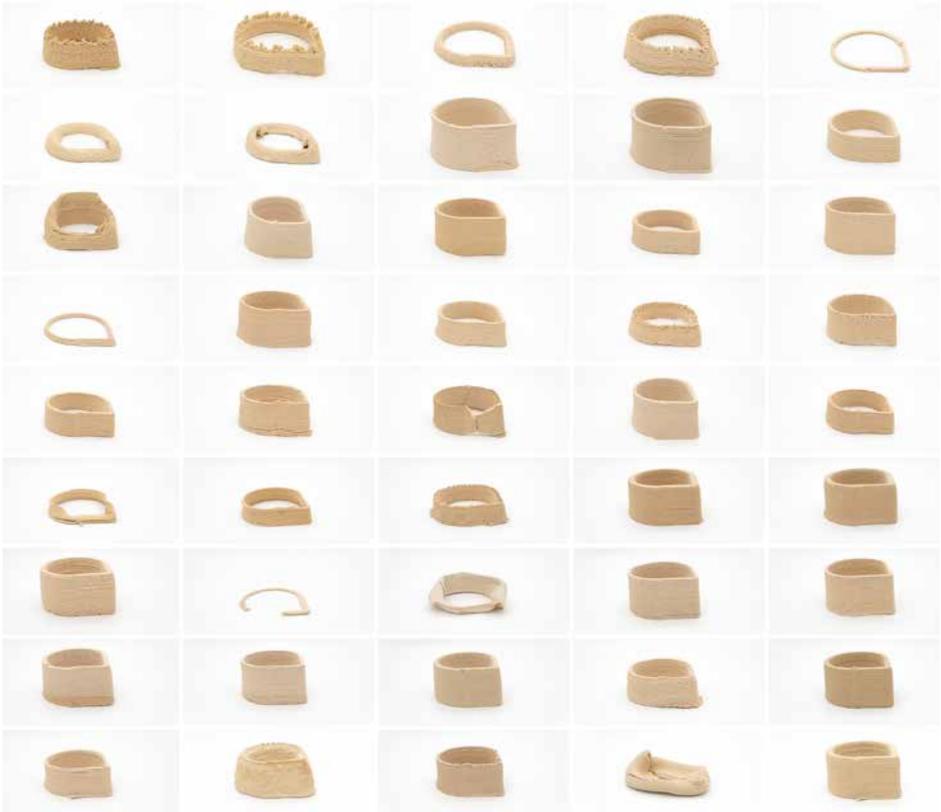


Fig. 6: A photographic overview of printed material samples

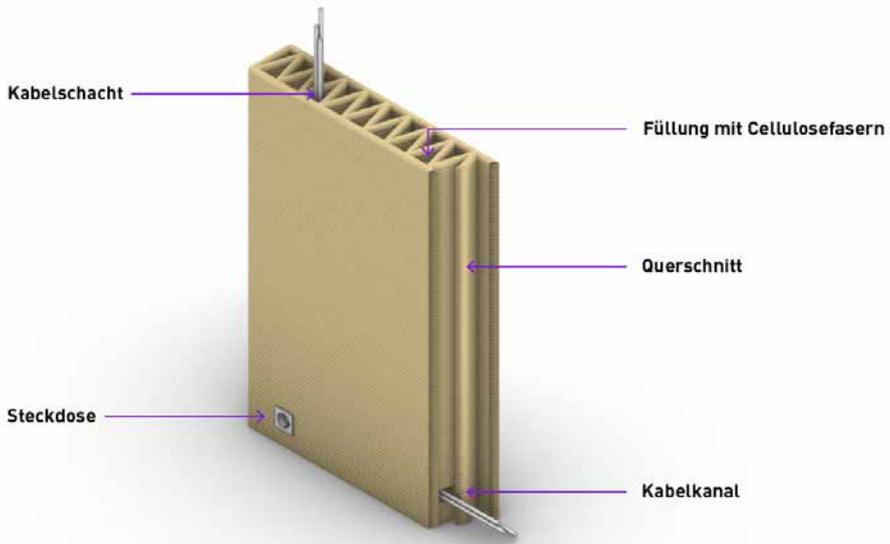


Fig. 8: Concept design for a non-load-bearing interior wall made of 3D-printed reclaimed wood

Future Application

The results of the ongoing research project indicate a favourable outlook for the planned application of wall construction, whereby generated waste wood is processed through a zero-waste approach into wall structures with integrated functionalities, including installation management. A circular processing process was established, comprising the following steps (see Fig. 9)) (1) raw and source material, (2) mixing, (3) 3D printing, (4) drying, (5) use case, and (6) recycling.

A design for a wall structure was developed based on 3D printing parameters and in compliance with building regulations (see Fig. 8). In further research work, the design and construction of the wall will be analysed and, if necessary, adapted to ensure that the formulation used can be applied on a 1:1 scale.

One advantage that has emerged is the ability to rely on established equipment and utilise the facilities of the construction industry. This provides an open and rapidly deployable system that does not require the manufacture and use of specific equipment, an important part of the sustainability strategy.

Acknowledgement

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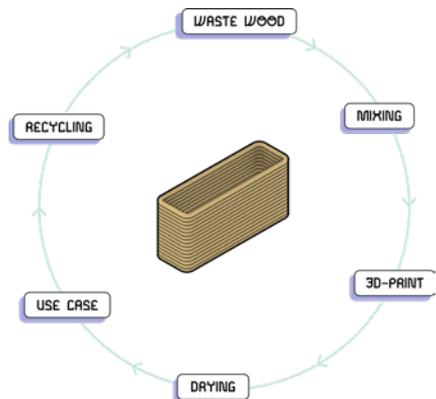


Fig. 9: Graphic visualisation of the circular processing process

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Fig. 1: Pulp Fraction

FROM ADDITIVE TO GROWTH-BASED FABRICATION

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Introduction

Human history has always been marked by a fascination with nature. Traces of biology's influence on the human made are visible throughout time. Some of the earliest signs of this are cave paintings depicting wildlife, human figures, and hand stencils. In ancient architecture, biological motifs are prevalent, often referred to as biomorphism - where organic shapes are applied to architecture, such as the acanthus leaf in Corinthian columns or the depictions of trees, lions, and other animal reliefs in Mesopotamian architecture. This influence extends into more recent times, manifested in stylizations such as the ones found in baroque and Art Nouveau. Later, biomimicry developed, aiming to transfer functions from natural structures to human-made ones by copying their geometries. While this can lead to higher performances and added functionality, it falls short of realizing the full potential of biological systems.

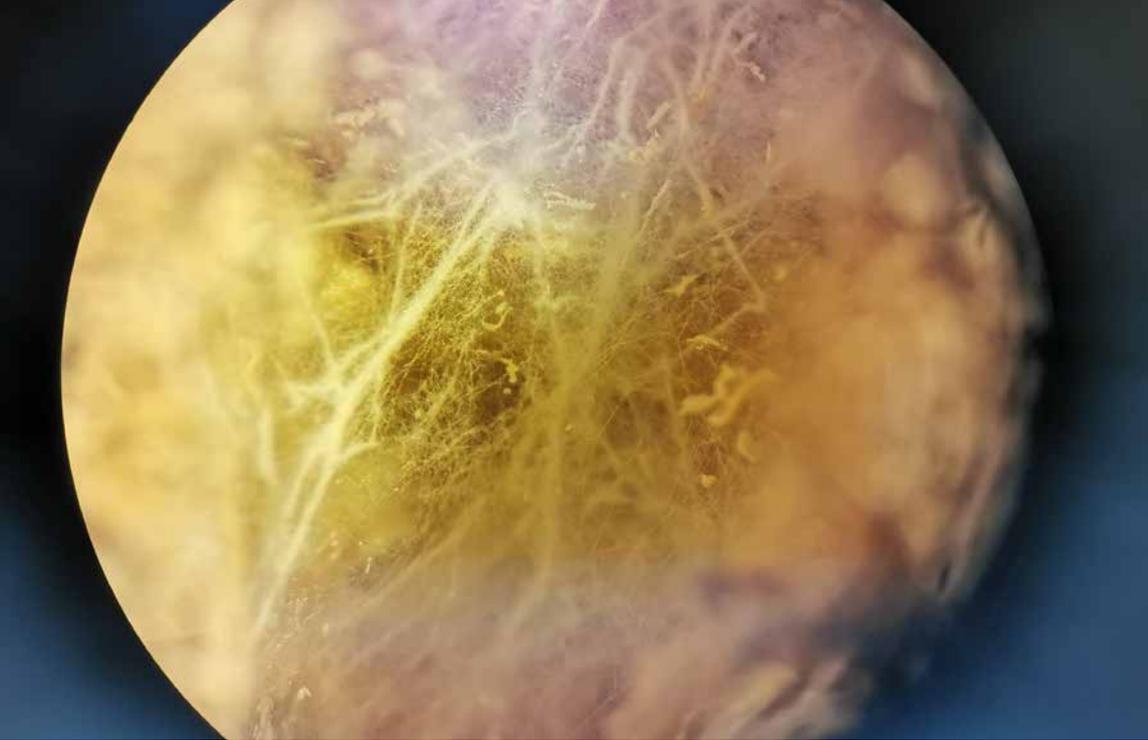
In recent years, the design world has seen an increased focus on biological processes, partially driven by the climate crisis and the need to respond with more sustainable material solutions. This shift includes everything from bio-based materials, which need as little as 7% biomass to qualify as such [4], to the use of living cells in structures.

But how can we truly utilize the power inherent in biology? The new frontier is perhaps one where design itself is not 'like' biological structures, and even not made 'with' parts of biological materials; but where design is materialized through biological processes.

The Evolution of Fabrication Methods

Through industrialization, materials have been homogenized to ensure predictability. For example, natural wood fibers are a product of highly contextual adaptation, growing in response to structural loads, winds, light, and other environmental factors. These fibers align themselves to efficiently bear loads. However, in industrial products like OSB (oriented strand board), wood is sliced into thin layers and glued with

alternating orientations, removing the material's inherent directionality. This desire for isotropic, uniform materials is favored in industrialized contexts that prioritize standardized building components. However, responsive materials that react to their environment can offer better performance. They harness the biological systems' capabilities to adapt over time, reacting to stimuli to optimize functionality.



3D printing revolutionized fabrication by enabling the construction of complex geometries with reduced waste. Still, current additive manufacturing processes remain top-down and fixed, with tightly predetermined outcomes. While performance variation can be introduced through geometry, it is far from the dynamic functionality of biological systems.

Growth-based fabrication can be the next step. Inspired by biological growth, it integrates not just the form but the process and function found in natural systems. Biological systems are self-organizing, with structures that grow through the interaction of genetic code and environmental feedback, leading to efficient, adaptive forms. The connection between phenotype and genotype in biology is dynamic, with environmental factors playing an important role in shaping both form and function,

mediated through processes like homeostasis [5].

One of the most exciting aspects of growth-based fabrication is its potential for self-repair. Materials could grow in response to wear and tear, healing cracks and adapting to stresses not anticipated in the design. This concept is already seen in bio-concrete, where bacteria embedded in the material calcify to repair cracks, even long after construction has completed [3].

Another aspect of the adaptive capabilities of living materials to self-repair can be used during construction. Building elements can grow into each other to provide a deeper joinery that is adapted to the specific circumstance of the structure. This is seen in early tests with mycelium composite materials, where parts undergo bio-welding when joined [1].



Transcality in Growth-Based Fabrication

Transcality is one way to explain how these complex behaviors are coordinated. In living organisms, functions are distributed across scales, where they are interdependent. From the cellular level, where processes like energy production or waste filtration take place, to the organismal level, where complex functions such as locomotion emerge. This interconnectivity of scales in complex systems is transcality, from cellular to organismal to ecosystem [2].

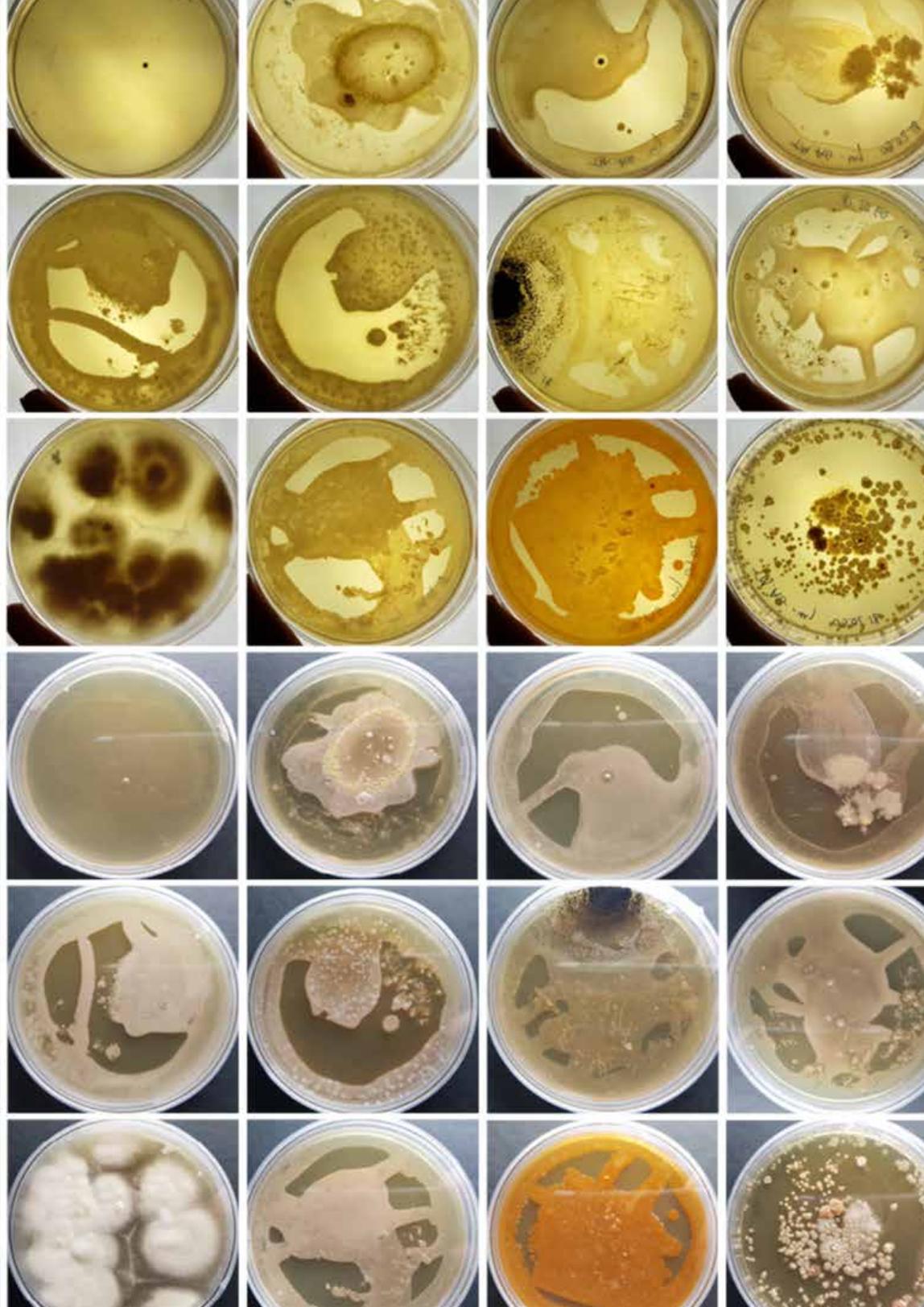
In construction, translating these nested, interdependent functionalities into human-built structures is challenging. However, computational tools and digital fabrication technologies can help manage this complexity. In biofabricated design, function can be addressed across multiple scales simultaneously. For example, at the micro-scale, materials can be designed to

absorb water or heat. At the meso-scale, these materials can channel air or distribute forces. At the macro-scale, these properties combine to form a functional building element that performs a variety of tasks.

Growth-based fabrication also emphasizes the use of local materials. Microorganisms can adapt to various substrates, and by using local microorganisms and feedstock, growth-based fabrication reduces the need for transporting materials over large distances. This approach can also convert regional waste streams into usable, upcycled products.

Additionally, digital additive manufacturing can enable the use of weaker or unconventional materials, as they can be intelligently placed to form higher performance parts that go beyond the capabilities of homogeneous material specifications.







Technological Integration

Additive manufacturing (AM) is highly compatible with biological growth, as it mimics the incremental, layered processes found in nature. By providing precise control over the material deposition, AM can serve as a digital informant of the growth process, and initiating the growth conditions. Pushing even further the form freedoms allowed by additive manufacturing, through growing design form and function can co-evolve, just as in biological organisms.

In nature, environmental factors such as light, humidity, and pressure shape how organisms grow. Similarly, in growth-based fabrication, external stimuli can influence how structures are built, allowing the process to respond to conditions in real-time. This blurs the

traditional boundaries between design and fabrication, as the growth process itself becomes the design process. In this model, function is not simply added later, but it is inherently built into the design as it grows and modifies.

Generative design plays a crucial role here. Through computational simulations, conditions like structural load and environmental factors can be predicted, allowing materials to respond and adapt. This results in structures that are functional, resilient, and tailored to their specific context. Rather than imposing fixed outcomes onto materials, growth-based fabrication cultivates materials, designing not only the final structure but also the process of growth.



Challenges and Future Directions

While growth-based fabrication has a high potential, scaling biological processes from the molecular to architectural dimensions presents challenges. The growth and transformation rates of materials and their scalability for large-scale applications must be thoroughly considered. Additionally, there is a current lack of production facilities that can accommodate both microbiology and construction at an architectural scale.

As with any new technological system, growth-based fabrication comes with some consideration. The manipulation of living systems raises questions about impact on biodiversity, and how the transition to large volume production can be made sustainably.

To address these and other, new challenges, interdisciplinary collaboration is essential. Fields such

as biology, chemistry, materials science, architecture, and engineering need to work together to develop new material systems and fabrication methods. These collaborations will enable the evolution of both growth-based fabrication techniques and the frameworks needed to scale them.

Conclusion

Growth-based fabrication has the potential to transform our current material culture into a more adaptive, sustainable, and resilient practice. As we continue to develop these technologies and integrate biological systems into construction, we move closer to an era where architecture itself can grow, adapt, and thrive alongside the natural world.

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Fig. 1. La Citadelle Des Savoirs-Faires ©B+G

RESEARCH AND DEVELOPMENT FOR 3DCP: CHALLENGES, OPPORTUNITIES AND SOLUTIONS IN CURRENT 3DCP REALIZATIONS FROM BOLLINGER+GROHMANN

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The Automated Construction Side

The construction industry has traditionally been slow to adopt automation and digital technologies, relying heavily on manual labor and conventional building techniques. However, the advent of 3D concrete printing (3DCP) has begun to transform this landscape, offering novel opportunities for innovation in design, sustainability, and efficiency. 3DCP, an additive manufacturing technology, allows for the automated fabrication of complex structures by layering material according to a digital model. This method not only reduces labor costs and the potential for worksite accidents, but also facilitates the creation of intricate architectural forms that would be costly or difficult to achieve with traditional methods.

The focus of interest in 3DCP is material innovation. While cement-based mortars are commonly used, new alternatives are emerging that offer lower environmental impact. For instance, Constructions-3D¹ is developing Termix-3D, a clay mortar that has three times less carbon content than conventional mortar, with the cement partially being replaced by heated clay and slag from Hauts-de-France [1]. The Institute for Advanced Architecture of Catalonia (IAAC)² is working on the impression of local earth that is mixed with additives and enzymes to ensure structural integrity and material elasticity (Fig. 2) [2], offering a more sustainable and locally-sourced solution for construction projects.

In this article, we explore the current state of 3DCP technology through a series of case studies, ranging from the construction of the tallest 3D-printed building in the world to innovative applications in infrastructure, such as pedestrian bridges. These case studies not only showcase the potential of 3DCP to revolutionize construction but also highlight the technological challenges such as material performance and the integration of reinforcement. By examining these projects, we aim to provide insights into how 3DCP can redefine the future of construction and architecture.

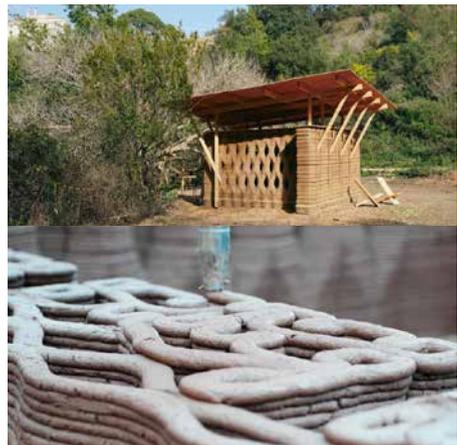


Fig. 2: Raw earth printing by IAAC ©Gregory Civera

Exploring 3D Printing Technology through Various Case Studies

(1) Robotic In-Situ Construction

Large-scale 3D printing is transforming the construction industry by enabling new methods of building that streamline the process and expand design possibilities. One of the most innovative approaches is in-situ 3D printing, which allows for the direct fabrication of structures on-site. This technology not only paves the way for more efficient and flexible building solutions while reducing the need for assembly and removing the logistical challenges associated with prefabrication, but also offers the potential for larger, more complex structures to be constructed in one piece.

Robotic systems play a key role in this transformation. Various types of robots, such as portal printers, mobile robots, and semi-mobile printers, each offer distinct advantages. Portal printers, while confined to a specific fabrication space, provide high precision and reliability. On the other hand, mobile robots, such as those studied by Kathrin Doerfler [3], overcome spatial limitations but

may sacrifice some accuracy. Semi-mobile robots, like the MaxiPrinter developed by Constructions-3D, strike a balance by offering mobility while maintaining stationary printing capabilities for improved precision.

Since 2021, Bollinger+Grohmann has been working with Constructions-3D, a manufacturer of 3D printing machines based in Bruay-sur-l'Escaut in northern France, to build the Citadelle Des Savoir-Faire (Fig. 3), which includes the tallest 3D-printed building worldwide. This new scientific discovery park will bring together the head office of Constructions-3D with innovative companies in 3D printing, 3D scanning³ and blockchain⁴.

The project includes multiple buildings between one and three stories high demonstrating a wide range of 3D printing methods. It is an opportunity to test and deploy innovative in-situ 3D printing technology on a large scale, with all the new challenges it presents.

The movement of the semi-mobile robot must be planned in detail during the provisional phase considering its reachability to account for its weight and size. The mobile spider legged robot must move horizontally and vertically to be able to cover the walls over multiple levels (Fig. 4).

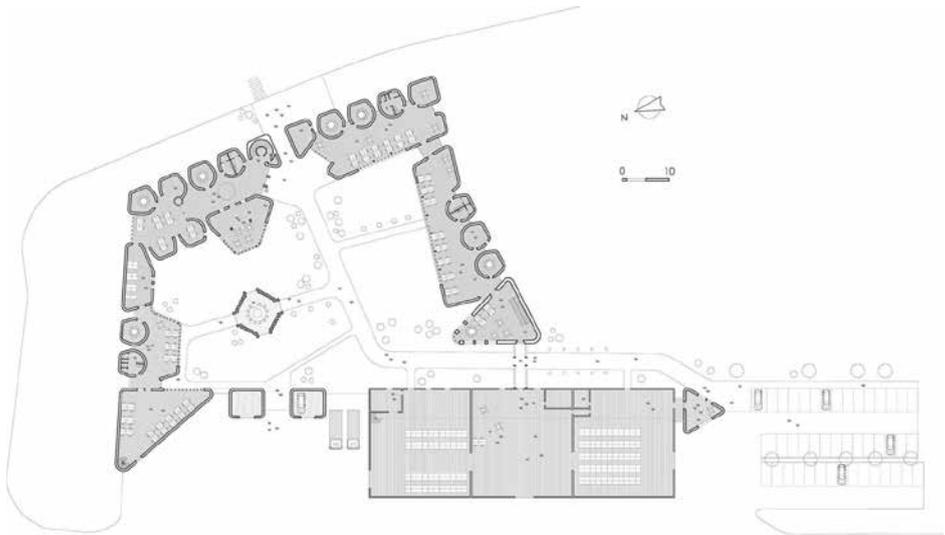


Fig. 3: Plan view of the Citadelle Des Savoir-Faire ©Sylvain Pierre Jean Architects



Fig. 4: La Citadelle Des Savoirs-Faires (right) and construction workers of the future printing the third level (left) ©B+G

A major restriction to in-situ fabrication is accuracy. The semi-mobile robot must be localized newly relative to the workpiece after each movement resulting in cumulative errors. A sufficient vertical overlap between the layers must be ensured, as well as a consistent thickness to ensure sufficient coverage of the reinforcement. Despite in-situ printing being able to minimize human workers on site, human intervention is generally still necessary on the augmented work side, for example to integrate reinforcement and ensure accurate and reliable fabrication. With the increase in robotization and automation, development on this human-robot collaboration is advancing, for example through the research by Daniela Mitterberger on the cooperative workflow [4], improving efficiency during 3D printing.

(2) Freedom of Form and Topological Optimization

The extruded material in 3D printed structures is commonly of low tensile strength and therefore, without reinforcement, limits the application of the fabrication method. Integrating reinforcement into the fabrication process poses a challenge partly due to the incompatibility between the layers and tangential reinforcement. Professor Harald Kloft and Norman

Hack solve this by spraying shotcrete directly onto a preinstalled reinforcement mesh [5]. Some companies, such as XtreeE⁵ in partnership with the CNRS⁶ and the Ecole des Ponts⁷ are working on the co-extrusion of long fibers during the material printing process with an adapted print head to reinforce the printed material [6]. Another common approach is to position the reinforcement in between two 3D printed walls and fill the remaining cavities with concrete.

Bollinger+Grohmann together with DesireSynthesis Architects⁸ and Siam Cement Group⁹ are working on the design of a footbridge in Thailand using this latter hybrid approach: a composite with 3D-printed concrete and infill in BFUP (Béton Fibré à Ultra haute Performance). 3D printing technology offers architects new freedom of form, experimenting on the topology of the structure allows for optimized use of material and reduction of the amount of required reinforcement. In the initial architectural design, the discontinuous arch creates a concentrated stress path. The second design with four supports showed tensile forces indicating bending at the supports and the convolution between the larger two bridge parts leading to the supports. A topological optimization of the geometry based on the force flow led to a reduction to three supports and eliminated any

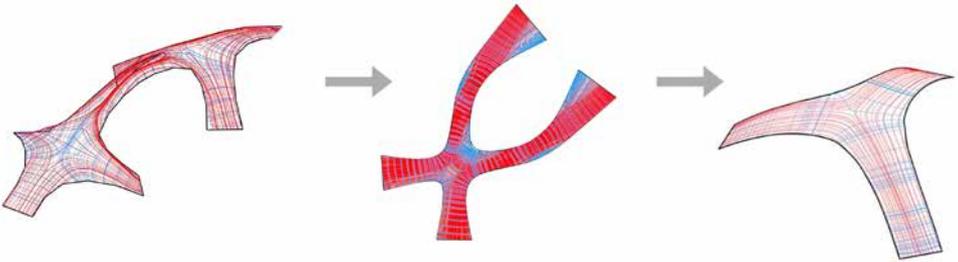


Fig. 5: From the initial design (left) towards Bollinger+Grohmann's final design (right) of a footbridge in Thailand with the help of principal stress lines ©B+G

tension in the principal load-bearing direction (Fig. 5). The bridge consists of custom ribbed concrete shells in an assembly inspired by the traditional voussoir system¹⁰ where each shell only fits into one position.

Structural optimization of the geometry was also applied to the design of a two-story 3D printed building that is built in collaboration between Bollinger+Grohmann together with Construction 3D for the Citadelle Des Savoir-Faire (Fig. 6). The floor slabs based on initial doctoral research from Saqib Aziz at KET¹¹ in partnership with HENN12 and SIKA [9] consist of custom prefabricated concrete shell elements in between which reinforcement is positioned before covering it in concrete. This method not only optimizes the used material drastically by increasing the lever arm of the reinforcement and therefore reducing the carbon footprint by 36%, but also eliminates the need for suspended acoustic damping which would reduce the room height.

Contrary to geometries made with traditional techniques that are constraint by the formwork, 3D printed concrete fabrication enables highly complex and customized shapes giving architects and engineers

flexibility in the positioning of material. However, to optimize the structure and minimize the use of material, the design should be centered towards the force flow. This requires a rethinking of the entire design process as the engineer must already be strongly involved in the early stages of concept design to be able to modify the design of the general structure when needed.

Towards Widespread Adoption of Digital Methods

As the construction industry grapples with the need for increased efficiency, sustainability, and innovation, 3D concrete printing emerges as a key technology with transformative potential. The case studies presented in this article demonstrate how 3DCP can overcome traditional limitations in design and fabrication, offering new possibilities for custom, complex structures that are both material-efficient and cost-effective. These examples also highlight the importance of interdisciplinary collaboration, where architects, engineers, and manufacturers work together to optimize both form and function in 3D-printed projects.



Fig. 6: 3DCP floor slabs at the Citadelle Des Savoir-Faire ©B+G ©KET, Saqib Aziz

While the exploration of different approaches such as in-situ construction with their own advantages and disadvantages provides answers to the question of how to build, scientific research must initiate and encourage those involved in construction to adopt these new methods. This also involves the creation of guidelines and regulations to ensure the reliable and safe application of 3D printing technologies in diverse construction contexts. Dubai, as one of the first countries, issued Decree No. (24) in 2021 regulating the use of 3D printing in construction which sets the goal to ensure that 25% of its buildings are constructed using 3D printing technology by 2030 [10]. Over the past year, Bollinger+Grohmann has been working together with French regulators on two projects to attain an ATEX¹³ [11] certification necessary for new construction methods for public buildings.

Existing solutions for materials such as concrete, steel, and wood hold the advantage in precision, predictability, and price control but still fall short when it comes to made-to-measure in terms of time, knowledge and resources. The emergence of methods such as 3D printing with digital manufacturing and modelling opens

the possibility of more targeted solutions with a reduced environmental impact and a close collaboration between designer and manufacturer. Despite their potential, these methods still require wider dissemination and a solid scientific knowledge base. The lessons learned highlight the importance of experimentation, the link between manufacturing and design, as well as bringing together exact science and innovative practices. The cases demonstrate the range of issues that arise and offer preliminary orientations and significant learnings in this context.

The shift toward digital methods, including 3DCP, represents more than just a technological evolution—it is an opportunity to rethink the entire construction process. By leveraging automation, digital design, and innovative materials, the construction industry can reduce its environmental impact, improve safety, and push the boundaries of architectural design. As experimentation continues and the knowledge base grows, 3DCP has the potential to redefine not only how we build but also what we can imagine building in the future.

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- [11] "Appréciation Technique d'Expérimentation (ATEX)"

Footnotes

- ¹ Constructions-3D | 3D Concrete Printers
- ² IAAC - Institute for Advanced Architecture of Catalonia
- ³ Process of three-dimensional digital modelling of a physical object using specialized scanners
- ⁴ Technology for storing and transmitting information securely and transparently, used in particular for cryptocurrencies
- ⁵ XtreeE | The large-scale 3D
- ⁶ Centre national de la recherche scientifique (CNRS)
- ⁷ ecoledesponts.fr | Ecole nationale des ponts et chaussées
- ⁸ DesireSynthesis | Facebook
- ⁹ The Siam Cement Group (scg.com)
- ¹⁰ The voussoir system traditionally refers to an assembly of wedge-shaped blocks (voussoirs) in a curve forming an arch. Thanks to the arch form each voussoir is primarily in compression allowing it to rest in place without any connection to the neighboring blocks [7].
- ¹¹ Konstruktives Entwerfen und Tragwerksplanung - Universität der Künste Berlin (udk-berlin.de)
- ¹² HENN - Architecture
- ¹³ Managed by the CSTB, the *Appréciation Technique d'Expérimentation (ATEX)* is a technical assessment procedure formulated by a group of experts on any innovative construction technique or original architectural concepts not yet covered by a technical standard and whose development requires experimental use.



Fig. 1: Hybrid manufacturing methods that combine conventional methods with additive manufacturing.

HYBRID ADDITIVE MANUFACTURING

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Abstract

Using digital tools our research at ITE investigates three core aspects of sustainable construction: reduce, reuse, and recycle. We aim to develop innovative computational design and fabrication methods to reduce material consumption, increase material efficiency, and minimize the environmental impact of the construction industry. In order to achieve this ambitious goal, many research projects have shown that purely additive manufacturing has reached its limits. For this reason, we are using the Digital Fabrication Laboratory (Fig 1) to investigate hybrid manufacturing methods that combine conventional methods with additive manufacturing or that combine additive with subtractive digital processing.

Reduce

The „Reduce“ focus area of research investigates new ways to design and fabricate structures that use minimal building materials while providing greater design flexibility and adaption. This area of research is supported by the development and testing of hybrid additive manufacturing techniques for construction on a 1:1 scale. One example of this is the 'Add-on Additive Fabrication Process', in which conventionally manufactured semi-finished products are upgraded using additive manufacturing. For concrete construction, one case study is the use of more efficient ribbed and joist slabs, as a hybrid production method that combines conventional casting with 3D printing [1]. This „add-on“ 3D printing technique aims to create thin concrete slabs reinforced with printed ribs tailored to the static requirements of

the structure. By printing these ribs onto freshly cast slabs before they harden, the advantages of Shotcrete 3D Printing (SC3DP) technology can be fully realized, enhancing layer bonding. Additionally, the process allows for the installation of longitudinal reinforcement without auxiliary support. This is achieved by pausing the robotic process when reaching the reinforcement position, enabling manual placement guided by embedded shear reinforcement. After placement, the reinforcement is covered with concrete. Combining traditional concreting methods with innovative SC3DP technology enables the cost-effective production of high-performance, material-efficient floor slabs and ceiling components, as well as architecturally expressive designs, such as the 16 m² slab element for a point-supported structure (Fig 2).



Fig. 2: Conventionally manufactured semi-finished product is upgraded using additive manufacturing such as SC3DP.

An example for a structurally efficient option in steel construction is the Hybrid Wire Arc Additive Manufacturing (WAAM) on I-beams, which serves as an alternative to traditional constant-height I-beams in terms of overall mass and Global Warming Potential (GWP) (Fig 3). WAAM is a 3D printing technique that utilizes robotic welding to incrementally deposit molten metal, enabling the additive production of steel components. This approach not only enhances material efficiency but also offers significant design flexibility for structural elements. Despite the carbon intensity associated with the WAAM process, the

overall GWP can be significantly decreased—by as much as 25%—thanks to the hybrid manufacturing approach that leverages the benefits of both mass production and tailored additive manufacturing [4]. In some instances, this method remains advantageous even when compared to I-profiles produced from renewable resources, while in other cases, standardized profiles may perform better. Considering material strength as a design factor makes the hybrid solution even more appealing. Additionally, the application of WAAM for reinforcing existing steel structures presents a promising area for application.



Fig. 3: WAAM reinforced IPE beams



Fig. 4: SC3DP column joint by precisely milled dry joints.

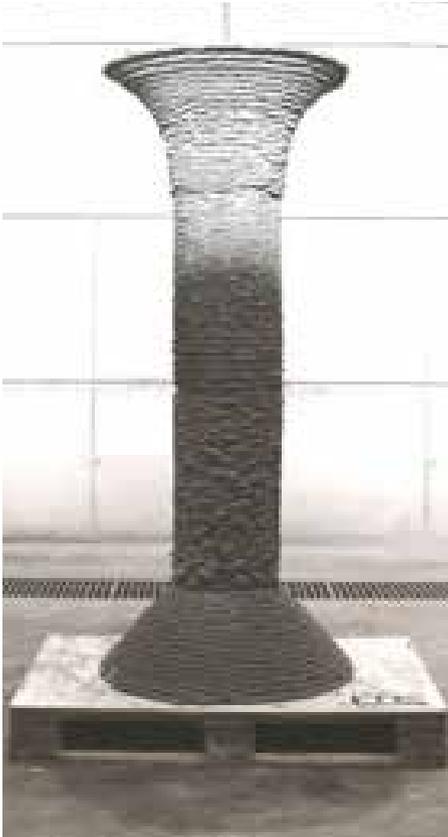


Fig. 5: SC3DP column joint by precisely milled dry joints.

Reuse

The „Reuse“ focus area aims on designing buildings for a circular economy, where components can be disassembled and reused. The architecture is designed for disassembly using durable and robust materials with reversible connections. The research also includes digital pre-fabrication of components, mobile robotics, and augmented reality for in-situ assembly. We investigate hybrid structural systems and the use of salvaged as well as custom-printed parts.

One illustrative example of structural innovation is a column fabricated using the SC3DP process. This element is designed and printed in segments, which allows for convenient assembly at the construction site [3]. After the printed component has cured, precise milling is performed to create exact connections between the segments. These accurately machined interfaces enable the components to be joined through structural prestressing, facilitating their eventual disassembly and reuse in different applications (Fig 4, 5).



Fig. 6: Sprayed Earth process to manufacture geometrically complex and sustainable building elements.

Recycle

The „Recycle“ focus area aims to minimize the construction industry's waste production by upcycling construction waste into higher-grade construction products through digital fabrication. This research stream explores two strategies: firstly, additive manufacturing using recyclable materials like earth or bio-polymers, and secondly robotic upcycling of building debris like crushed bricks and concrete.

An example of recycling material is the process of robotic sprayed earth, in which the methods of shotcrete 3D printing are transferred to a fully recyclable material [2,6]. Typically, earth-based materials consist of various clay mixtures that serve as binders, combined with aggregates and water, and may also include natural fibres such as straw or hemp. In our Sprayed Earth Additive Manufacturing process, natural fibers are incorporated

using a customized toolhead that chops continuous fibers directly in the spray nozzle, adding them to the sprayed material on the fly. In order to connect the prefabricated components on site with the necessary precision, the precise connections are cnc milled [Fig 6].

The second strategy involves the use of recycled demolition material. The Large Particle 3D Concrete Printing (LP3DCP) method merges particle bed printing with the shotcrete process, emphasizing resource-efficient production and enhanced geometric flexibility [5]. This technique selectively binds coarse aggregates (8-32 mm) within a printed structure using shotcrete, which significantly reduces the need for cementitious binders compared to other additive manufacturing (AM) methods.



Fig. 7: Large Particle Bed 3D Concrete Printing utilising recycled aggregates.

Fabrication occurs within simple formwork that contains loose material laterally. The process begins with the deposition of a layer of coarse aggregate, followed by the application of cementitious mortar as the binder [Fig 7]. This layering continues until the desired geometry is achieved. After the binder sets, the formwork is removed, and any non-bonded aggregate is discarded. This method allows for considerable design freedom without the need for complex, single-use formwork. Additionally, varying the rheology of the shotcrete through the addition of accelerators and plasticizers facilitates a wide range of porosities. LP3DCP not only supports sustainable construction through the recycling of crushed concrete but also optimizes the structural integrity of massive elements, adapting to stress flow patterns. A subsequent subtractive process allows a clear definition of the edges.

These terazzo-like surfaces can function either as dry joints or as a visual contrast to the rough surfaces of the bonded aggregates.

Hybrid additive manufacturing processes allow the efficiency and precision of conventional processes to be combined with the individuality of digital processes. The forms for this are diverse and vary depending on the application. These approaches are highly versatile and can be adapted to various applications. For instance, the speed of casting can be integrated with the customization of printing, or the adaptability of 3D printing can be paired with the precision of subtractive techniques. This level of flexibility allows for addressing a broad spectrum of challenges in construction that cannot be met by purely additive methods alone.

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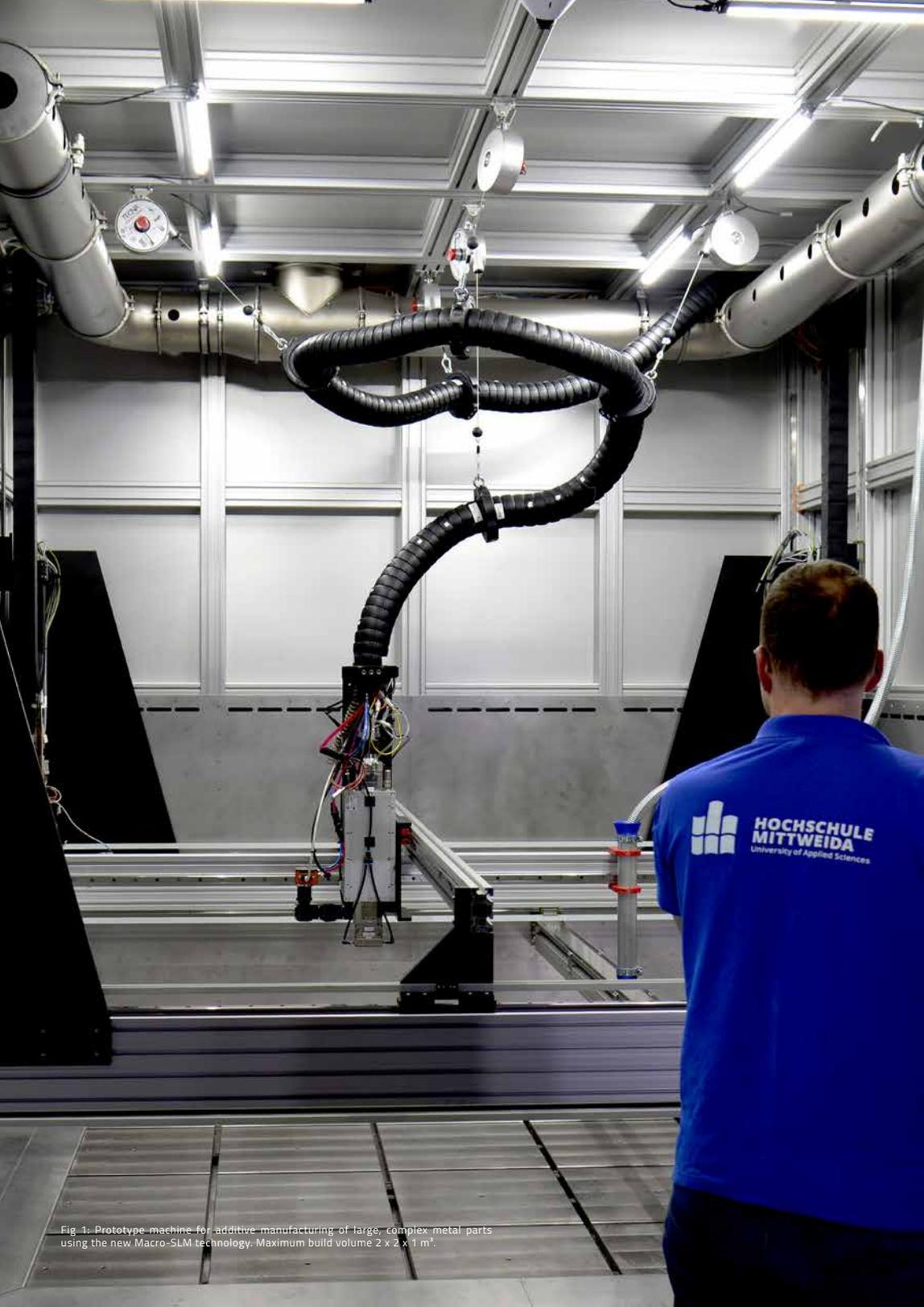


Fig. 1: Prototype machine for additive manufacturing of large, complex metal parts using the new Macro-SLM technology. Maximum build volume 2 x 2 x 1 m³.

METAL ADDITIVE MANUFACTURING ON A NEW LEVEL: BIGGER, FASTER AND MORE DESIGN FREEDOM

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Abstract

Macro-SLM, is a new innovative additive manufacturing process that combines the advantages of the powder bed-based process (SLM or L-PBF) with the direct energy deposition processes (e.g. WAAM or LBAM). It enables high build-up rates of currently up to 10 kg/h with enormous design freedom at the same time. In addition, production costs can be reduced by up to 90 % compared to conventional SLM processes. This makes it possible to produce highly complex, large-volume metal components in cubic meter dimensions and thus represents a genuine alternative to metal casting and milling. Two applications in the construction and architecture sector are being tested with the new additive manufacturing processes. Firstly, the efficient production of geometrically individual connecting nodes for curved facades and roof constructions and secondly, the production of innovative frames for concrete block production.

Introduction

Over the last few decades, additive manufacturing (AM) has developed from the laboratories of universities and universities of applied sciences into the production halls of numerous industries and is now a key technology for the efficient and cost-effective production of customized, complex components. In architecture and construction, however, AM technology is still in its infancy. Thanks to recent advances in software, manufacturing processes and automation, the breakthrough will also succeed here and increasingly establish itself as a complementary manufacturing technology.

Macro-SLM

The Macro-SLM process developed at the Laserinstitut Hochschule Mittweida (LHM) can help to accelerate the progress of AM technology in architecture and construction. By increasing the laser power, spot diameter, layer thickness and powder grain size, structural resolution in the millimeter range is achieved instead of the usual micrometer range. This in turn enables an enormous increase in the build-up rate up to currently 10 kg/h. It is therefore similar to the structure resolution and build-up rates of the DED process. However, the supporting powder bed offers the advantage of being able to realize more complex geometries through overhangs



Fig. 2: 3D Benchy made of stainless steel without support structures in 1 hour.



Fig. 3: Free-moving planetary gears made of stainless steel in 4 hours.

and bridges. Macro-SLM thus combines the advantages of both worlds: high design freedom and high productivity at the same time. The use of cost-effective metal granulate (up to 10 times cheaper than classic SLM powder) also significantly reduces costs. This means that complex, near-net-shape metal components can be produced in cubic meter dimensions. In combination with subtractive processes, all necessary functional surfaces can then be reworked and brought to their final dimensions. To develop the new technology, the focus was initially placed on stainless steel (1.4301). This enabled component densities of > 99.5 % to be achieved. Tensile and fatigue strength tests also show that the values achieved are within the material specifications. Recent research has also focused on the use of case-hardening steels, low-alloy carbon steels and aluminum alloys.

To demonstrate the potential of the Macro-SLM process, a new machine concept with a build volume of 2 x 2 x 1 m³ has been installed (Fig. 1). The concept is highly scalable and therefore suitable for different applications. The preliminary goal of the first prototype system is the production of steel molds for the concrete block industry in cooperation with the company Kobra Formen GmbH. Another focus is 3D printing and the development of a suitable process cycle for individual facade nodes together with the FLEX research group at the Leipzig University of Applied Sciences (HTWK Leipzig).

To demonstrate the geometric freedom of design and

the high build rate of the Macro-SLM, two demonstrators well known in the AM community were chosen. One is the so-called „3D benchy“ and the other is a planetary gear. The 3D benchy was built in only one hour and all features could be printed without additional support structures (Fig. 2). The planetary gear is completely free moving, has a lightweight infill structure and was produced in 4 hours (Fig. 3).

Application 1: Topology-optimized lightweight frame structure for concrete block production

Kobra Formen GmbH, a world leader in the production of steel molds for the concrete block industry, is already using metal 3D printing in its production, but conventional processes are reaching their limits in terms of build volume, productivity and cost for larger metal parts. As described above, this is where the potential of Macro-SLM technology lies, as it pushes the boundaries and offers completely new possibilities for more efficient production.

The new technology will be tested in particular in the production of frames, mold inserts, cores and tampershoes, as shown in Fig. 4 above. Previous production methods require many individual operations and produce up to 70 % waste that needs to be recycled. With Macro-SLM, material consumption can be drastically reduced, and production costs and times can be significantly reduced.

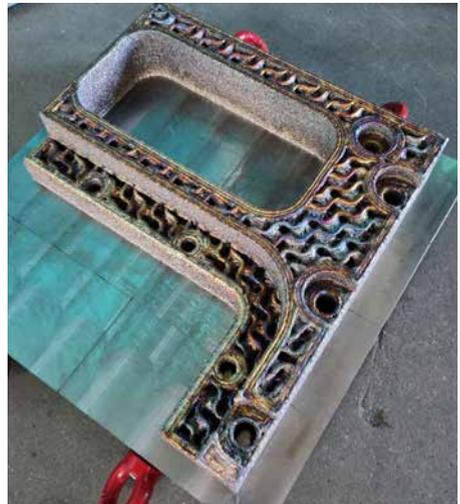
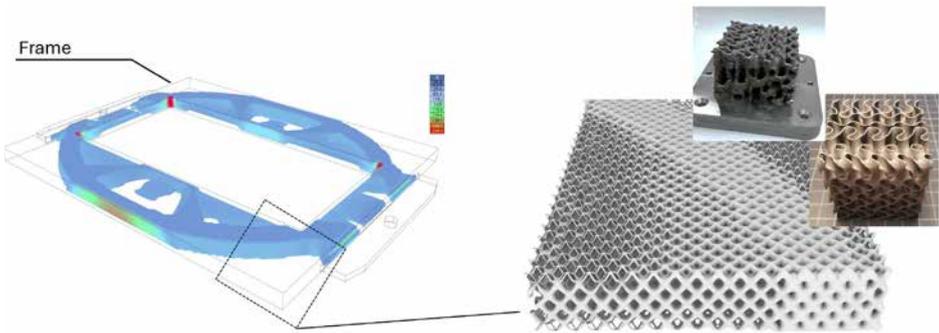
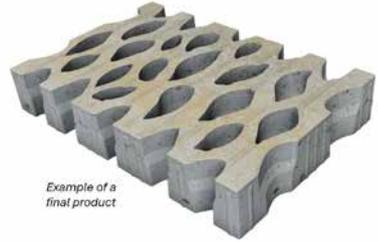
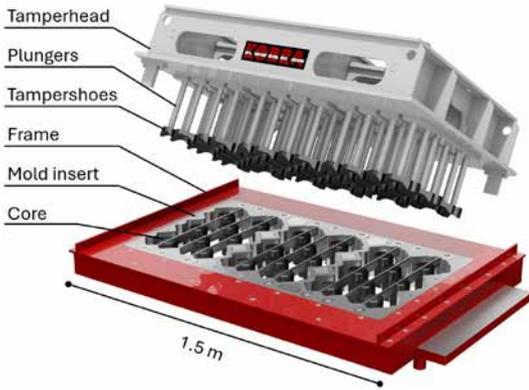


Figure 4: Description of the project to 3D print a frame for the production of concrete blocks. Above: Assembly with all relevant components for the production of concrete blocks. Middle: Topology optimized frame by adjusting infill density and first tests with SLS and Macro-SLM. Bottom: AM manufactured section of the frame.

Current research efforts are focused on the manufacturing of the frame. Lightweight structures based on topology-optimized infill are to be used. The goal is to keep the weight and thus the construction time low without sacrificing the stability of the component. Topology-optimized infill structures are a relatively new approach in AM and are being developed in cooperation with the HTWK Leipzig. They are used when walls are required for the closed part. The infill structures then also serve as support structures. Typically, topology-optimized designs are visible and look more like a tree structure (Fig. 4, middle left). A first simplified model with the new infill structure has already been printed (Fig. 4, middle right) and will be transferred to the frame in the future. The frame itself was first built in parts using Macro-SLM

technology for test purposes to test different concepts (Fig. 4, bottom). One concept is to use the building platform as the base plate for the frame, eliminating the need to cut it off. The top plate was omitted in order to assess the quality of the infill.

Another goal of Kobra Formen GmbH is to establish a circular economy. Waste and scrap from existing production is processed in the company's own powder atomization systems to produce the raw material for 3D printing. This ensures efficient use of resources and promotes sustainable production. Additive manufacturing can also address the shortage of qualified workers by automating and simplifying work processes. Kobra Formen GmbH wants to be well prepared for future challenges.

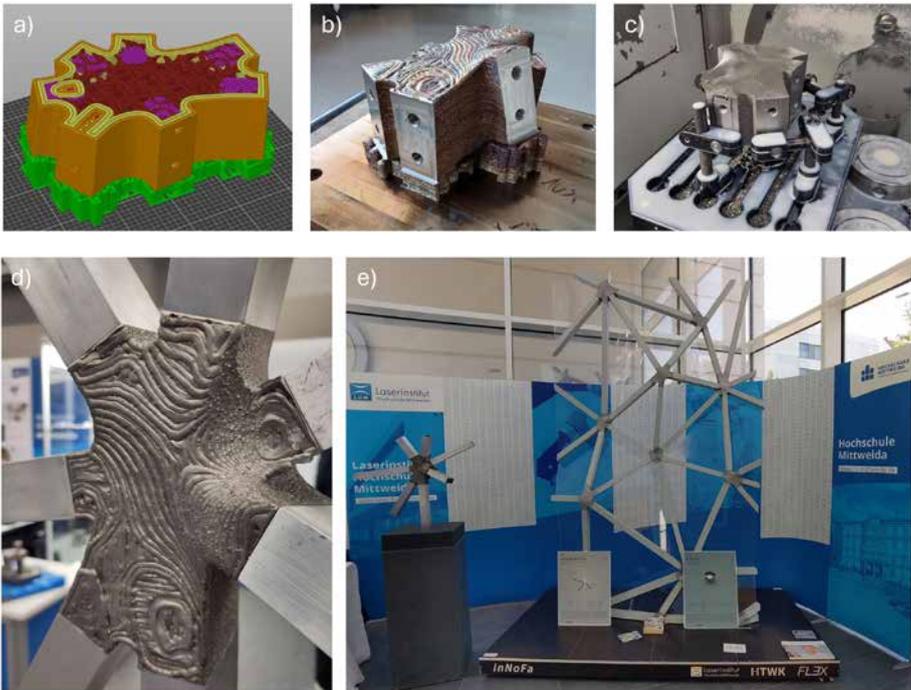


Figure 5: Production steps of a 3D printed facade node and exhibition of a free-form wall. (a) Sliced 3D model with visible infill structure. (b) Node with over-milled connection surfaces before separation from the build plate. (c) Separated node in the CNC machine after milling over the underside and support structures. (d) Detail view of the top surface of the node. (e) Interior view of freeform feature wall.

Application 2: Geometrically individual connection nodes for freeform facades

In cooperation with the HTWK Leipzig, the production of individual node elements for the construction industry is being investigated under consideration of bionic structural principles. In the realization of curved, free-form facade and roof constructions, prefabricated, easily transportable, straight bar profiles are connected by means of individual node elements. These connectors are geometrically complex and very costly to produce using conventional manufacturing methods and are therefore often uneconomical. SLM is also too time-consuming and costly to produce node elements. The high structural resolution of SLM is not required, and post-processing of the mating surfaces is also necessary. The Macro-SLM process is therefore ideally suited for this purpose. The potential has already been demonstrated with the first additively manufactured prototypes of the node elements and the construction of a section of a facade surface (Fig. 5).

Stainless steel (1.4301) was initially chosen as the material, but with the new processes, structural steel or aluminum alloys can also be used. The nodes were designed with a lightweight internal structure to reduce mass and construction time while improving resource utilization. To further exploit the potential of AM technology, ducts for power lines and sprinkler systems will be integrated in the future. The post-production process has also been tested and optimized. This includes determining an appropriate contour offset for subsequent CNC machining, 3D scanning of the printed node to calculate CNC path control, reducing support structures to minimize post-processing, and more.

Comparing the pure production on the machine, the construction time for the largest node was reduced from 80 hours to 5 hours and the production costs (only energy, gas and material costs) were reduced to one fifth compared to the SLM process.

Conclusion

The newly developed Macro-SLM technology enables fast, cost-effective and complex production of large metal parts in near-net-shape. This technology complements existing additive manufacturing processes and is particularly advantageous where the currently established powder bed and DED processes reach their limits. The potential of the new technology was demonstrated in two application examples. The transfer to industrial implementation is already well underway. The technology still offers great potential for innovation and some promising ideas are already being planned.



Fig. 1: Printing process of glass, Maple Glass Printing Ltd.

ENHANCING GLASS PLATES THROUGH 3D PRINTING: A RESEARCH BASED ON THE 3XCHANGE APPROACH

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Abstract

Additive manufacturing (AM) of glass has undergone significant advancements since its initial hype in 2017. In 2024, reliable 3D printers for soda-lime silicate glass, commonly used in the built environment (BE), have emerged. A primary focus is the application of AM glass in flat glass panels, which dominate structural glass applications. Concepts such as glass panel stiffening, façade supports, and insulation sealings are being explored. A recent case study from the Glass Competence Center (GCC) demonstrated material savings of up to 70% by stiffening glass panels with AM. Novel deposition methods, such as Spray Printing Glass (SPG), also show potential for faster production and improved structural resilience. However, challenges remain in scaling up, process integration, and ensuring compliance with standards. The essay highlights the importance of generational, industrial, and craft collaboration (3Xchange), which has advanced the research projects quickly and efficiently.

Introduction

After the initial hype around glass 3D printing in 2017 [9], a new wave is now emerging as more companies and universities showcase reliable glass 3D printers suitable for applications in the built environment (BE). The most promising printers for BE are those that can handle soda-lime silicate glass, which is used in 99% of BE applications. FDM (Fused Deposition Modeling) printers (see Fig.1) [7] have proven to be the most effective for this purpose; alternatively, the DED (Directed Energy Deposition) process [3] is also suitable. However, there is still ongoing development in the field of deposition methods, as mentioned later in this essay.

But what changed in comparison to the hype seven years ago? The answer is experience. Companies and universities have developed several versions of their printers over the past few years, continuously improving their speed, reliability, and performance. As a result, we now have in 2024 the opportunity to bring concepts to life that were previously just theoretical ideas.

Requirements

The practical implementation of these concepts in BE involves numerous demanding requirements, which are rarely encountered in this number in engineering. When these concepts are applied to the exterior of buildings, they are expected to last at least 50 years, depending on the specifications, and are often used beyond this service life. During this time, they are exposed to wind, weather, usage, and other external influences. Additional mechanical requirements are established by relevant standards [2], which dictate that AM glass components must withstand various conditions, including ULS (Ultimate Limit State), SLS (Serviceability Limit State), FLS (Fatigue Limit State), and PFLS (Post-Failure Limit State). Furthermore, there are additional demands regarding optics, building physics, fire safety, maintenance, cleaning and many others. As a result, extensive research is required to meet all these criteria during the implementation of these concepts.



Fig. 2: Rendering: Glass panels stiffened with AM glass of a high rise building

Concepts

The concepts developed so far for AM glass in BE can be divided into two categories [6]:

- Stand-alone AM glass components such as columns, walls, furniture, stairs, etc.
- AM glass elements applied to flat glass panels.

The research presented here focuses on AM glass on flat glass panels. The reason for this is that 96% of the glass used in structural glass applications is flat glass [4], as well as for ecological considerations. In recent years, the following promising concepts have emerged from the combination of flat glass and AM glass:

- Application of AM glass as point and/or linear supports for façade glazing.
- Long-lasting sealings of insulated glass units (IGUs) using AM glass.
- Stiffening of façade glass panels with AM glass.
- Practical applications such as shelves, shading systems, handrails, etc.
- Aesthetic applications such as logos, designs, art, etc.

Stiffening of Glass Plates with AM Glass

The stiffening of glass panels with AM glass has been presented as a concept in several publications [6,9], but it has never been thoroughly investigated. The idea itself is simple and well-known from steel and concrete construction. Glass panels in façades are primarily subjected to wind loads perpendicular to the surface, where they are structurally inefficient (similar to how a sheet of paper is weak when loaded in perpendicular direction). By extending this structure into the third dimension, more efficient and lightweight glass façades can be produced.

This concept was explored in a case study by the Glass Competence Center (GCC) for a high-rise building in Frankfurt a. M. [4]. Topology and shape optimization approaches were used, revealing a wide range of potential designs. The stiffening geometry (see Fig. 2) proved to be highly versatile while maintaining similar performance levels, as the stiffening mass is significantly smaller compared to the mass of the base glass panels. For this case study, material savings of up to 60% for four-sided supported glass panels and up to 70% for two-sided supported glass panels were achieved compared to the



Fig. 3: Model of Fig.2 in Scale 1:10: Soda lime silicate glass printed onto a glass plate

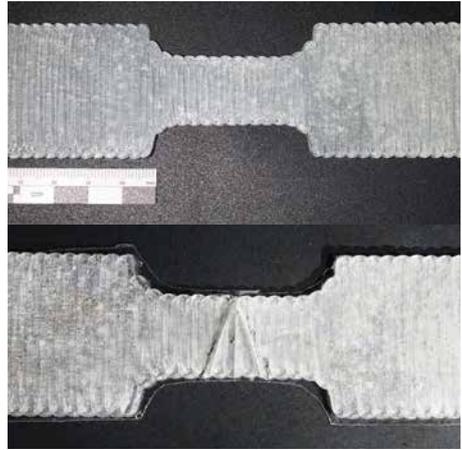


Fig. 4: Strength test of annealed AM glass samples

use of conventional flat glass [4]. The design constraints were primarily based on the capabilities of FDM glass printing, ensuring that the designs developed could be easily manufactured using soda-lime glass, as shown in Figure 3.

Material model

For use in construction, engineering calculations are essential to ensure a safe and reliable component. In the field of AM glass, however, very few studies have been conducted to provide foundational knowledge regarding strength and material behavior [1]. As part of this research project, new testing methods were developed for brittle AM components to quantify strength across different layer orientations. These tests proved to be highly reliable, easy to conduct, and showed minimal variance for glass [4]. Notably, the typical 3D printing ridges from the FDM-AM glass process had a significantly lower impact on strength than previously assumed. The key factor influencing strength was the temperature management during printing, which directly affected the bonding between the individual layers.

The strength of annealed AM glass samples, produced by Maple Glass Printing Ltd. from soda-lime glass, had

a mean fracture strength of 56 MPa (with a standard deviation of 7 MPa for 15 specimen) [4]. While this is slightly lower than the strength of the raw material, it is sufficiently high for engineering applications in BE.

New 3D printing process – Spray Printing Glass

In 2022, alongside the research on FDM glass printers, -process, and -components at the GCC, a new project in the field of AM glass was initiated. What started as a crazy idea - wondering if glass could be sprayed like from a spray can - evolved into a promising new technology: Spray Printing Glass (SPG). A feasibility study demonstrated that through a hot spray process of glass particles, both translucent and transparent prints could be applied to glass panels (see Figure 7, 8). The deposition rate is significantly higher compared to FDM glass printing [5].

During the project, issues with air inclusions revealed an interesting anomaly: AM glass components with numerous air inclusions exhibited no traditional crack propagation. As a result, when damaged or overstrained, the component maintained a high residual load-bearing capacity [5].



Fig. 5, 6: Design vision of spray printed glass





Fig. 7: Spray printed glass translucent



Fig. 8: Spary printed glass transparent

Sustainability

Sustainability and the life cycle of AM glass components must not be overlooked at this point. Glass is, and remains, an energy-intensive material, and therefore also a luxury item. However, due to its psychological, building-physical, and aesthetic importance in construction, it cannot be replaced. As previously mentioned, AM glass offers significant potential for material savings, particularly in façade applications, which can lead to substantial CO₂ reductions. In addition to using less material, this also reduces the deadload of buildings. Recycling through AM glass presents great potential as well, but since glass is highly sensitive to changes in chemical composition, much more research is needed in this area. A current challenge is the printing chambers of glass 3D printers, which need to be heated to 530°C for each printing cycle – an energy-intensive process [4]. If future innovations can integrate the printing process directly into processes like glass tempering and thus make the heating process redundant, AM glass holds the potential to make glass construction significantly more sustainable.

3Xchange - Research in exchange between generations, handcraft and industry

The GCC follows the xchange approach of TU Darmstadt, which has significantly shaped the research presented here. While „exchange“ typically suggests collaboration between researchers and universities, the GCC's 3Xchange approach focuses on three entirely different focal points. The first focal point is generational exchange. This approach emphasizes age diversity within research

teams, enabling students, PhD students, postdocs, and professors to work together on equal footing. This brings enormous advantages. For example, the SPG research team consisted of members ranging from 19 to 60 years old. Younger team members, with their unbiasedness, initiated ideas that experienced glass specialists initially deemed impossible. Conversely, the experienced members guided the project in the right direction, allowing this feasibility study to be completed successfully within a few months, leading to the development of a completely new, unprecedented process [5].

Equally important is the second focal point, the exchange with the handcraft sector. Many researchers working with “new” materials often overlook the fact that these materials have been handled for centuries by craftsmen. Both the SPG and FDM research projects benefited from the expertise of glass apparatus builders. Their experience allowed them to accurately estimate burner and glass temperatures, predict the behavior of glass in its liquid and solid states, and fine-tune process parameters.

The third focal point is industrial exchange. In addition to their expertise, industries are closest to the market and know what is needed, where, and how. At the same time, they rely heavily on universities for investigations, in-depth knowledge, and new ideas. Unfortunately, industrial-academic collaboration, especially in Germany, has waned in recent decades. During this research, collaboration took place with both glass 3D-printing manufacturers and engineering offices, strengthening the exchange between academia and industry.



Fig. 9: Rendering of stiffened glass panels through local bending

Conclusion and Outlook

AM glass offers an exciting range of possibilities for enhancing glass panels. Unlike in previous years, many of these concepts have become feasible to implement and test since 2024. As a result, the previously theoretical ideas are becoming more concrete, highlighting the potential for making glass construction more sustainable in the future. Key challenges in the near future will include scaling up the process to print on large-format glass panels, integrating the process into existing glass production workflows, conducting extensive testing and practical trials, and achieving compliance with existing regulations to allow the use of AM glass components in BE.

Acknowledgements

Special thanks to Dylan Vlahopoulos and Nick Birbills from Maple Glass Printing Ltd. in Melbourne, Australia, for this fantastic research collaboration, which was initiated at BE-AM 2023. You are an amazing team, for whom no idea is too crazy! A special thanks also goes to glass apparatus maker Maria Voß, whose craftsmanship played a key role in the success of the SPG project. The author would also like to thank the entire team of ISM+D at TU Darmstadt for their support, especially Marcel Hörbert and Kay Schuchmann, without their assistance, none of the experiments would have been possible.

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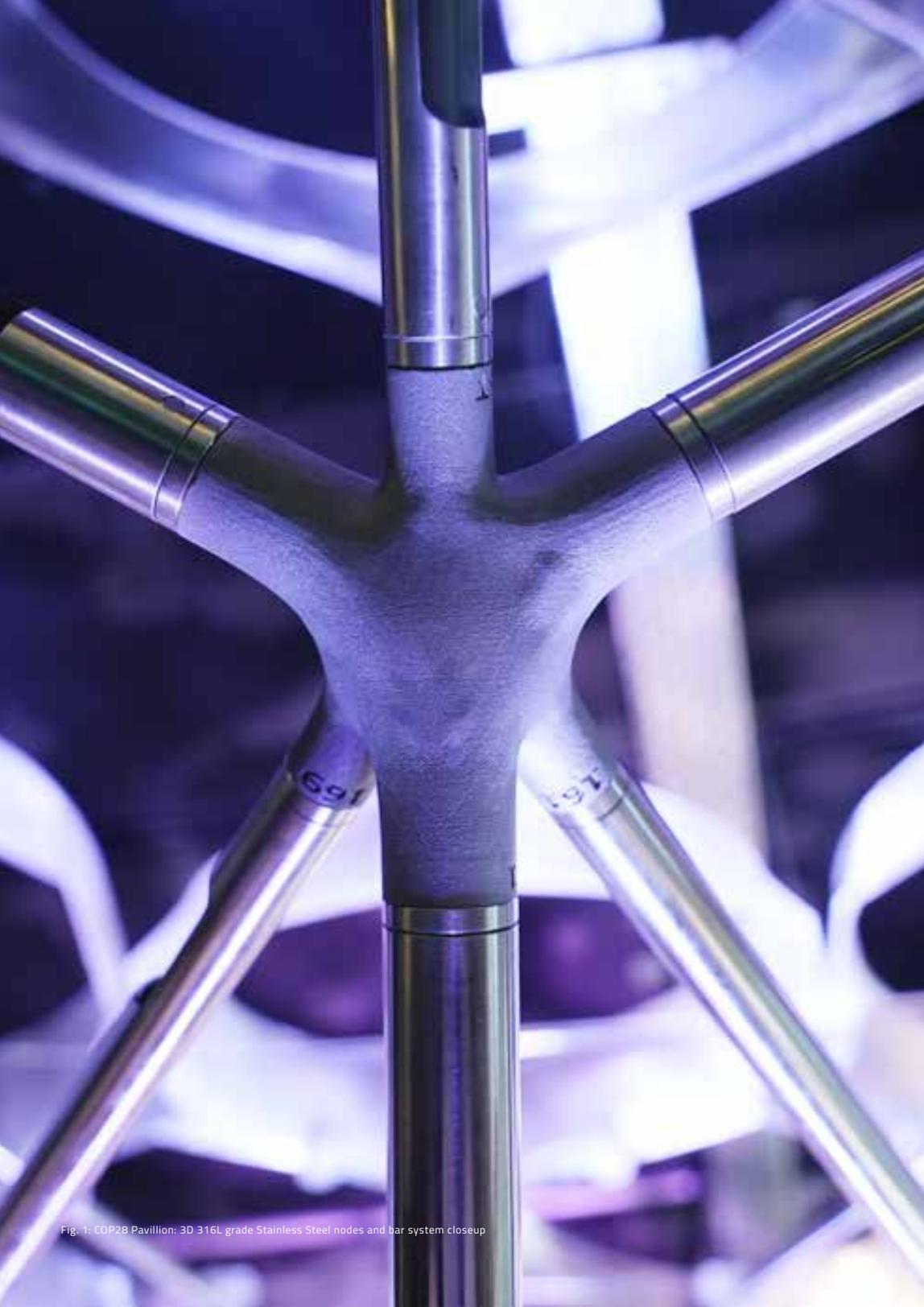


Fig. 1: COP28 Pavillion: 3D 316L grade Stainless Steel nodes and bar system closeup

RETHINKING ARCHITECTURAL TECTONICS: THE ROLE OF CONNECTIONS IN HYBRID 3D-PRINTED STRUCTURES

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Abstract

Additive manufacturing in architecture is transforming the construction landscape by enabling unprecedented design freedom and precision. Unlike traditional construction, which relies heavily on standardized components and often results in material inefficiency, 3D printing offers a more flexible and customizable approach. This shift challenges conventional practices and opens up possibilities for more seamless integration of systems. By focusing on connections through a hybrid printed/standard paradigm, architects can redefine how components are assembled, resulting in enhanced design flexibility, structural performance, and aesthetic value.

This paper explores the development and implementation of custom construction details, particularly within space frame structures that utilize 3D-printed nodal connectors. Through five case studies – including Sombra Verde, (Ultra) Light Network at iLight Marina Bay, AirMesh Pavilion, COP28 Pavilion, and SIBOS24 Pavilion – it demonstrates how bespoke 3D-printed connections facilitate innovative assembly methods and efficient material use. The research highlights how the integration of 3D printing not only increases material efficiency and reduces costs but also allows for the production of highly customized, structurally efficient joints that elevate both the functional and aesthetic performance of architectural designs. By examining the design-to-fabrication workflow, from digital modeling to on-site assembly, this study contributes to the growing discourse on digital fabrication and advocates for broader adoption of 3D printing in complex, bespoke architectural elements.

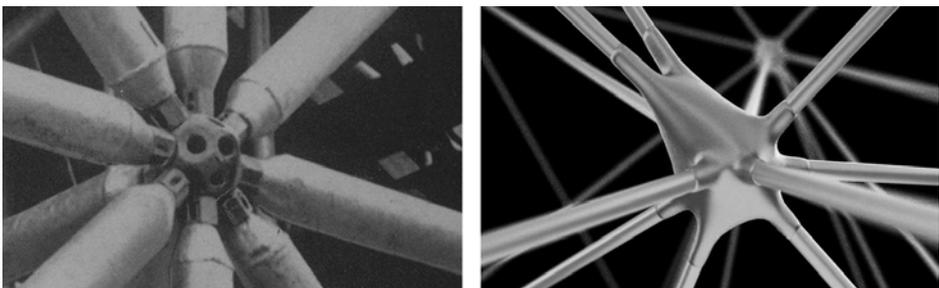


Fig. 2: Left: Traditional Mero node with standardized, prefabricated components. Right: Bespoke 3D-printed node showcasing customized geometry and enhanced integration capabilities..

The Limitations of Traditional Construction Methods

Traditional construction relies on standardized components to streamline manufacturing and reduce costs. However, this approach significantly limits design flexibility and can result in material waste. Standard components are rarely optimized for specific needs, leading to over-engineering and inefficiency, which conflicts with sustainability goals. Additionally, off-the-shelf parts often hinder the seamless integration of different building systems, leading to disjointed and less efficient assemblies.

These limitations necessitate innovative methods that prioritize flexibility, efficiency, and sustainability. The hybrid printed/standard approach combines standard elements with bespoke 3D-printed components, focusing on connections to create adaptable, expressive, and efficient structures.

The Hybrid Printed/Standard Paradigm: Redefining Connections

The hybrid printed/standard paradigm is a construction approach that strategically combines standard, readily available components with bespoke 3D-printed elements to optimize both resource efficiency and design flexibility. At its core, this paradigm focuses on redefining connections—the interfaces where structural elements meet and interact.

Additive Manufacturing allows for intricate, customized connections, enabling complex geometries unattainable with traditional methods. This approach minimizes waste and enhances structural efficiency. Bespoke connections streamline the integration of building systems, merging structural, technical, and aesthetic functions. Advances in automation and new materials improve performance and sustainability (Figure 3).

Reimagined connections optimize load paths, enabling lighter and more efficient structures. Bespoke connections blur the line between structure and ornament, enhancing both aesthetics and functionality. They can also accommodate additional functions, such as housing technical systems or adapting to variable geometries, improving overall adaptability.

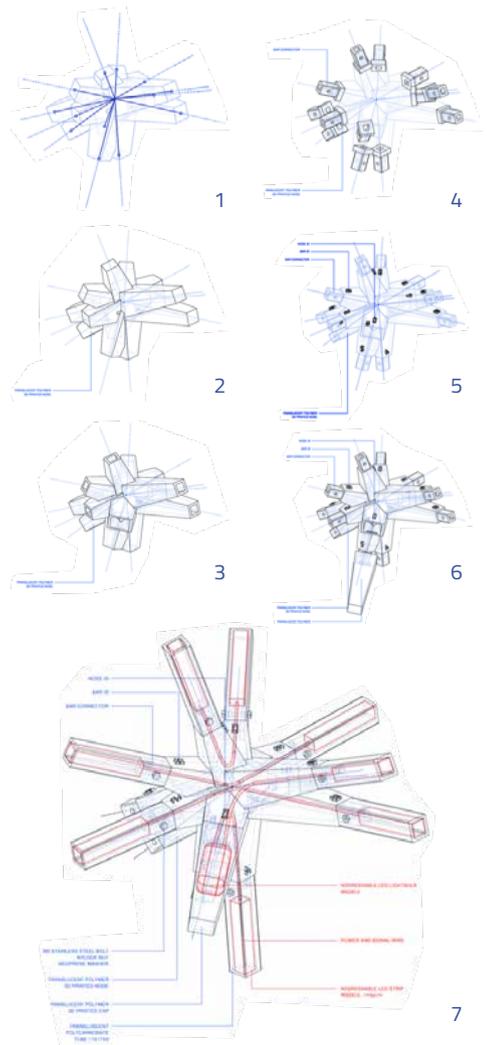


Fig. 3: Diagram illustrating the generation of custom 3D-printed connectors, designed to interface standardized rectangular profiles with electronic components

Case Studies: Demonstrating the Transformative Potential

The following case studies exemplify the application of bespoke 3D-printed connections within the hybrid printed/standard paradigm, showcasing how this approach addresses specific challenges and achieves quantifiable benefits in structural performance, material efficiency, and construction time.



Fig. 4: Left: Detail of a PLA connector interfacing eight bamboo poles. Right: Sombra Verde pavilion in use at Tanjong Pagar, Singapore.

Sombra Verde: Precise Integration of Non-Uniform Organic Matter through Bespoke Connections

| **Challenges Addressed:** Adapting to the irregular geometries of natural materials and achieving rapid assembly for temporary bamboo structures.

The Sombra Verde pavilion explores the interfacing of organic materials with 3D-printed connections. By combining bamboo poles with biodegradable Fused Filament Fabrication (FFF) 3D-printed nodes, the pavilion creates a seamless blend of natural and manufactured materials. An innovative workflow involves the 2D scanning the irregular ends of bamboo poles, generating a database from which bespoke connectors are automatically designed to adapt precisely to each pole's unique geometry.

The connection system hides mechanical fasteners, enhancing the pavilion's aesthetic appeal and emphasizing the seamless integration of components. Assembled in less than a day, the pavilion demonstrates the efficiency of the hybrid approach and its potential applicability in deployable structures and disaster relief scenarios.

| **Design Rationale:** Custom connectors allow for the utilization of locally sourced, non-standardized bamboo, reducing material costs and environmental impact while accommodating natural irregularities.

| **Quantifiable Benefits:**

- **Adaptability:** Connectors tailored to each unique bamboo pole.
- **Construction Time:** Assembly completed in under 8 hours.
- **Regenerative Capacity:** Use of biodegradable materials and local resources reduced carbon footprint.



Fig. 5: Left: Close-up of a node integrating LEDs. Right: (Ultra) Final installation at Marina Bay, Singapore.

(Ultra) Light Network at iLight Marina Bay: Multifunctional Integration

| **Challenges Addressed:** Integrating structural elements with complex lighting systems while maintaining a lightweight appearance.

The (Ultra) Light Network installation demonstrates the integration of multiple functions within bespoke 3D-printed connections. The 3D-printed nodes house wiring and electronic components, supporting an intricate lighting system embedded within the structure. The installation employs 152 ABS and nylon nodes connected to 715 polycarbonate bars, forming a suspended mesh that supports over 50,000 individually addressable LED points.

Electronic systems are integrated into the parametric model, allowing precise spatial positioning and coherent animations controlled via custom software. The design hides structural supports within the form, achieving a visually lightweight and ethereal appearance while maintaining structural integrity.

| **Design Rationale:** Embedding technical systems within structural nodes achieves seamless integration of form and function, enhancing aesthetic impact.

| **Quantifiable Benefits:**

- **Multifunctionality:** Combined structural support and housing for electronics.
- **Aesthetic Quality:** Achieved a lightweight appearance without compromising stability.
- **Efficiency:** Reduced installation time by integrating components during fabrication.



Fig. 6: Left: 3D-printed node using binder jetting with stainless steel. Right: AirMesh pavilion installed at Gardens by the Bay, Singapore.

AirMesh Pavilion: Pushing the Boundaries of Structural Efficiency

| Challenges Addressed: Creating a large-scale, structurally efficient pavilion with complex geometries while obtaining regulatory approval.

The AirMesh Pavilion represents a significant advancement in combining 3D-printed connections with standard components in a large-scale structure. Featuring 54 3D-printed stainless-steel nodes and 216 standard stainless steel tubes, the pavilion achieves complex geometries with high structural performance. The nodes host female connections, while bolts within the bars are fastened through access slots, streamlining the assembly process and reducing construction time by 60%.

The pavilion incorporates architectural elements such as ramps, skylights, and seating areas, demonstrating the versatility of the hybrid approach. Notably, AirMesh is the first 3D-printed structure approved as a functional building by Singapore's Building Construction Authority, setting a precedent for future projects.

| Design Rationale: Bespoke nodes enabled the creation of complex geometries and integrated features difficult to achieve with standard components.

| Quantifiable Benefits:

- Structural Performance: Withstood service and wind loads per building codes (Eurocode)
- Regulatory Milestone: First approved 3D-printed functional building in Singapore
- Construction Time: Significantly reduced assembly time, completed within a single workday.



Fig. 7: Left: 3D 316L grade Stainless Steel nodes and bar system closeup. Right: stand-alone 3d printed tree-shape structure at COP28.

COP28 Pavilion: Resource-Efficiency Innovation through Local Production

| Challenges Addressed: Demonstrating sustainability through material efficiency and local production at a high-profile international event.

At the United Nations Climate Change Conference COP28 in Dubai, the Singapore Pavilion exemplified circular design principles through the use of bespoke 3D-printed connections. The pavilion minimized material consumption and upcycled plastic waste into 3D-printed components, such as metal nodes and hexagonal tiles, showcasing resource efficiency. Stainless steel 316L nodes were fabricated using Direct Metal Laser Sintering (DMLS), achieving zero-tolerance errors in the printed threads. A non-trained team of five assembled 54 nodes and 216 bars in less than five hours, highlighting the practicality of the design. The pavilion was specifically designed for rapid assembly, standing on three points, with versatile configuration options. It could be assembled as individual canopies or combined into a larger structure, which will serve as the COP29 pavilion. This multi-use design enhances versatility and adaptability.

Structural components, such as the bars and nodes, were optimized and reduced to their minimum size through finite element method (FEM) analysis, ensuring efficient use of materials without compromising structural integrity. The pavilion stands as a model for sustainable and flexible architectural practices.

| Design Rationale: Utilizing upcycled materials and local production aligned the pavilion with sustainability themes, while bespoke connections facilitated rapid assembly.

| Quantifiable Benefits:

- Material Reuse: Upcycled PET waste utilized for 3D-printed canopy components.
- Assembly Efficiency: 57 stainless steel 316L nodes and 244 bars assembled in under five hours.
- Sustainability: Lowered environmental impact through local production and optimized material usage.



Fig. 8: Left: Nodal connection integrating a PA12 inner core, FDM case, and stainless-steel threaded bars. Right: Fully installed SIBOS24 Pavilion in Beijing

SIBOS24 Pavilion in Beijing: Large-Scale, Low-Density Design with Visual Impact

| Challenges Addressed: Achieving precise and complex spatial grid designs and captivating visuals while ensuring structural integrity and efficient assembly.

The SIBOS24 Pavilion in Beijing showcases the innovative application of complex 3D-printed connections in spatial grid structures. PA12 nylon nodes, produced via Selective Laser Sintering (SLS), are designed for a 90-degree orthogonal grid and feature spaces for diagonal tensors and integrated assembly threads, eliminating the need for post-production rethreading. The 3D-printed acrylic bar caps are precisely calibrated for a perfect friction fit and bonded with a strong adhesive to ensure structural integrity.

The pavilion incorporates 1,024 orange fire-retardant PLA cases, magnetically connected to create striking visuals while concealing internal nodes and allowing for adjustments to cables and bars. This level of customization was made possible through 3D printing and bespoke design details, enabling the seamless integration of dissimilar structural components. The structural system, guided by Karamba analysis, uses strategically placed diagonals to enhance stability and reduce shear forces. In total, 1,024 nodes and 2,882 bars were assembled in just eight hours, showcasing the efficiency of the hybrid design.

The bespoke node and cap system, made from PA12, is optimized in weight to handle compression, tension, and shear forces. Three types of nodes were created to meet different structural load requirements, maximizing cost-efficiency and minimizing material usage. Standardized acrylic tubes were used for the profiles, locally produced and treated. No additional structural elements were needed beyond the 3D-printed components and acrylic tubes, with strategically placed diagonals providing structural bracing.

| Design Rationale: Bespoke nodes and magnetic cases allowed for rapid assembly and disassembly, facilitating transportation and reusability while providing striking aesthetics.

| Quantifiable Benefits:

- Efficiency: The pavilion was conceived, and fabricated within three months.
- Structural Performance: Enhanced stability through strategic diagonals.
- Visual Impact: Achieved captivating aesthetics while concealing structural components.



Fig. 9: (Ultra) Light Network at iLight Marina Bay, Close-up a node integrating LEDs

Redefining Architectural Tectonics and Future Directions in Additive Manufacturing

The focus on bespoke 3D-printed connections is reshaping architectural tectonics, enabling cohesive, efficient, and expressive structures. These connections, made possible through additive manufacturing, support intricate geometries and the seamless integration of technical systems like wiring and sensors, enhancing both structural performance and material efficiency. By merging form and function, this approach opens new possibilities for adaptive and optimized designs.

Advances in multi-material 3D printing and generative design tools allow for customized connections that improve resilience, energy efficiency, and multifunctionality, particularly in temporary or deployable structures like pop-up pavilions and emergency shelters. The ease of assembly, disassembly, and reuse aligns with circular economy principles and sustainable design goals. Looking ahead, new materials, computational optimization, and robotics integration promise further advancements in structural efficiency and environmental impact, while future studies should focus on long-term performance and cost-effectiveness.

As architects embrace these innovations, 3D-printed connections will continue to redefine architectural tectonics, offering scalable and versatile solutions. The potential to embed sensors in these connections paves the way for adaptive, smart structures, merging aesthetics, functionality, and sustainability to meet the demands of a rapidly changing world.



Fig. 1: Volumetric structure: columns, credits: MAS T2, 2023
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IMPACT PRINTING: A NOVEL ROBOTIC ADDITIVE MANUFACTURING METHOD FOR CIRCULAR, HIGH-VOLUME CONSTRUCTION

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Abstract

Impact printing is a novel robotic additive manufacturing construction method enabling the controlled high-velocity deposition of discrete extruded dense materials parts. This particular additive manufacturing method is developed specifically for circular and sustainable materials, such as excavated materials. . The AM process and custom tool is developed for multiple construction scenarios including off-site prefabrication and onsite in situ robotic construction with autonomous construction machines. Preliminary results suggest that this method may be more efficient than 3D printing, requires minimal supports and no custom formwork, and may require less stabilizers and enable higher height buildup per day due to relatively higher initial yield stress during initial material deposition.

Project vision: an efficient offsite and onsite robotic additive manufacturing method

Impact printing is developed as an interdisciplinary collaboration at ETH-Zurich, between Gramazio Kohler Research, the Chair of Sustainable Construction, and the Robotic Systems Lab. The project vision is to develop an efficient and highly automated additive manufacturing method for earth-based materials, to be realized on the full building scale, in order to produce unreinforced 1 to 2-story structures. Using earth-based materials is one important strategy to decarbonize the building industry [3]

Many criteria and targets are taken into consideration in development: an efficient building rate, a high level of automation and autonomy, and material circularity and end-of-life recyclability. The additive manufacturing method is developed for implementation on both high-payload gantry systems and autonomous construction machines. By targeting integration on the HEAP platform, an autonomous legged excavator developed by the Robotic Systems Lab at ETH-Zurich [6], the project also aims to surpass restrictions common to on-site 3D printing: enabling in-situ construction in unstructured, mountainous terrain.

Printing fast, printing high, and printing sustainably?

Contemporary fabrication methods for earth-based, ecological, and low embodied GHG materials, such as rammed earth and poured earth, require formwork construction and are labor intensive [5]. The high costs, slow construction speeds, and high dependency on manual labor limit their broad application in construction. In contrast, emerging additive manufacturing solutions such as extrusion-based 3D printing are usually done with high-cement ratio concrete. Cementitious materials modified for printing generally come with relatively higher CO₂ emissions per volume, due to smaller aggregates and extra additives, canceling benefits from efficient material use [4].

When extrusion-based 3D printing is adapted towards earth-based materials, build rates can be even slower. Significantly, the allowable continuous vertical height buildup before a plastic or buckling failure is extremely limited, given in the literature as 0.3 meters to 0.5 meters.

A robust and flexible additive manufacturing method for industrialized construction must be both efficient and enable continuous vertical height - buildup. However, there is typically an inherent trade-off between efficiency and sustainability: to expedite green strength for faster printing and fast vertical build-up requires additional additives or stabilizers that can compromise end-of-life circularity and increase embodied emissions.

An additive manufacturing method for high-velocity deposition of discrete, dense parts

Impact printing is a robotic additive manufacturing construction method based on the controlled high-velocity deposition of discrete extruded dense material parts. The process was investigated previously on a small scale, with parts of weight 2.2g, with a prototypical setup [7]. With this research project, funded initially by ETH grants, the process was upscaled. A 3 subsystem mechanism, arranged in a vertical fashion, enables the

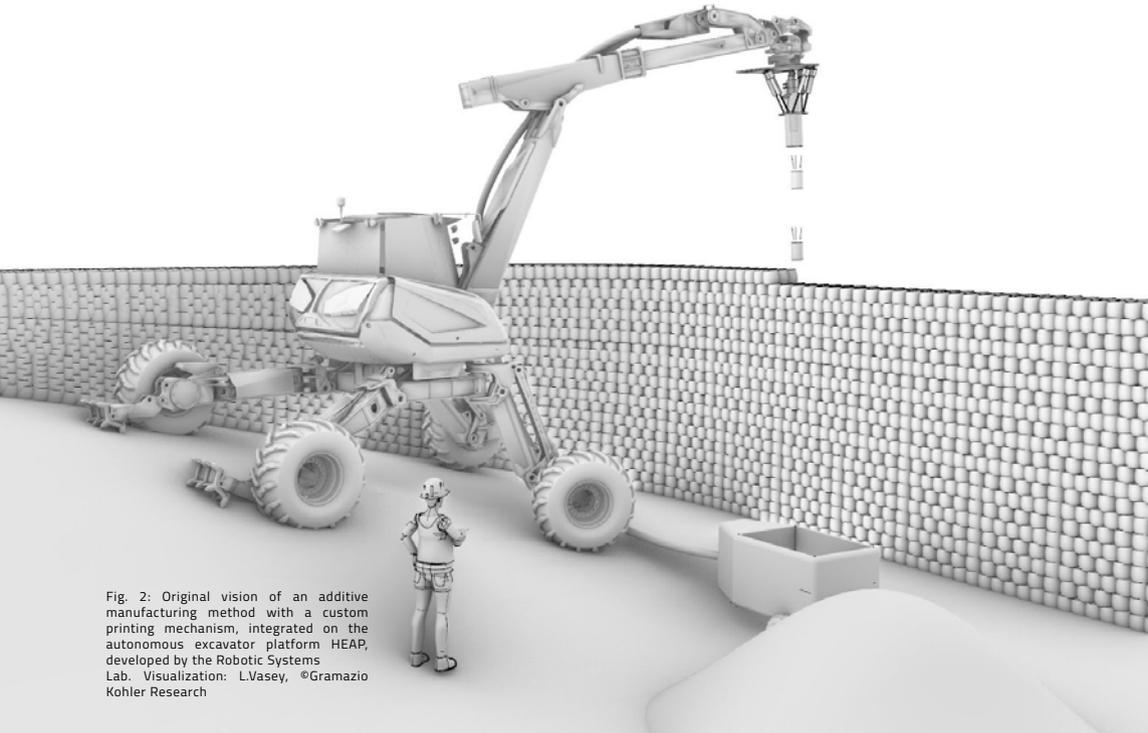


Fig. 2: Original vision of an additive manufacturing method with a custom printing mechanism, integrated on the autonomous excavator platform HEAP, developed by the Robotic Systems Lab. Visualization: L.Vasey, ©Gramazio Kohler Research



Fig. 3: This robotic additive manufacturing process is based on high-velocity (> 10 meters/second) discrete deposition of dense pre-mixed material. By depositing material at high velocity, the process enables bonding between adjacent parts and mitigates the possibility of dry joints. The prototypes can be cut and no joints are visible. ©Gramazio Kohler Research

extruding, portioning, and shooting dense pre-mixed material (2300 kg/m³) with high velocity. The custom printing mechanism can deposit material parts at velocities up to 8-12 meters / second with 1-3 millimeters positional accuracy. It has been integrated initially on the ETH robotic gantry system, which enables coordinated and controlled movement in Cartesian space according to digitally sent instructions from design software.

For this process, a mix design composed primarily of an excavated material from an industry partner, Eberhard Unternehmungen, was developed by the Chair of Sustainable Construction.

Preliminary results and concept validation

On the prefabrication setup, the custom printing mechanism can successfully extrude, portion, and deposit dense earth-based materials in a relatively high-yield stress state (> 28 kPa). The method also introduces deposition velocity as an extra parameter in an additive manufacturing process: more viscous materials with higher yield stress can be deposited with relatively higher

velocity. By controlling the deposition velocity, a bond can be enabled between adjacent parts and dry joints can be mitigated. The hypothesis put forth is that material can be deposited with enough green strength to already withstand significant vertical height build-up. Therefore, the process may rely less on accelerating the green strength during construction, compared to extrusion-based 3D printing. Because the mix design requires a very minimal percentage of a mineral stabilizer, the process is relatively lower in embodied emissions, compared to extrusion-based 3D printing [1]. Furthermore, there may be additional process potentials due to the unique material yield stress development overtime: material is deposited in a load-bearing state but is still workable enough to enable post-processing and detailing. This property may be exploited in further steps towards commercialization.

On the prefabrication setup, the process has been used to construct standard, straight sections with high control over surface thickness, in addition to customized structures such as volumetric columns [2].



Fig. 4: The method has realized extremely slender structures with minimal geometric stiffness (0.12 meter thickness) up to 1.85 meters in a single uninterrupted process. This is a significant advantage over other AM processes with earth-based materials, which require pauses earlier pauses to mitigate plastic and elastic failures. ©Gramazio Kohler Research

From Offsite to Onsite Construction

The technology and additive manufacturing process is developed to transition from off-site prefabrication to on-site construction. Constructing structures directly in their final position, and sourcing material locally, can enable many advantages from the perspective of a circular economy [8]. In order to target an autonomously controlled hydraulic excavator as a final platform, the underlying research questions are how accurate does the novel construction method need to be for “buildability,” and similarly, how accurate can an autonomous construction platform be? Such a strategy requires both modular hardware, as well as platform-agnostic software.

Commercialization

The team aims to commercialize the robotic printing technology through the establishment of an ETH spin-off. The spin-off will first enter the pre-fabrication market, developing pre-fabricated earth and timber hybrid structures that can be sold by pre-fabrication companies. Developments currently underway also include robotic surface finishing, and adaptive detailing concepts. The aim is to develop a building product that can be cost competitive by reducing dependency on manual steps, using cheap locally sourced materials, and increasing the speed of construction. The proposed building products would also have performative advantages such as high thermal inertia.



Fig. 5: The process has been used to make volumetric structures such as columns Credits: MAS T2, 2023 ©Gramazio Kohler Research



Fig. 6: Due to the extended window of material workability after deposition, the additive manufacturing method enables post-processing. Wall prototypes can be wire cut after material deposition. L. Vasey and K.Chadha ©Gramazio Kohler Research

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Fig. 1: 3D printed truss structure prototype developed at Navier Laboratory.
Photo credits: Stefano Borghi

ANISOTROPIC CONCRETE: A COMPOSITE LOOK ON THE ENGINEERING AND ARCHITECTURE OF CONCRETE CONSTRUCTION

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Introduction

As they are abundant, inexpensive and relatively strong, cementitious materials are massively used to build and renovate, from housing to infrastructure. However, the large environmental impact of cement requires us to reinvent the way we use it, to develop more material-efficient techniques than the traditional, massive concrete casting construction. In this regard, the optimization possibilities offered by additive manufacturing are now well understood: the toolpaths traced by the printing machines open a new, lighter formal vocabulary of surfaces and grids, the potential of which is clear to see in comparison to the massiveness of most contemporary cast concrete structures. But it is also a new requirement for the material, which still needs to be reinforced, and to which the steel rebar-reinforced concrete technique cannot respond in the best way, because of the great thicknesses of concrete that must encase each rebar, and its complexity (the steels must be cut, shaped and installed in parallel with the printing).

Long-fiber composite materials, which have already taken on a major role in automotive, aviation and the naval industries, are characterized by very fine-scale reinforcement, which is much more suited to printing, but also by their anisotropy, an additional parameter that gives designers the opportunity to place not only the right material in the right place (which is common to

all additive manufacturing processes) but also the right reinforcement in the right direction. "Thinking composite" in structural design, by optimizing both the layout of continuous reinforcement orientations and material distributions, has already led to breakthroughs across the aforementioned industries riding the "composite wave": construction of the fastest sailboats, reduction of aircraft structure weight to 20% compared to aluminum designs according to Boeing [1], manufacturing more than 40-m long wind turbine blades. While these milestones certainly cannot be directly translated into the field of construction, being driven by very different constraints, it is however clear that the time is right to explore how composite engineering can bridge into the emerging field of concrete 3D printing construction. While it has been already shown that short-fiber addition is possible for extrusion-based 3D printing, the reinforcement rate remains relatively low, because of the pumpability requirements of such materials, which undoubtedly limits the attainable performances. On the other hand, several research teams, including ours, worked on the development of long-fiber composite inspired technologies.

In this essay, we introduce the patented Flow-based Pultrusion process, developed at the Navier Laboratory. It applies to extrusion-based 3D printing, and enables to print ductile structural concrete components, thanks to

the unidirectional reinforcement of laces in their printing direction with long fibers. In the first Section, the process and apparatus are outlined. In a second Section, the obtained “anisotropic concrete” is presented, along with its potential and limitations compared to traditional steel-reinforced concrete. The third Section presents the first large-scale prototypes and provides some ideas on future anisotropic concrete applications.

The Flow-Based Pultrusion process

The Flow-Based Pultrusion (FBP) technology is described in patent [2]. The principle, illustrated in Figure 3, is to entrain and impregnate passively multiple continuous small-diameter fibre strands (such as glass, basalt, or carbon) into the extruded concrete lace. This makes it an anisotropic concrete, reinforced along the printing direction. The controlled rheological behavior of the extruded concrete matrix ensures the routing and impregnation of the strands without the need for motorization. Compared to active routing solutions, this simplicity offers several advantages: it is probably more reliable since there are less points of failure (no motors), cost-effective, and simpler to control.

A first prototype was developed at the Navier Laboratory and adapted to a two-component concrete 3D printing system from XtreeE using fine-grained mortar (Figure 2). Such a two-component system (2K) is characterized by the fact that the mortar texture is changing inside the print head. It makes it especially suitable for Flow-Based Pultrusion: Indeed, the fibre

reinforcements are inserted directly inside the print head, where the mortar flows. At the print head entry (and fibre insertion point), the mortar is very fluid, allowing for optimal fiber impregnation. The mortar then transitions to a thick, pasty consistency thanks to the in-line addition of an accelerator additive. This change in texture makes it possible for the mortar flow to pull the fibers through the print head.

The fibers are routed inside through small PTFE pins, drawing a minimal path from their bobbins that are directly attached to the print head. The idea of this setup is to minimize friction through the fiber path to ease its pulling, a critical parameter as the pulling force brought by the pasty flow of mortar remains relatively small. A limitation of this first prototype is the fiber carriage capacity, which is limited to 10 spools of 120 meters of fiber each. This constraint only permits the printing of relatively small objects. New industrial prototypes are under development in collaboration with XtreeE, which allows us to print the first large objects, typically several meters long. The flexibility of the reinforcement strand used is a major challenge to make sure it can follow the printed lace curvature, and well bond to the mortar. The first tests using metallic “piano cord” wires were unsuccessful due to these reasons [5]. Conversely, roving yarns, composed of multiple microfilaments, have demonstrated superior efficacy. These yarns possess remarkable flexibility, like hair strands. They also bond easily with the mortar. More details on the process technology can be found in [3].



Fig. 2: Prototype of flow-based pultrusion device developed at the Laboratory Navier. Left: view of the XtreeE printing head with the device attached, Middle: detail of the device, Right: printing of a sample.

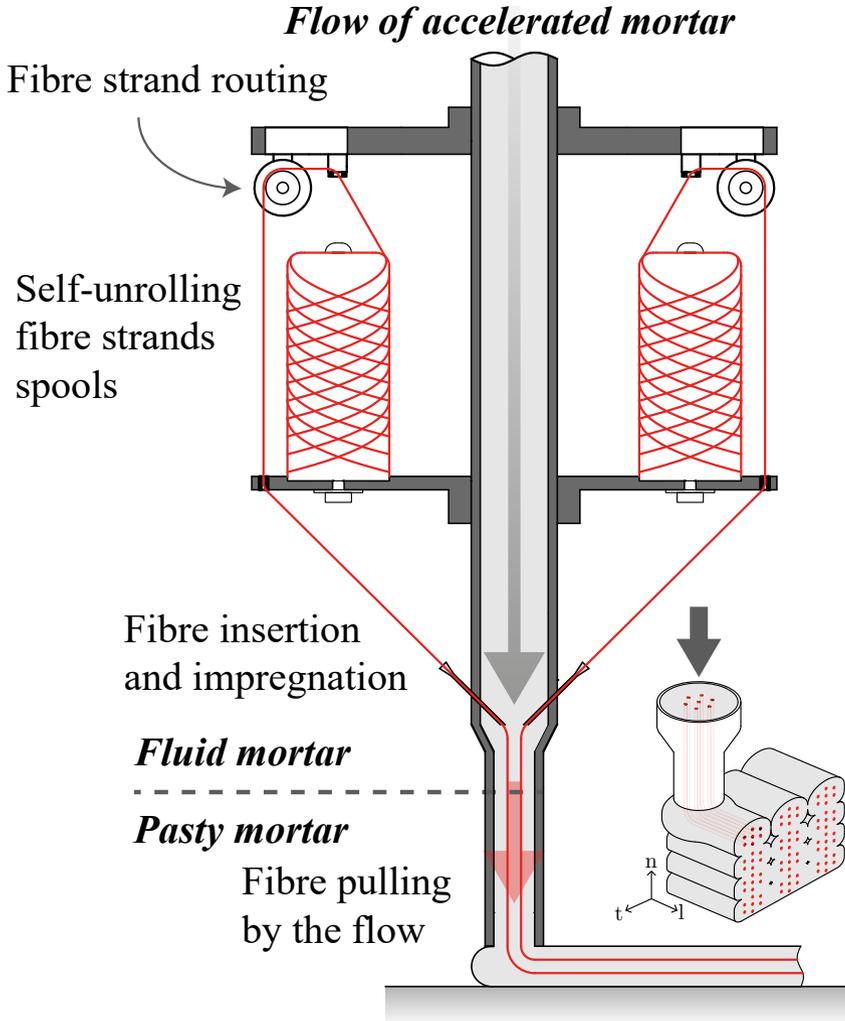


Fig. 3: Left: Fiber printing device: 1/coils 2/pulleys 3/guides 4/drive head. Bottom right: Transverse isotropic arrangement in the printing direction via the patented Flow-Based Pultrusion process.

The Anisotropic Concrete material

After the technology was set up, initial prints of Anisotropic Concrete have been made with glass, basalt, and carbon rovings, up to 6% fiber by volume of printed material. Mechanical tests carried on small printed specimens have shown that with an adequate setting of key process parameters (mortar strength, fiber dosing and impregnation quality), the obtained anisotropic concrete have significantly improved mechanical properties in tension compared to the brittle unreinforced material. Along the fiber direction, it becomes stronger, and most notably, ductile, which means that it elongates under excessive stresses until a smooth failure. Figure 4-5 illustrates a typical tensile test result, in the direction of reinforcement. The strain levels measured are comparable to construction-grade steel reinforcements, up to 2% deformation. This ductility is due to what is called multicracking [4], a well-known phenomenon in the field of cementitious composites which relates to micromechanical interactions between the fibers and the mortar (most notably, the deviation of cracks through fiber-matrix interfaces and the ability of continuous fibers to “bridge” cracked areas and sustain stress transfer). This makes a reliable construction material,

that fails in a smooth and predictable manner, and able to absorb localized impacts. It is notable, however, that the multicracking ductility occurs as soon as the concrete starts to crack. This differs from reinforced concrete, for which there can be some delay between the first concrete cracks and the plasticization of steels. The anisotropic concrete post-cracking stiffness is then a key parameter, that will also drive the potential material's savings : the stiffer the material, the less we will need to put into a structure to make sure it is not only strong but also remains sufficiently stiff after its first cracks, which may occur during the life of the structure.

This specificity should be considered in the dimensioning process, as well as the anisotropy, as previously emphasized, i.e. choosing where to align these fibres into newly designed building components to account for the most significative stresses. This will be an interesting exercise for structural designers, but in line with what is already done with reinforced concrete. Indeed, it is no coincidence that some steel reinforcements are aligned to the main longitudinal direction of a beam, so to sustain tension stresses from bending. Similarly, fiber alignment should be tailored to optimize the structural performance.

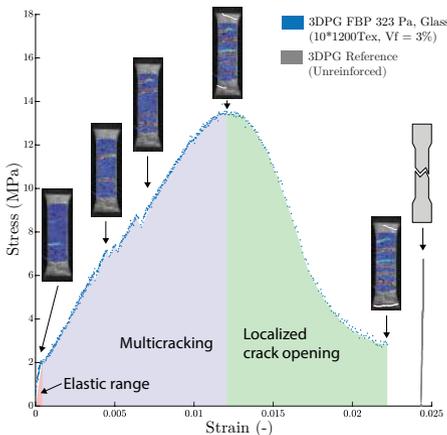


Fig. 4: Typical stress-strain curve obtained by the tensile test.

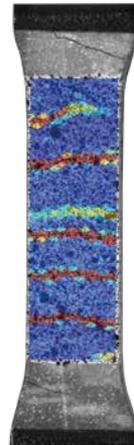


Fig. 5: Tensile test of anisotropic concrete, color gradients highlight the strains and multiple cracking.



Fig. 6: 3-point bending test of an anisotropic concrete plate.

Anisotropic Concrete and its applications

After the previous explorations of the material's performance at the scale of the printed lace, and to demonstrate its applicability and performance at a larger, structural scale, larger objects were produced and tested. A first 1.5m long plate, very bendable, highlights again the material's ductility (Figure 6). A 1.5m beam prototype was then made in collaboration with XtreeE. In this first design, just like steel rebars, here fibers are aligned along the longitudinal direction of the beam, to sustain most of the tensile stresses due to bending. 800 tex carbon fiber rovings are used, providing a 2.5% reinforcement ratio. A reversed T-shape cross-section is chosen: The top part, which is compressed by bending, has a small cross-section area, because the printed material is made from a mortar mixture that has excellent compressive properties, so a small cross-section is sufficient. The bottom part, which is tensed, is larger because the anisotropic concrete is weaker in tension than in compression, and more material is required here to sustain the tensile stresses in the beam. A three-point bending test has been carried out on the beam, showing a very ductile behavior at the onset of cracking, with



Fig. 7: 3-point bending test of the beam and shear cracks.

visible multicracking on the bottom (tensed) side of the beam. The final ruin, however, was not due to a failure of such reinforcement, but to shear stresses which were not aligned with the tensed fibers (Figure 7). This early-stage test indicated the need for design adaptations, but nonetheless confirmed the effectiveness of anisotropic concrete at the structural level.

After the beam, it was proposed to explore another structural typology, familiar to composite designers: thin shells, very common in composite laminates (gas tanks, turbine blades, ...), and which also exists in concrete construction, such as the famous Heinz Isler's covering structures. In thin shells, stresses remain mostly membranar: the in-plane reinforcement of the material provided by anisotropic concrete is sufficient, and it is not necessary to reinforce in the perpendicular direction. A prototype of printed shell was made, presented in [6], where the chosen design results from an optimization process accounting for the material anisotropy. Tubular or box-like shell casing structures can be imagined next and turned into hybrid components: As an example, by bringing a bulk fill material inside to provide thermal or soundproofing performances (Figure 9). This is a usual strategy in historic masonry construction, applied more recently with composite shells during the making of

the Louise M. Davies Symphony Hall (1980) designed by Skidmore, Owings & Merrill and Pietro Belluschi in San Francisco, where soundproofing fiber-reinforced plastic composite cases were assembled on-site and filled with sand. Such technique could help develop alternatives to contemporary thick, CO₂-intensive cast concrete slabs, where most of the concrete mass is not structurally useful, but only allows for better soundproofing or thermal inertia.

A third typology, grid structures, can certainly be scaled up to new structural applications thanks to anisotropic concrete. As an example, previous research from our team showed how the use of polyhedral supports for the extrusion allows the making of very light concrete structures, by forming 3D grid trusses [6] (Figure 8). Without reinforcement, the technique is limited to the typical use of block/mortar systems, but it would be particularly advantageous to construct these trusses

using anisotropic concrete, as the principal stresses align with the laces direction, and thus with the reinforcement. One could then use these reinforced trusses to build parts of primary structural importance, such as roofings or flooring components.

Finally, even a minimal amount of reinforcement with anisotropic concrete can be a game-changer in existing applications. In cases where cracks in an unreinforced concrete turn into a catastrophe, for example during the handling and transport phases of printed elements, anisotropic concrete provides a solution by managing these small cracks. This would also certainly extend the lifespan of such elements, and facilitate the development of concrete 3D printing prefabrication, which we believe is the most impactful approach. It offers full control over production conditions, reducing the uncertainties and safety factors that limit the optimization potential of additively manufactured parts.

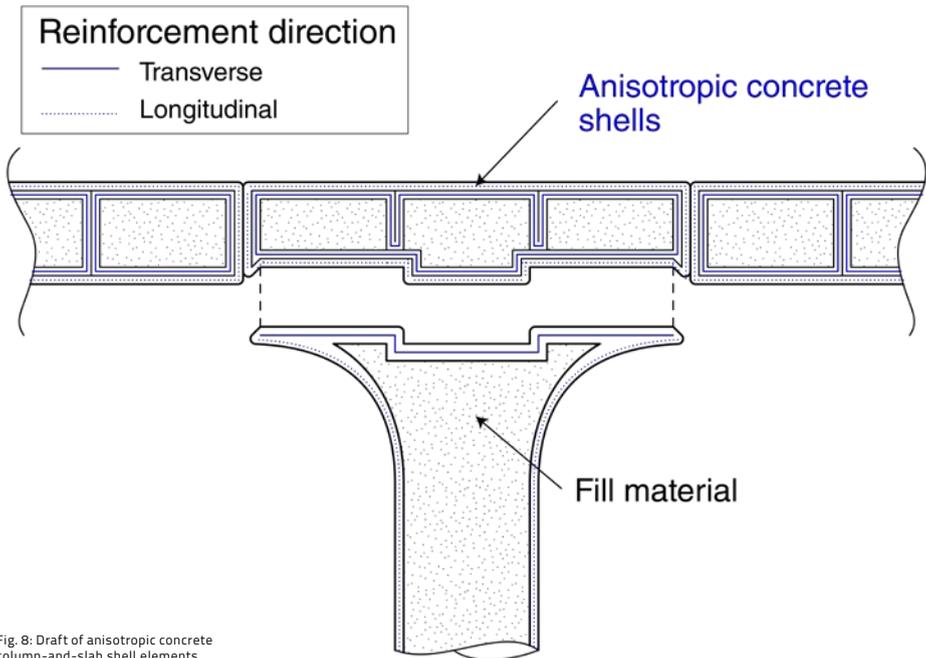


Fig. 8: Draft of anisotropic concrete column-and-slab shell elements.



Fig. 9: 3D printed truss structure prototype developed at Navier Laboratory.
Photo credits: Stefano Borghi

Conclusion

The exploration of the use of long-fiber composite materials in the field of concrete 3D printing represents a significant topic. Compared to steel-reinforced concrete, it has the potential to open more disruptive structural applications by bringing high mechanical performances at the material scale, reduce structure weight and help for a more environmentally efficient use of the cementitious materials which are integral to modern construction. The Flow-Based Pultrusion (FBP) process, developed at the Navier Laboratory, exemplifies this innovation, providing a simple means to produce an anisotropic concrete with

improved mechanical properties and ductility. By drawing inspiration from composite engineering, the material's anisotropy can be leveraged into structural components, by putting the right reinforcement in the right direction. A first, early-stage beam demonstrator highlights the potential for anisotropic concrete to go large-scale. Thin shells and 3D trusses provide opportunities to use this 3D printed material in an efficient way, and the first demonstrators could be upscaled for more virtuous constructions.

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Fig. 1. Robotically 3D printed hollow strand building element with FGF BX

MULTI-MATERIAL HOLLOW-STRANDS BY BLOW EXTRUSION (BX) 3D PRINTING

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Abstract

Blow Extrusion (BX) 3D Printing is an advanced additive manufacturing (AM) technique that allows 3D fabrication with hollow strands. We present BX using Fused Granular Fabrication (FGF) and Fused Filament Fabrication (FFF) which combines multi-material 3D printing, blow extrusion, robotic fabrication, and computational design. Our technique decreases material and resource consumption due to the hollow strands with an adjustable diameter of their cross sections.

Large-scale 3D printing with thermoplastics is becoming an increasingly widespread technology in technology-driven research for the architecture, engineering and construction (AEC) industry [12]. Real-world construction applications, such as interior walls [1], acoustic elements [11], exterior façade elements [10], and concrete formwork [3], have been used in research and practice. BX 3D Printing decreases material consumption while creating lightweight and robust elements. Our BX technique allows for a significant reduction in material consumption (up to 85%) compared to printing with solid cross sections and, more importantly, precise control of the material flow. Moreover, our method for printing hollow strands enables large-scale 3D printing with variable sections by controlling air flow during extrusion to inflate the strand.

Here we outline the design-to-fabrication framework and the mechanical development of Fused Granular Fabrication Blow Extrusion (FGFBX) and multi-material Fused Filament Fabrication Blow Extrusion (FFFBX) with variable sections. Additionally, we showcase some of our early-stage research outcomes for construction industry applications, such as lightweight façade elements, formwork systems, and displacement bodies in concrete ceilings.

Introduction

The construction industry is responsible for approximately 20 percent of plastic consumption in Europe [2]. Thermoplastics cover a large part of used plastics that allow for recycling and reuse [7], which makes it a suitable material for construction industry [4]. Additive manufacturing and large-scale robotic 3D

printing have become a constantly expanding, well-developed research field in the AEC industries with a great market capacity [8, 9]. Our proposed method allows for significant material reduction in large-scale 3D printing with thermoplastics through the extrusion of hollow strands instead of solid material.



Fig. 2: left: BX 3D Printing with Fused Granular Fabrication (FGF), right: BX 3D printing with four colors Fused filament fabrication (FFF). Both specimens were manufactured using the same nozzle but different parameters for air flow.

Background

Large-scale additive manufacturing with thermoplastics is challenging: (a) In AEC industries plastic consumption and printing time has to be reused. From a mechanical perspective, the limited material throughput, thermally induced deformations, and the required time for solidification are problems to solve. Our research aims to address issues at both AEC industries application as well as improvement of mechanical properties through the replacement of conventional (solid) filament deposition by the extrusion of hollow strands. The ring-shaped extrusion encloses a coaxial nozzle that is used to change the pressure within the extruded strands, leading to variable cross sections. With this we generate hollow strands instead of solid plastic layers reducing significantly the plastic consumption per volume. The encapsulated air speeds up the cooling process. leading to a higher throughput and faster printing.

3D Printing of hollow strands using filament as a feedstock has been introduced by (Hopkins et al., 2020). Pellets as feedstock for robotic 3D printing of hollow strands was presented by Leschok et al. of DBT at ETH Zürich [5]. Their method uses Fused Granular Fabrication (FGF), which allows for a throughput ratio of 50 kg/h, whereas Fused Filament Fabrication allows around 0.5 kg/h. Comparing the throughput ratios of FFF and FGF demonstrates a 100-fold difference, which explains why it appears uneconomical to 3D print hollow strands on a large scale with filaments.

The Fused Filament Fabrication allows for more precise control of material deposition along the extrusion path. Our method, FFFBX, allows for 3D printing with hollow strands that can vary in their cross-section with precise control. FFFBX allows for synchronized extrusion with (at the time) four different materials along the extrusion trajectory, enabling variations in material properties, such as appearance or stiffness, along the extrusion. Using the robotic arm and our design-to-fabrication framework allows us to control the direction of material placement along the extrusion path, enabling more specific control over the workflow and precise deployment

Methodology

The methodology includes a series of prototypes and the evaluation of the procedure through monitoring the processes. In our studies, we have developed and showcased the combination of this advanced extrusion technique in two directions: (a) FGFBX, which allows for mono-material extrusion from pellets with variable cross-sections, and (b) FFFBX, which allows for multi-material extrusion from filaments with variable cross-sections. At this stage of the research, prototyping has reinforced the progression to estimate the feasibility of the processes and project the potential application capacities of both FGFBX and FFFBX. A great portion of the technical development has been focused on mechanical challenges.

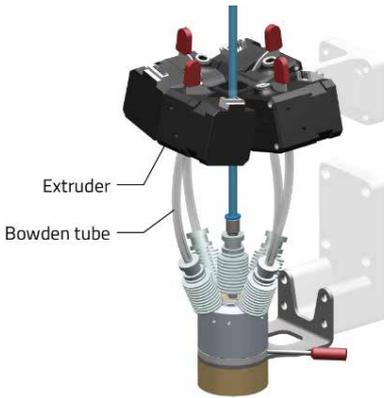


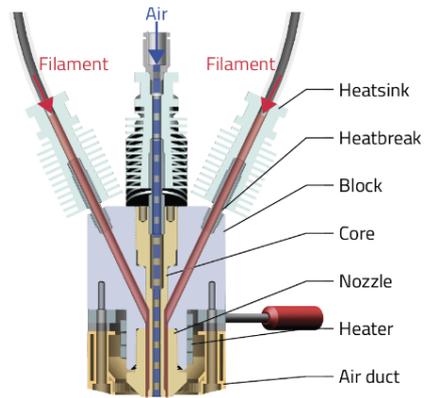
Fig. 3: FFFBX mechanical setup and printhead assembly

Mechanical challenges

The challenges involved in the mechanical design of the print heads include (a) material throughput, (b) nozzle design and (c) precise control of the air for inflation.

(a) Filament as feedstock (in FFFBX) was reported as a limiting factor for Blow Extrusion by Hopkins [6]. We overcome this limitation with our approach, which includes four high push-force extruders and a sufficiently long melting channel to allow high volumetric flow. This also enables multi-material printing with up to four different materials. When using pellets as feedstock (FGFBX), sufficiently high volumetric flow rates are provided.

(b) Independent of the feedstock, the nozzles require a design that allows air to be introduced through the center of the molten material. We achieve this by using a coaxial nozzle with a modular design. For FFFBX the four



channels in the heated block (Fig. 03) hit a core and are fed into the nozzle. The tube diameter at the outlet is 8 mm on the outside and 6.5 mm on the inside in a non-expanded state. For FGFBX, the nozzle is installed on the existing pellet extruder and is characterized by a three-piece design consisting of block, core and barrel (see Fig. 04). In this case, the extrudate diameter is 10 mm on the outside and 8 mm on the inside in a non-expanded state.

(c) The air volume flow is selected as the control variable for regulating the inflation. Provided that the strand is sealed at the start of the process, the desired outer diameter can be set from the ratio of extrusion speed, printhead travel speed and nozzle diameter, which results in the required air volume flow. For this purpose, a mass flow controller is controlled simultaneously with the extruders via a digital interface.

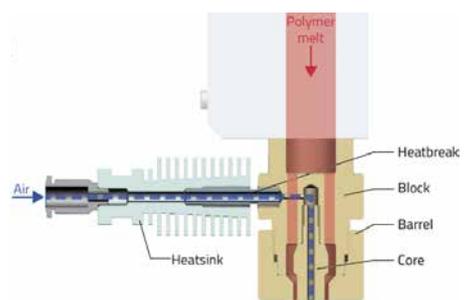
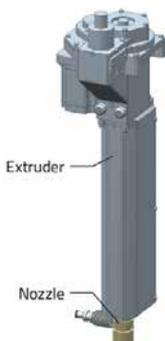


Fig. 4: FGFBX mechanical setup and printhead assembly

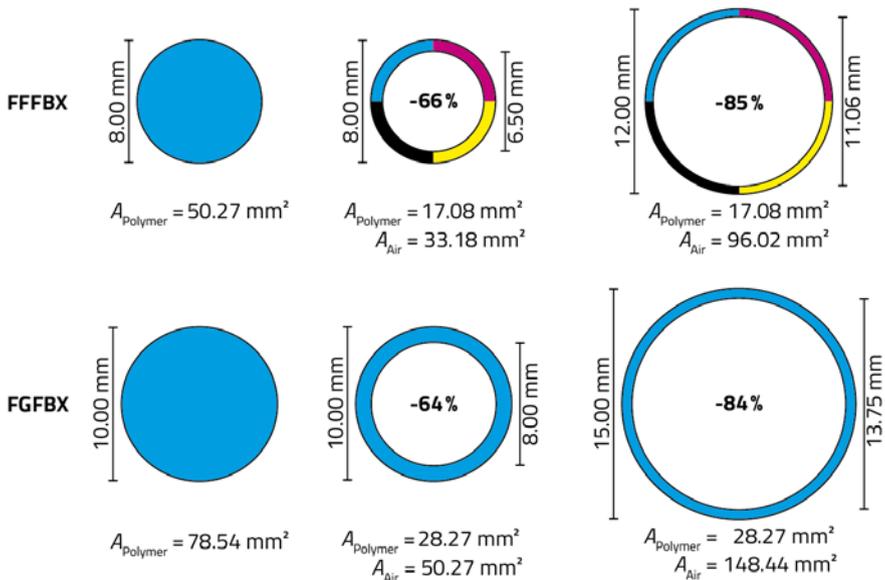


Fig. 5: Material reduction in percent compared to the full cross-section (left) for hollow strands produced using FFFBX and FGF BX without inflation (center) and with an increase in size by a factor of 1.5 (right) by Blow Extrusion where A represents the area.

Digital to physical framework for robotic 3D printing

The digital framework for these processes includes the geometric slicer, a robotic simulation, and the synchronized communication between the UR10 robotic arm and the custom made extruder setup. The continuous and seamless digital to physical process starts with the geometry in the 3D modeling and parametric design environment Rhinoceros and Grasshopper. Our custom made slicer allows to program and visualize the variable cross sections. The custom made client is in charge for the real time data transition to both robotic arm and extruder setup. We use an open API framework (Moonraker/Klipper) for data transfer, which allows for synchronized control of all extruders, air pressure and robotic arm to move synchronously.

Prototyping and Results

By substituting polymer with air, we were able to achieve a material reduction of approx. 65 % without further expansion of the strand and up to 85 % by expanding to 1.5 times the diameter using our BX technology (Fig. 05). With early-stage prototyping we first tested printing maximum dimensions defined the reach of the UR10 robotic arm (Fig. 06.a.). Secondly, we varied the hollow strand cross section (Fig. 06.b.). Thirdly, the spatial trajectory 3D printing without support material has been tested and showcased (Fig. 06.c.). The demonstrators were built with transparent PETG for the FGF BX procedure and four-color PETG (CMYK - cyan, magenta, yellow, key/black) for FFFBX. The column-like linear element, slab-like flat element, and an interior wall demonstrator (Fig. 06) address the challenges of automation and large-scale AM with minimal material in relation to the volume.

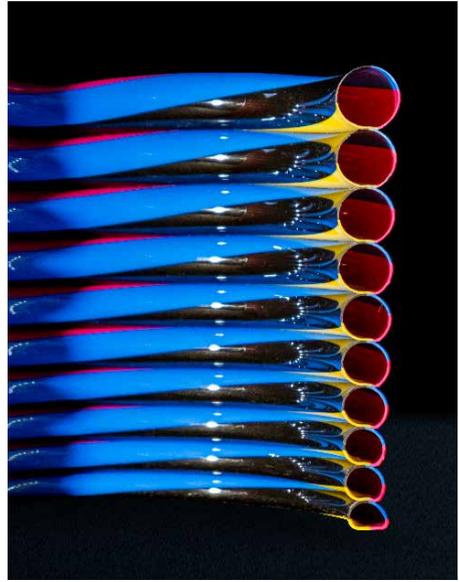
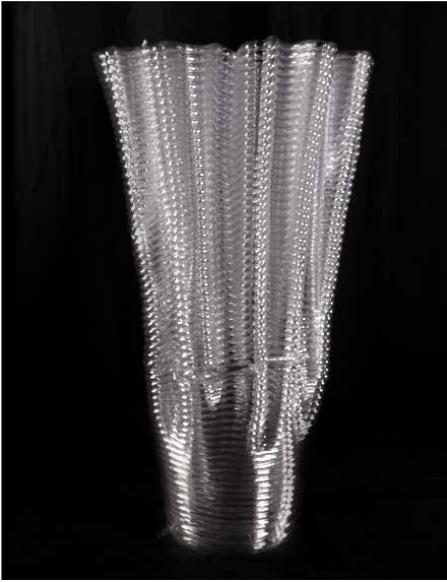


Fig. 6: left: BX 3D printed results with robotic arm FGFBX (segment of a Column prototype), right: varied the hollow strand cross sections with multi-material FFFBX

Conclusion and outlook

This essay presents the early-stage research development and results of hollow strands with variable cross-sections. Both FGFBX and multi material FFFBX allow for lightweight manufacturing and significant reduction of printing material (up to 85%). Moreover, the presented work demonstrates that printing hollow strands with multi-material along the extrusion path is feasible and scalable up to the size of architectural building elements. Our mechanical developments show that we are able to increase the volumetric throughput up to six times compared to solid FFF and FGF procedures, making FFFBX a relevant AM method in the AEC industries by reducing printing time. The demonstrators examine the capacity for function integration inside the cavity of pipe-like hollow strands within the lightweight 3D-printed elements. Moreover, our methods offer great potential for design with material cavities and explore the material programming research area by programming the cavity and weight distribution inside building elements.

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Fig. 1: The Cadenza Stair, Credit: Andrei Jipa DBT ETH Zurich

DIGITAL CRAFTSMANSHIP: SHAPING A SUSTAINABLE BUILT ENVIRONMENT

JÖRG PETRI

NEW DIGITAL CRAFT GMBH

Abstract

New Digital Craft is revolutionizing the architecture and interior design industries by blending traditional craftsmanship with cutting-edge digital technology. Their work focuses on computational design and large-format 3D printing to produce innovative, sustainable structures while reducing environmental impact. By using only eco-friendly materials and employing low-carbon concrete, the company cuts CO2 emissions by up to 80% and further towards a net positive environmental impact, by binding CO2 into their building products.

New Digital Craft's approach ensures precision and creativity in design, while emphasizing sustainability in every project, creating a future where modern construction not only honors traditional craftsmanship but also fosters a sustainable built environment.

This document highlights three exemplary projects, where the work of New Digital Craft illustrates the efficiency and sustainability on how 3D-printed formworks in constructing can lead to future-proof building components. Each project showcases, how advanced digital tools and additive manufacturing can overcome traditional fabrication limitations, reduce material waste, and deliver complex, bespoke designs with outstanding sustainable results

The Cadenza Stair

Stairs are more than just functional elements in buildings; they also serve as architectural symbols that define the aesthetic and spatial character of a space. However, creating bespoke concrete stairs presents a significant challenge when using conventional formwork, due to their complexity and the high costs associated with customization. The Cadenza Stair at the NEST in Zurich, addressed these challenges and shows what can be done, if a team of experts, led by the Chair of Digital Building Technologies at ETH Zurich and the architecture firm ROK utilized the full potential of computer-aided design and 3D printing.

The 17 steps were manufactured using a single reusable 3D-printed formwork, which allows for a complex and extremely material-reduced shape. The pretensioning technology of the Empa spin-off re-fer, which is based on a shape memory alloy, fixed the steps that were threaded onto each other. The expertise of New Digital Craft for 3D printing the formwork together with the team of the BASF subsidiary Forward AM who were responsible for the right material choice, as well as the precast concrete parts manufacturer SW Umwelttechnik and the engineering firm Walt Galmarini, contributed to the realization of the eye-catching component. Together,



Fig. 2, 4: The Cadenza Stair, Credit: Zoëy Braun



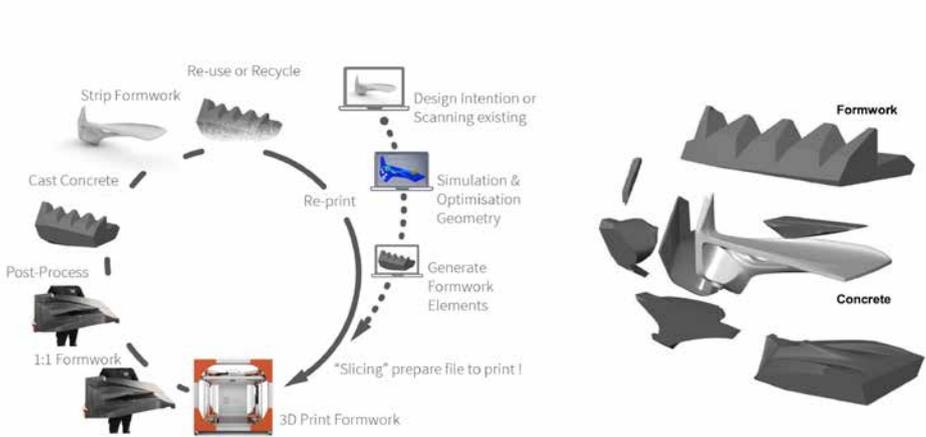


Fig. 4: The Cadenca Stair, Process Circle & Formwork Assembly

they have developed a ready-to-use solution for individual construction projects that is not only suitable for customized concrete staircases, but also contributes to efficient and high-performance design solutions in general thanks to digital planning and production.

The “Cadenza Stair” represents a breakthrough in 3D-printed formworks, offering an advanced solution to the typical difficulties of fabricating custom stairs. By leveraging computational design and additive manufacturing, the team streamlined the design-to-production process, reducing material waste and lowering costs. Through the integration of ultra-high-performance fiber-reinforced concrete (UHPFRC), they were able to craft thin, intricate shapes that are impossible with traditional methods.

The design and engineering of the formwork and stair were achieved through close collaboration among all partners involved. Working in an „open innovation”

approach, the team collectively evaluated tests and results, leveraging their combined expertise to find the optimal solution. This collaborative, equal-participation model proved highly effective in addressing the complexities of the project.

Despite its complex appearance, the stair is built from individual prefabricated steps, each reinforced by an innovative post-tensioning system using shape memory alloys. This assembly process not only guarantees structural efficiency but also facilitates ease of on-site construction. In addition, the stair’s surfaces were precisely engineered with functional and aesthetic elements, such as anti-slip textures, glossy finishes, and embedded conduits, all controlled through parametric design.

The creation of this stairway illustrates how digital tools can revolutionize architectural design and construction, pushing the boundaries of what is possible



Fig. 5: The Cadenza Stair. One out of seven formwork parts, Credit: New Digital Craft.

with concrete while drastically reducing environmental impact, by minimizing the material usage and lowering construction costs.

A key factor for the system was ensuring the formwork could be reused to produce multiple steps. At the same time, it was essential to account for the requirements of 3D printing, the material properties, and the conditions during the filling of the formwork. Meeting these requirements relied heavily on close collaboration within the entire project team. „To make the 3D-printed formwork reusable for several steps, we selected a suitable coating. From a sustainability standpoint, we chose a material that could be easily removed from the formwork. This allows us to ensure that the material is separated and properly sorted,” explains Jörg Petri of New Digital Craft. As the material has shown good performance for the formwork of the “Cadenza” stair with great “peel-off” qualities, we continue to use this material for all our projects with similar requirements. There is

still room for improvement in controlling the overall consistency of the thickness of the coating. However, this has now been resolved with a new approach and a slightly adjusted recipe for the coating.

This project served as a definitive proof of concept, demonstrating that the chosen 3D printing technology by New Digital Craft, when paired with the appropriate materials, is capable of producing high-end formworks required for such a unique and complex staircase design. It was not initially clear whether this technology could achieve the precision required to assemble the seven individual formwork parts. But through the success of realizing the stair, we have validated our approach and confirmed that our solution can effectively address even the most intricate geometries and building components, providing a versatile and scalable method for future applications in construction.

Digital Stones for Re-build

In historic architecture, stone masonry has long been the standard for detailed window framings and other decorative elements. However, the restoration or reproduction of such elements can be costly and time-consuming. To address this, New Digital Craft has developed a method for the rapid and sustainable reconstruction of stone masonry works, as demonstrated in their project at the Winery Stallmann-Hiestand in Rheinhessen, Germany.

The project involved the restoration of a guesthouse facade, where traditional stone masonry would have been impractical due to both time and cost constraints. Instead, New Digital Craft implemented their “scan-to-production” process, which begins with scanning existing stone elements using laser technology. The scans are then used to generate a precise parametric 3D model, from which a 3D-printed formwork is created in which the concrete is casted. This digital process not only shortens the production time but also ensures that the resulting stone elements can be produced thermally insulating, eliminating cold bridges, which is a common issue in traditional stone masonry. Compared to traditional stone carving, this digital approach is also more cost-effective,

reducing expenses by up to 40%. The process is fully sustainable, as the formworks used in construction are recyclable, and can be reprinted on demand for future projects.

In future projects of this nature, New Digital Craft plans to utilize alternative geopolymers binders for producing window framings, eliminating the need for Portland cement and potentially reducing CO2 emissions by up to 80%. Through extensive material testing and accumulated expertise, we have developed a suitable recipe to replace traditional Portland cement. We are confident, and our tests confirm, that the geopolymer solution offers additional benefits beyond CO2 reduction. These include high mechanical strength, chemical resistance, heat resistance, minimal hydraulic shrinkage, thermal conductivity, water resistance (even in seawater), fireproofing, no need for additives, and exceptional UV resistance and colorfastness.

This initiative demonstrates New Digital Craft’s commitment to sustainability and their ability to combine craftsmanship with digital tools to create affordable, eco-friendly building solutions. By reimagining how traditional stone masonry can be reconstructed, the company offers a contemporary, sustainable alternative that aligns with modern environmental goals.

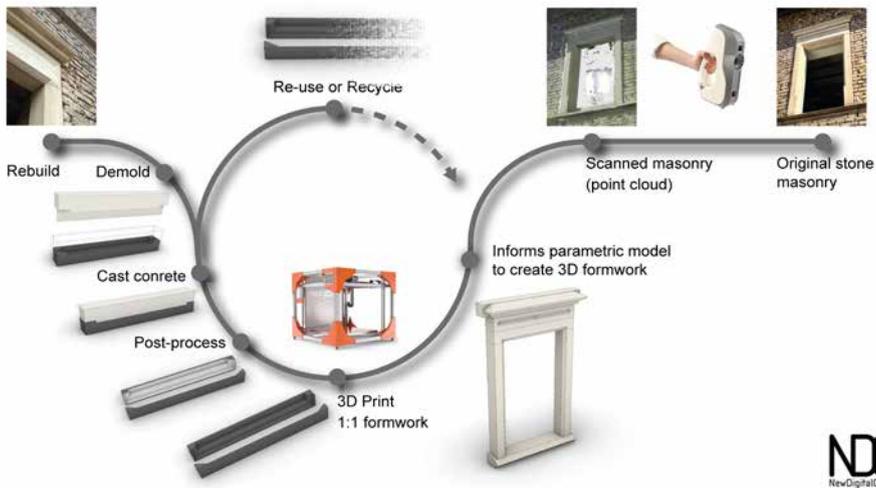


Fig. 6: „Digital Stone“ coherent digital process chain „Scan-to-Production“ for re-build



Fig. 7: „Digital Stone“3D Scan of the complete south facade, 3D Scan of original carving, reproduced new window carving.

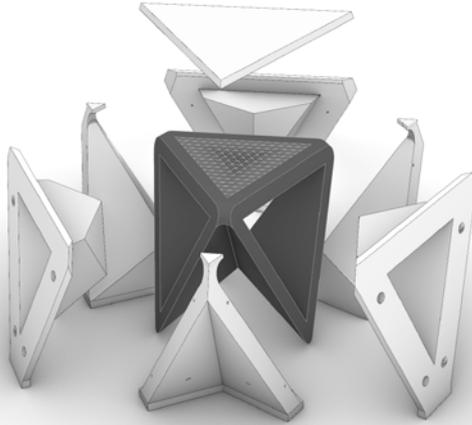


Fig. 8: Coalymer Stool: Isometric view of the interlocking formwork and digital model final stool.

The Coalymer Stool

One of the most pressing issues in construction is the industry's high carbon emissions. What if building materials could not only reduce CO₂ emissions but also permanently store carbon? New Digital Craft, in collaboration with the Generative Design Lab at TU Darmstadt, is exploring this innovative concept with their "Coalymer Stool" project.

The "Coalymer Stool" represents a new frontier in sustainable construction materials, utilizing a geopolymer mixture infused with biochar in form of a CLWA (carbon lightweight aggregate). Biochar, a byproduct of plant material pyrolysis, has been recognized for its ability to store significant amounts of carbon, making it a valuable material in the fight against climate change. By incorporating biochar into their low-carbon geopolymer mixture, New Digital Craft and the Generative Design Lab at TU Darmstadt have developed a building component that not only emits zero carbon during production but also actively stores CO₂. Using 3D-printed formwork technology, New Digital Craft was able to design and produce the "Coalymer Stool" with high precision

and efficiency, demonstrating the versatility of their manufacturing techniques. The stool is lightweight, durable, and suitable for use in public and private outdoor spaces, showcasing how sustainable design can intersect with everyday functionality.

By infusing the geopolymer mixture with CLWA, it was important to fine-tune the right amounts and sizes of the biochar material. The team is still at the beginning of this optimization process, but could already bind a good amount of CO₂ into the building component. The challenge was to keep the CLWA evenly distributed within the mixture, as the lightweight of the biochar tended to make the particles and pieces float to the top. In the first cast of the "Coalymer" Stool we were able to mix 13,3 mass % of biochar within a CLWA of 20 mass % to the overall recipe of the geopolymer-based concrete. With this figure it is important to know that 20% CLWA is almost 50 volume % due to its lightweight.

Biochar is a highly effective material for carbon capture due to its ability to store carbon derived from organic matter. On average, 1 ton of biochar can capture and store



Fig. 9: Coalymer Stool: Assembled formwork and first cast of the carbon sink stool.

approximately 2.6 to 3 tons of CO₂. Based on this ratio, 2 kg of biochar can sequester about 4 to 6 kg of CO₂.

The exact amount can vary depending on factors such as the feedstock used to produce the biochar and the specific pyrolysis process employed, but this range provides a general guideline for biochar's carbon storage potential. When combined with local materials in the form of additional aggregates and a geopolymer binder, building components produced in this way have the potential to become significant carbon sinks. The efficiency of these CO₂ sinks is currently the subject of our research, and we aim to present a precise LCA calculation to quantify exactly how much CO₂ is stored in each of our building components. This project is particularly important because it presents a model for how future construction materials can contribute to a net positive environmental impact. By creating building components that store carbon, New Digital Craft in cooperation with the Generative Design Lab at TU Darmstadt are offering a tangible solution to one of the greatest challenges facing the construction industry today.

Conclusion

Through these three projects: The "Cadenza Stair", the "Digital Stones for Re-build", and the "Coalymer Stool", New Digital Craft showcases how digital craftsmanship can shape a sustainable built environment. By harnessing the power of computational design, 3D printing, and eco-friendly materials, the company is not only pushing the boundaries of architectural innovation but also significantly reducing the environmental impact of construction.

Their work highlights the immense potential of 3D-printed formworks in creating bespoke, sustainable, and cost-efficient building components. As the construction industry continues to evolve, New Digital Craft's pioneering methods offer a blueprint for the future of sustainable architecture, where creativity, precision, and environmental responsibility seamlessly come together.



Fig. 1: AI generated image © TM-EU

THE EVOLUTION OF ARCHITECTURAL PRACTICE: FROM HAND DRAWINGS TO COMPUTER-AIDED DESIGN TO AI INTEGRATION

HAMID HASSANZADEH, REYYAN DOGAN

PARAMETRIC ARCHITECTURE EDITORIAL TEAM

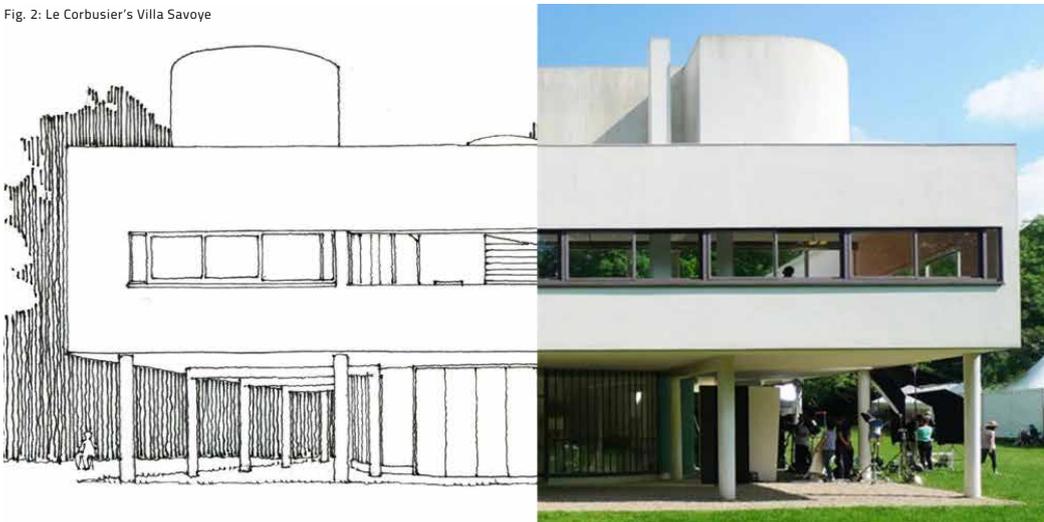
Introduction

The developing technology has had an impact on architecture over time, as in any other sector. It has affected how buildings are designed and constructed. Looking from the beforehand technical perspective, architectural practice started from hand drawings to advanced computer-aided design (CAD) tools, and now we have the integration of artificial intelligence (AI). Technology has increased precision, efficiency, and collaboration. This evolution not only affected the design process but also expanded the possibilities for sustainable and innovative structures that gratify the modern world's demands.

The journey started with hand-drawn architectural designs, and now AI marks a transformative shift in the practice with its integration into the process. In the early periods of the practice, architects had long relied on manual craftsmanship to bring their visions to life, and these hand-drawn sketches and blueprints were seen as great examples of artistry. As technology advanced, computer-aided design (CAD) revolutionized the field, enabling better precision and efficiency. Now, the emergence and increasing popularity of AI trigger the beginning of a new era, where machines collaborate with architects to generate innovative, data-driven designs and solutions.

With a closer review, it is easily possible to encounter the three periods of architecture. This article aims to summarize the three eras of architecture that are going through changes in line with developing technology.

Fig. 2: Le Corbusier's Villa Savoye



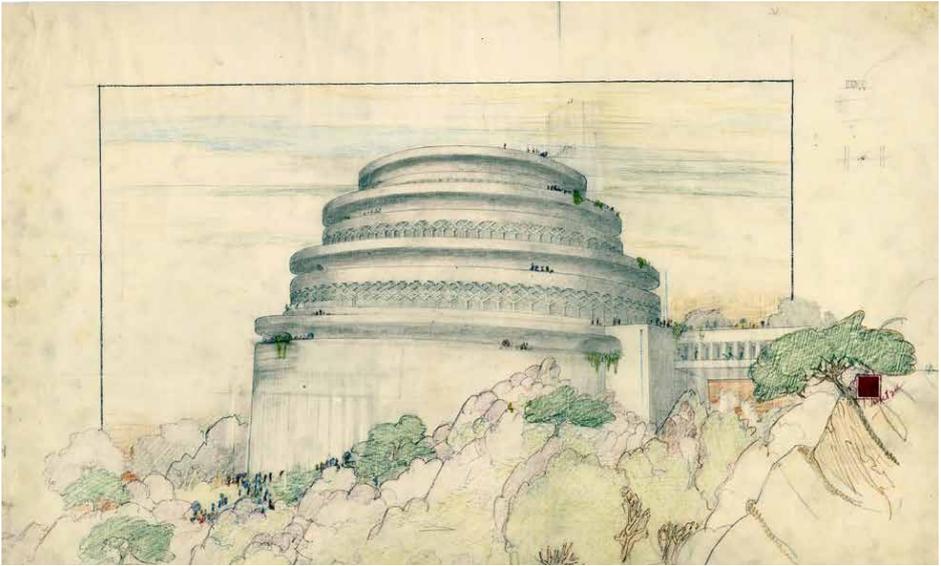


Fig. 3: Frank Lloyd Wright (American, 1867–1959). Gordon Strong Automobile Objective and Planetarium, Sugarloaf Mountain, Maryland. Pencil and colored pencil on tracing paper. © The Frank Lloyd Wright Foundation Archives

(1) Hand-Drawing Era

Origins of architectural drawings

The history of hand-drawn architectural drawings dates far back in history. Architectural drawings are the visual documentation of where architects and builders convey their visions and what needs to be executed. These drawings include information such as dimensions, materials, and orientations. One of the first civilizations with architectural drawing recordings is the Egyptians. These drawings were mostly on papyrus using a reed pen and ink. The Ancient Greeks also have recordings of early architectural drawings with detailed designs for buildings like the Parthenon. They mostly used wax tablets to create sketches and transferred these sketches to parchment paper. One of the biggest developments in the history of architectural drawings was Roman architect Vitruvius' architectural guidebook "De Architectura." The book included comprehensive details about building techniques, materials, etc.

Hand-drawn architectural drawings improved significantly more during the Middle Ages. To make

the concept come to reality, the intricate and detailed designs of Gothic buildings required precise drawings. Cathedrals and other Gothic buildings were meticulously sketched by architects like Villard de Honnecourt and Guido da Vigevano—these sketches, which were frequently created on parchment paper and were intended to be portable.

Architectural prints increased significantly during the Renaissance. A thorough set of architectural designs by the Italian architect Andrea Palladio were printed and widely dispersed. A printing press was used to reproduce these drawings, which were first drawn with ink on paper. This technology allowed architects to share their plans with others and allowed builders to use those plans to build structures. Architectural printing technology made great advancements throughout the Industrial Revolution. With the invention of lithography, architects could create large-scale prints with great speed and accuracy. Lithography made it feasible to create prints on a range of materials, including stone, metal, and fabric. This made it simpler for builders to carry out the designs by enabling architects to prepare comprehensive blueprints on a greater scale.



Fig. 4: General Motors engineers in 1956, before AutoCAD

Life before CAD

Keeping in mind the large historical background of architectural drawings, let's take a closer look at the closer history. Before computer-aided design programs, architects and engineers were working with quite large equipment and in large groups to complete the drawings of a project. Many types of tools were necessary, including a drawing board, different-grade pencils, erasers, T-squares, set squares, etc. One of the biggest disadvantages of this type of paper-based drawing is that there is no margin for error and no chance of returning after the drawing is put on paper. This meant that a change to the design had to redo the entire drawing.

These hand-based drawings were not only technical drawings but also were seen as a form of art, that is conducted by skilled designers. However, the time and energy-consuming process of this production has opened a space for a change in the practice. The developing technology and the room for an opportunity to create more precise, quick, and beneficial ways of producing architectural drawings led to the change. Hand drawings are still being used by a lot of architects in the design and

drafting phases. The reason for this can be put forward as the idea of flexibility and creativity in the hand-drawing process.

Pros and cons of hand based drawings approach

Hand drawings in architecture did not completely disappear with the development of technology. There are different reasons behind this continuation. Even though the advancing technology created major changes and provided multiple benefits, the process of hand-drawing in practice had and still has its own pros and cons.

Starting with the advantages of hand-based drawings, one of the most prominent is the Artistic Expression. Hand-drawn drawings allow architects to convey their artistic vision and design intent with a unique, personal touch. The drawings have the potential to carry a sense of emotion and creativity that digital productions might lack. Another advantage of hand drawings can be counted as Intuitive Exploration. In the words of well-known Australian Architect Glenn Murcutt, "The hand can discover before the eye sees."

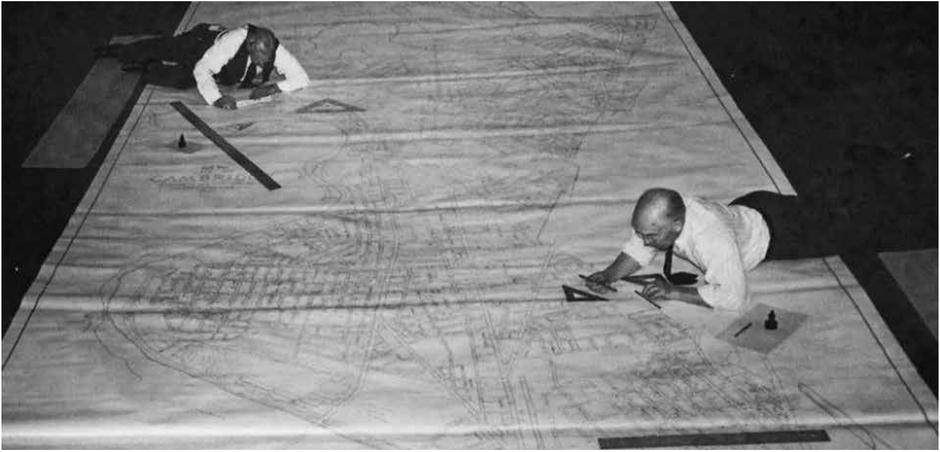


Fig. 5: Urban designers before AutoCAD

Influenced by this statement, it is possible to say that hand sketches can trigger and encourage architects to spontaneous exploration during the work. Hand-drawing production can be seen as Less Intimidating to the clients and stakeholders. They can be more relatable for the ones who might not have the technical expertise and can help bridge the communication gap and convey design concepts in a more approachable manner. Some of the obvious disadvantages of hand-drawing productions have led to improvements in technical drawings with developing technology and digitalization. Being Time-Consuming is one of the most obvious and problematic disadvantages of hand drawings.

Drawing by hand is a slow process, especially for complex projects. Increasing production time with start-overs and collaborations can cause the extension of the project's timeline. Revision Challenges can increase the project's time and can waste the architect's and engineer's work done so far. Drawings on paper do not have a margin for error and no chance of return. Another disadvantage can be counted as Limited Precision. As well as the architect's drawing talents, achieving the same level of precision as digital tools can be challenging. Hand-drawn drawings might lack the accuracy needed for detailed technical plans.

(2) Computer-Aided Design (Cad) Revolution

The rise of CAD software and their implications

The method of creating virtual three-dimensional models and two-dimensional drawings of products using computers and specialized software is known as computer-aided design (CAD). The history of CAD dates back to the 1960s, the studies and innovations in CAD started with the necessity to improve the accuracy and speed of design tasks. The program offers an interactive experience where designs are generated as digital models, replacing the conventional manual drafting process with an automated one. Drawing with accurate measurements and a high level of detail that goes beyond what can be done manually is made possible by CAD software. Designers can visually test a concept before building a real prototype with the use of CAD software, simulating how it will work under various conditions.

CAD software can be categorized as 2D and 3D. Commonly used 2D CAD software can be counted as AutoCAD which is typically used for flat drawings such as plans, sections, or any other two-dimensional productions. Although AutoCAD has also included 3D drawing opportunities, they are not widely used because of the presence of easier and more beneficial software for



Fig. 6: IBM 360/67 – 1967 © Fairchild Camera & Instrument Corporation

three-dimensional productions. For instance SolidWorks or Inventor. The rise of BIM also has a great influence on the improvement of 3D productions with software in architecture. The shift from hand drawings to the use of software brought various advantages to the process of production in architectural practice.

Advantages of CAD in precision and efficiency

Computer-Aided Design (CAD) has revolutionized architectural drawings by offering great advantages in terms of precision and efficiency. Through CAD software, architects can achieve Enhanced Precision that would not be easy to reach with hand drawings. The Consistent Measurements that CAD provides between units during the design process create an advantage while eliminating the potential for errors that can arise from manual conversions. With basic automatized settings, CAD can Minimize Human Errors.

One of CAD's most transformative features is its ability to enable swift and Effortless Iterations. Design modifications can be made and adjusted seamlessly without the need for starting from scratch, saving valuable time and effort. Some of the other advantages can be counted as Better Visualization, Real-Time Alterations, Simulations, and Faster Documentation.



Fig. 7: evolving technology, © ChuanYang Chen

Designers can produce 3D models, which enable them to observe their creations from any angle and make changes in real time. The spatial relationships within the design may be better understood with these 3D models, which also makes it easier to spot any possible problems before they come up during the production stage. In addition, a lot of CAD systems offer simulation environments where the behavior of the planned object may be evaluated and studied. The earlier possible defects or weaknesses are discovered, the more likely it is that the final product will be stronger, necessitating fewer physical prototypes and saving time and resources.

The advantages of CAD can go beyond merely the efficiency and precision of design. It is essential for enhancing accessibility and collaboration, enabling design teams to work more fluidly and creatively. With the growth of CAD, design and production processes are moving toward a future that is more digital, linked, and effective

(3) AI Integration

The development of computer-aided can be related more to technical productions. Meanwhile, increasing and developing potentials of artificial intelligence in the field of design and creativity also has the potential of being effective in architectural practice both in the design



Fig. 8: AI generated Image ©Tim Fu

process and the optimization of data. The development of AI created another and the most recent shift in architecture as well as in many different fields. AI has influenced and helps architectural practice with how buildings are designed, constructed, and operated, offering different and various opportunities for innovation, sustainability, and efficiency.

The ability of AI's optimizations on design processes is one of its major contributions to the field of architecture. AI systems can evaluate a great amount of data and produce design solutions that can satisfy particular requirements by utilizing developed algorithms and machine learning. This makes it possible for architects to investigate a wide range of options, optimizing elements like spatial organization, energy efficiency, structural integrity, and aesthetic appeal. AI-powered tools can help to produce parametric designs, enable architects to swiftly iterate and improve their work, and result in more innovative and optimized solutions. AI architecture can also help architects to improve their creativity by putting forward inspirational examples. With AI technologies, architects can explore new design possibilities, overcome conventional limitations, and push the limits.

AI-powered solutions are not only beneficial during the design stage but also can be very helpful in both construction and occupied phases. They can help to overcome project management, scheduling improvements, and resource allocation effectively. They can also be used to track and assess a building's performance, find development opportunities, and facilitate predictive maintenance.

The ethical considerations of AI use in architecture

As beneficial as AI can be, there are always some ethical considerations about its use, especially in a creative field such as architecture. In a rational sense, AI can provide beneficial solutions and can create efficient, safe, and sustainable processes. Meanwhile, questions start to arise about the distancing relationship of architects with the design process. Using AI as a tool, a trigger of creative impulses, and a beneficial medium to gain information is

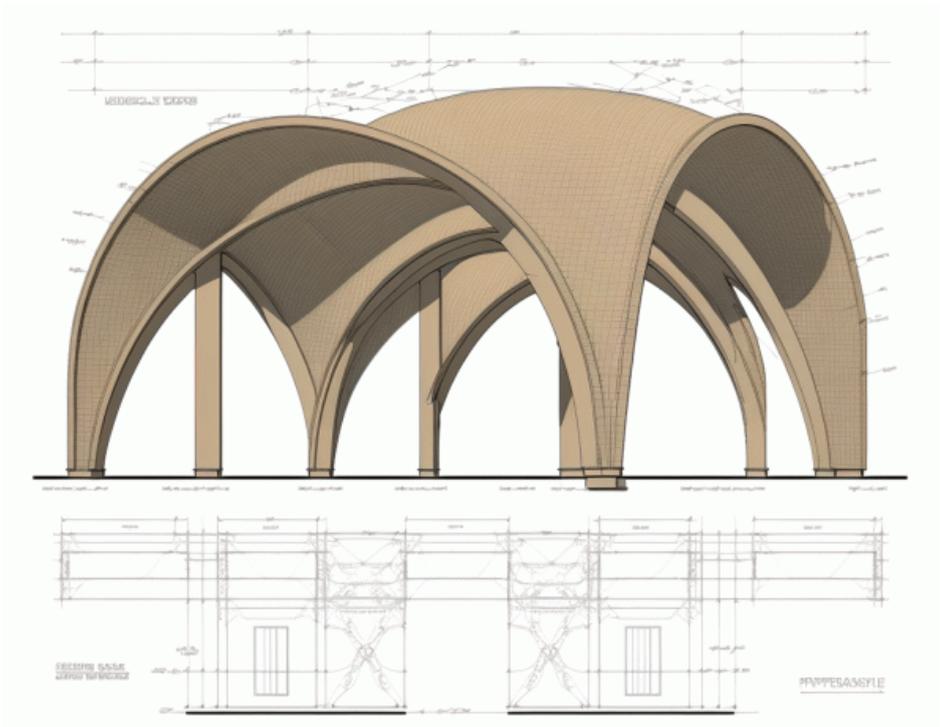


Fig. 9: © Coorlas Architecture

thought to be perfect as long as the architects keep their presence throughout the process to infuse designs with human sensitivity and cultural relevance.

AI can play an important role in simulating and predicting architectural performance. AI-powered simulations offer architects helpful insights to create structures that are environmentally responsible and secure, from energy efficiency analysis to environmental effect evaluation. For example, AI can simulate the building's reactions in different conditions, such as an earthquake, fire, or extreme weather. These simulations help the architect to consider the vulnerabilities. However, the lack of human-centered thinking in AI can create problematic results in the case of occupants' lives.

It mostly depends on how AI is being trained. Therefore, one of the most discussed considerations of AI use is the biased or unreliable views that it can produce.

While the positive effects of AI use in architecture in

the subjects such as efficiency, or sustainability, one of the most discussed questions is: How do we strike the right balance between efficiency-driven designs and the deeply human aspects of architecture? And one of the common ideas is that: While AI can optimize layouts and reduce costs, it might inadvertently overshadow the cultural, social, and emotional significance of architecture. These considerations can lead to the idea that the solution to navigating this ethical challenge is the architect's strong existence throughout the process.

Using AI as a tool, as a collaborator that can help through various challenges, and keeping the human-centric outcomes in mind can help to create balanced and beneficial work between the architect and AI. Without the emphatic view of AI, people would look for a more human approach to architecture. Therefore it is possible to say that AI is the new collaborator of architects in this developing period and not a job displacer at least for now.

PROJECTS

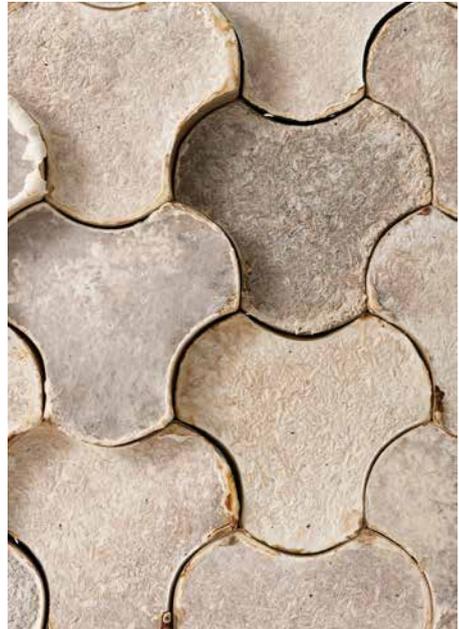
MYCO-LOCK

University of Kassel, Experimental and Digital Design and Construction (EDEK)
Andrea Rossi, Nadja Nolte, Eda Özdemir, Philipp Eversmann, Zoë Kaufmann, Longbiao Shi

Aiming at reducing the CO2 impact associated with interior construction, the prototype presents a model for developing sustainable and circular partition system for office interiors. This combines research on topological interlocking assemblies (TIA), a class of structural systems based on kinematically interlocking elements, with additive manufacturing using bioplastics and biofabrication with mycelium-based composites. Through additive manufacturing, a bioplastic permanent formwork is produced, to be used for the cultivation of

mycelium, a sustainable material derived from the root structure of mushrooms. The presence of wood particles in the printed material ensures that the mycelium would feed on the printed shell and provide a strong bond. Through this combination, it is possible to produce a partition wall prototype consisting of 112 interlocking blocks, where the unique characteristics and variability of mycelium materials are celebrated, while assembly precision is maintained through the printed interfaces.

Photos Credits: Nicolas Werfer



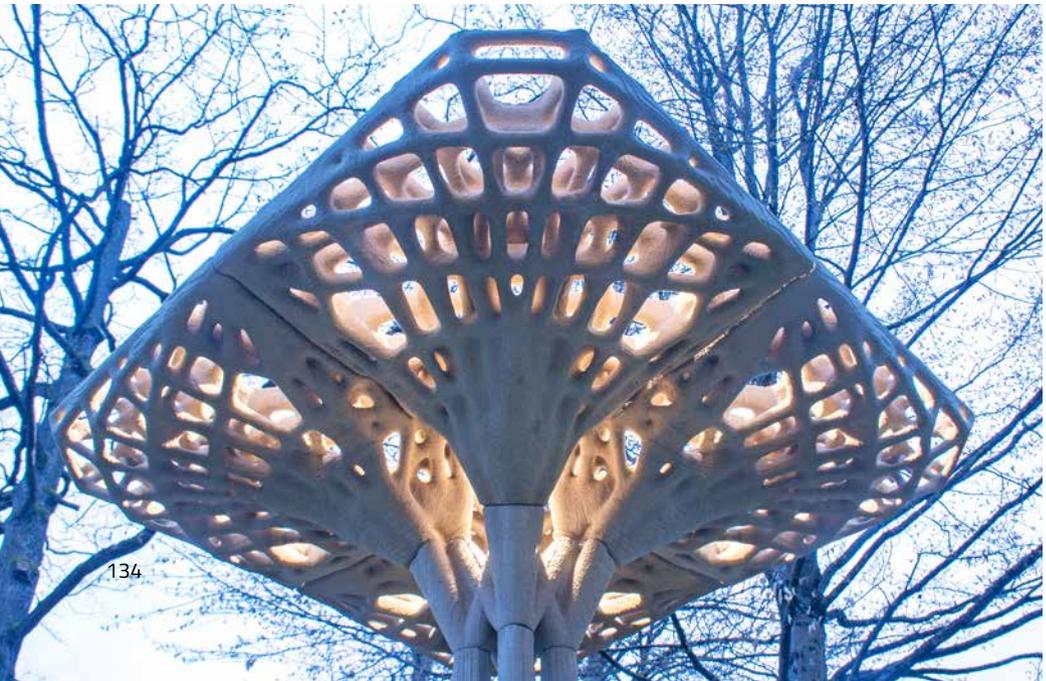


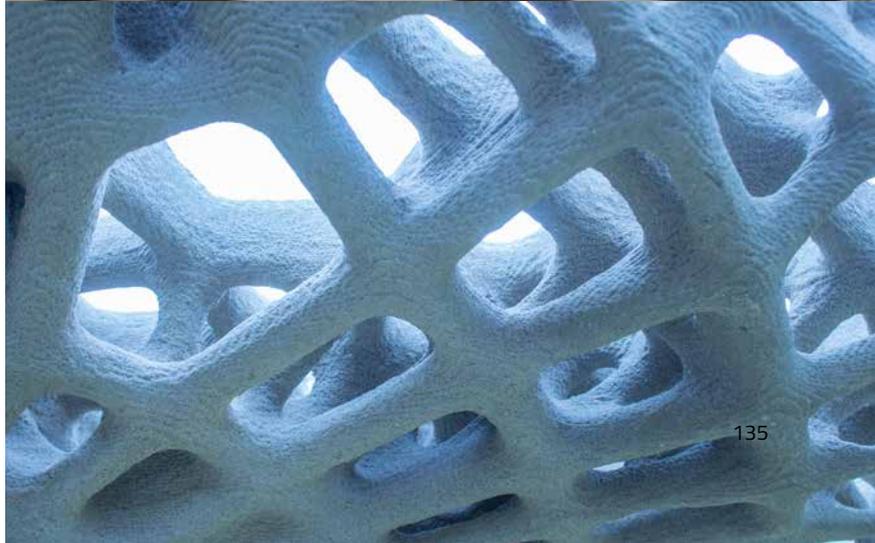
MARINARESSA CORAL TREE

University of Stuttgart, Institute for Lightweight Structures and Conceptual Design
Daria Kovaleva, Maximilian Nistler, Alexander Verl, Lucio Blandini

For the BE-AM 2024 exhibition, a filigree concrete structure and its 3D-printed water-soluble sand formwork are proposed. The concrete structure is a 1:3 scale mock-up of the Marinaressa Coral Tree, an architectural demonstrator designed and built for the Venice Architecture Biennale 2023 by the Institute for Lightweight Structures and Conceptual Design (ILEK) in collaboration with the Institute for Control Engineering of Machine Tools (ISW) from the University of Stuttgart. The mock-up demonstrates the potential of a new production technology developed within a research project investigating the zero-waste production of lightweight concrete structures using a recyclable formwork system. The technology is based on the additive manufacturing of water-soluble sand molds for casting geometrically complex concrete components using a specially

developed mixture of sand and a bio-based dextrin binder. The molds are printed on a specially designed powder bed 3D printer by activating the sand and binder mixture with a water-jetting by a DoD printhead, followed by drying with infrared emitters. The resulting 3D-printed molds withstand the hydrostatic pressure of concrete during casting while being dissolvable in water. This allows concrete components to be easily demolded, and the formwork material recycled in a single production run. The water solubility of formwork also enables a broader spectrum of producible structural typologies, including spatial, multi-scale structures obtained through computational optimization techniques. This facilitates the sustainable realization of resource-efficient concrete structures and can promote the decarbonization of the construction industry.





AM BRIDGE

Technical University of Darmstadt, Institute of Constructive Design and Building Construction
Stefan Schäfer, Nikola Bisevac

The Institute KGBauko is excited to announce the realization of an additively manufactured bridge on the Lichtwiese campus as part of the upcoming semester's course "Constructive Design Project". The span of this unique, entirely robotically manufactured bridge is approximately 6 meters. This collaborative initiative brings together students, industry experts, and cutting-edge technologies to explore and innovate in the field of construction and environmental engineering. Through partnerships with leading companies like Sika and Staikos 3D, we aim to provide students with hands-on experience and valuable insights into real-world applications. The project represents a continuation of the Interdisciplinary Project (IPBU) conducted at Technical

University of Darmstadt in cooperation with the Institutes of Façade Technology and Steel Construction at the Department of Civil and Environmental Engineering. The incorporation of additive manufacturing and robotics into the Constructive Design Project provides students with the opportunity to learn about and apply these technologies in a real project environment. Through collaboration with the participating companies, students also gain insights into current developments and can benefit from the expertise of industrial partners. Thus, the project makes an important contribution to the practical education of students and promotes innovation and technology in the field of construction.





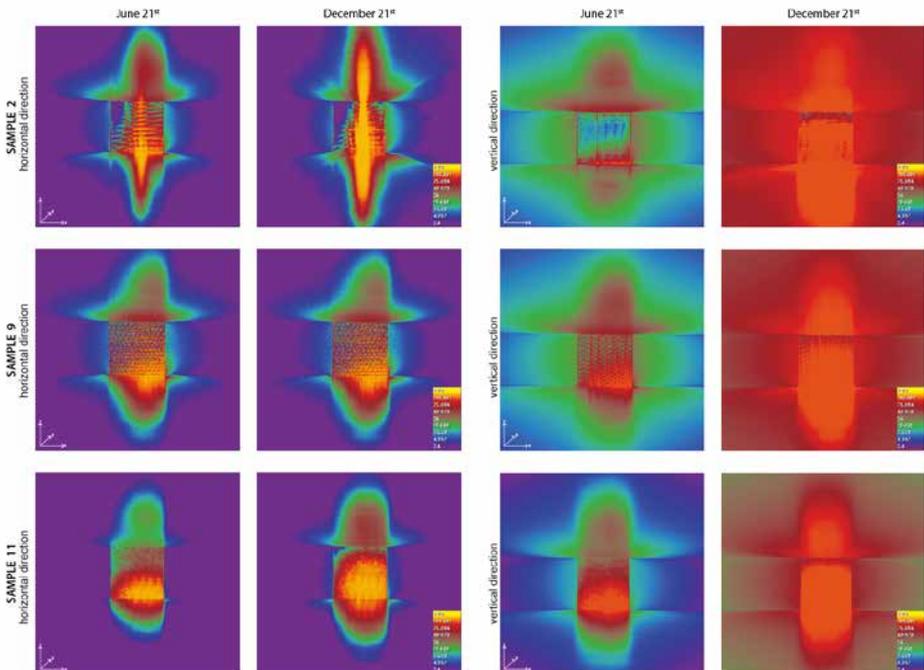
LIGHT DISTRIBUTION IN 3D-PRINTED THERMOPLASTICS

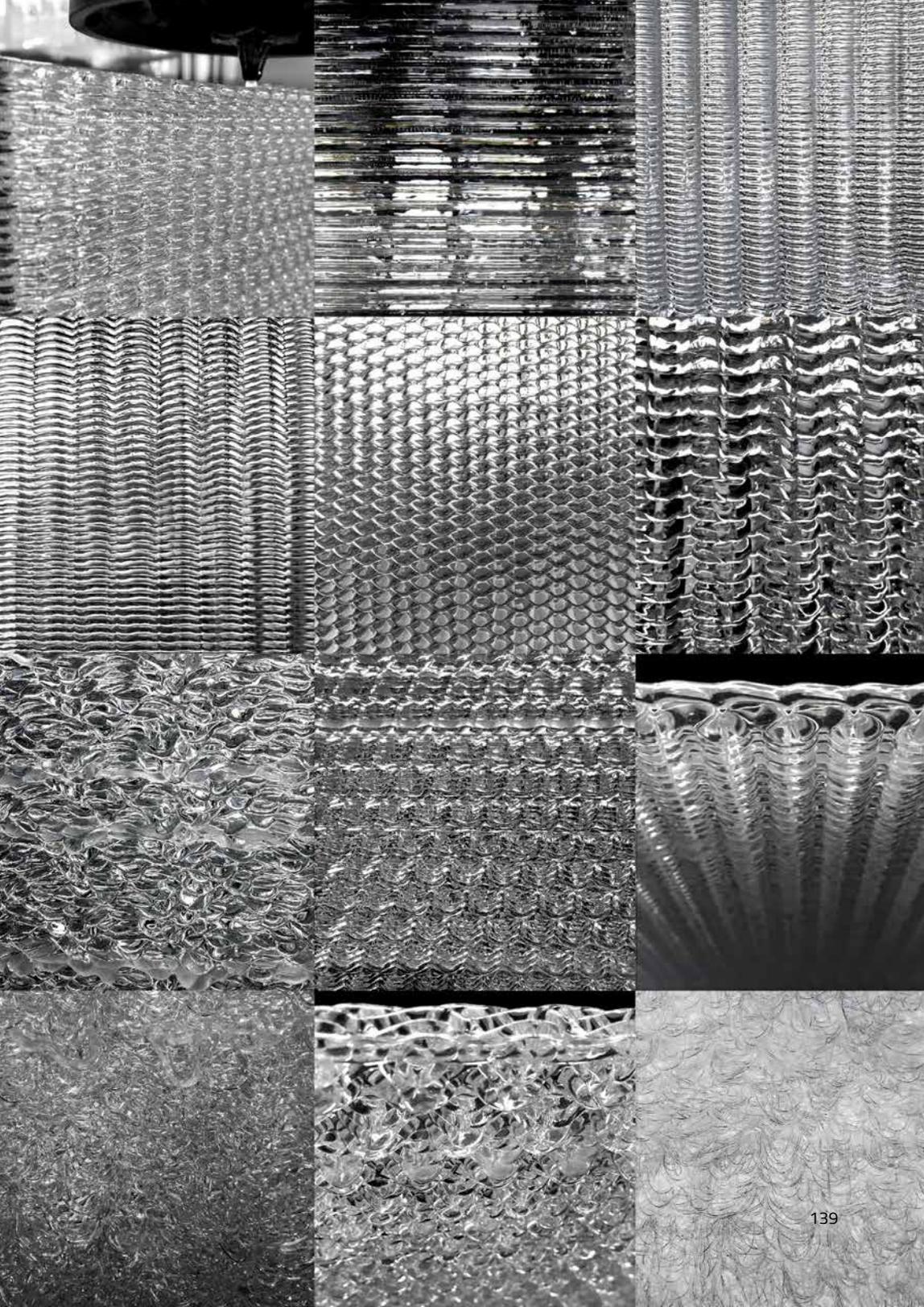
Flemish Institute for Technological Research (VITO)

Ina Cheibas, Valeria Piccioni, Ena Lloret-Fritschi, Matthias Leschok, Arno Schluter, Benjamin Dillenburg, Fabio Gramazio, Matthias Kohler

Daylight distribution is an essential performance parameter for building facades that aim to maximize user comfort while maintaining energy efficiency. These samples display how 3D-printed thermoplastic can bring customized daylight distribution and transmission. Twelve samples with various patterns were robotically fabricated. In a physical simulation of spring, summer, and winter, a robotic arm was used to direct light onto the samples in both the vertical and horizontal print pattern

directions. In addition, three samples of conventional facade materials, including a polycarbonate panel, a polycarbonate sheet, and a single sheet of glass, were compared with the 3D-printed samples. All these samples were examined and compared using high dynamic range imaging to qualitatively characterize luminance. The data analysis demonstrated that 3D-printed geometry can successfully generate customizable diffusive light distribution based on the needs of the user.





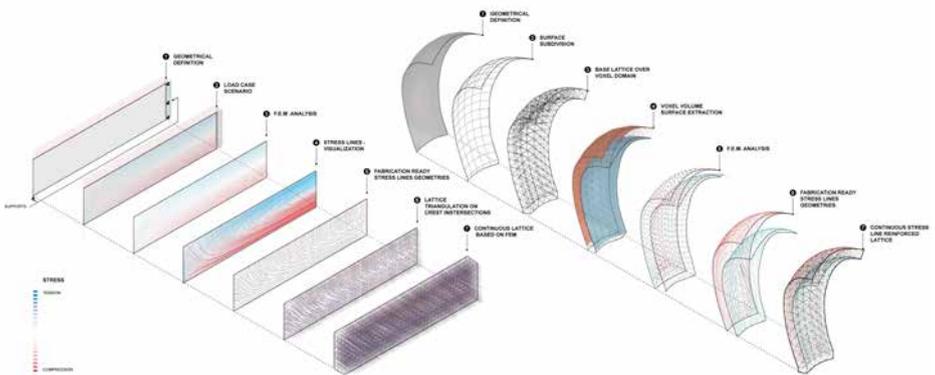
CONTINUOUS COMPOSITE SPATIAL 3D PRINTING

Institute for Advanced Architecture of Catalonia & Swinburne University of Technology, Advanced architecture group

Eduardo Chamorro Martin, Marky Burry, Mathilde Marengo

Additive manufacturing (AM) has been rapidly adopted in architecture, engineering, and construction (AEC) due to the integration of digital fabrication processes and geometric design workflows. However, current AM optimization techniques often overlook mechanical anisotropy, leading to low structural properties by focusing on layer-by-layer or 2D deposition methods. Materials with high anisotropy, as composites have been sparsely researched in 3D printing, despite their potential to improve AM processes. This project investigates the advantages of using continuous fibre additive manufacturing and topology optimization within three-dimensional non-standard lattices to create architectural structures through integrated AM processes. Lightweight, high-performing load-bearing structures can be achieved by employing specific non-standard lattice geometries which maximize structural efficiency and minimize material usage. Unlike conventional CAD/CAM workflows, this research's structural

generation modelling workflow used stress line additive manufacturing theories to create a continuous fibre material deposition intricately woven into a spatial lattice structures. Continuous fibre additive manufacturing (CFAM) technology enables material deposition in mid-air, fostering the creation of aggregated continuous truss-like elements. The research developed a CFAM tool and large-scale prototypes to validate the proposed approach. The prototypes were fabricated using continuous carbon-fibre rovings with a thermopolymer binder and manufactured with robotics arms. The beam structural prototype results in a load-bearing element capable of withstanding 4kn/m^2 of forces weighing less than 4kg . This study illustrates the potential of computational design workflows incorporating continuous fibre AM for structural design and material optimization within AEC, addressing resource and material economy challenges and fostering a globalized design-for-manufacturing culture.





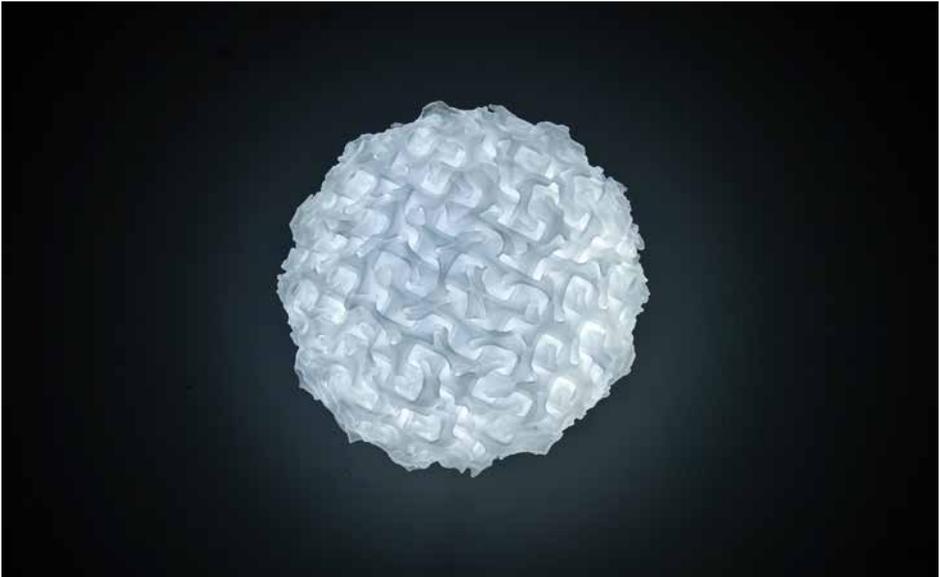
RHODOTUS

Pixolid UG

Pixolid UG, Lilian Van Daal, Zvonko Vugreshek

The Rhodotus is a unique light created with Artificial Intelligence (AI) support from a text input (prompt) and through 3D printing technology. The inspiration behind the design comes from the structure of the mushroom species *Rhodotus Palmatus*, which represents a series of triply periodic minimal surfaces. According to Zvonko Vugreshek, these mathematical models describe repeating patterns in three-dimensional space found in many natural structures. The Rhodotus is the result of a collaboration of Zvonko Vugreshek from Pixolid, a Berlin-based collective for the implementation of generative AI into design and manufacturing processes, and Lilian Van Daal, a Dutch designer who has been experimenting with 3D-printing

technologies and structures to mimic nature meticulously. Her 3D printing technology and materials expertise helped bring this vision to life. The intricate patterns and intertwining surface 3D ornaments that represent the driving element of the design were created using these mathematical models. The result is a functional light object that plays with transparency, complex structures, and light in an aesthetic way. The light is made using state-of-the-art processes which allow us to replicate the complex natural structure, enriching any space it has been placed into. It has been proven that incorporating organic and biomorphic patterns contribute to human well-being and their connection to the natural world.





HEXASTONE PAVILION

Technical University Lübeck, computational methods in Design and Engineering (coDE), Robotic Fabrication Laboratory (RoboLab)

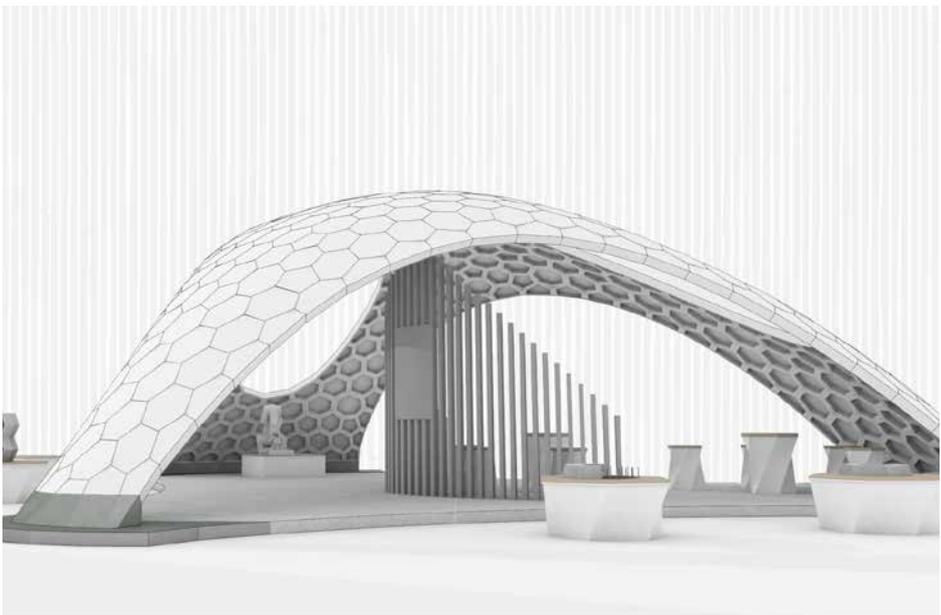
Anton Brodman, Anna Prell, Efstathios Damtsas, Christoph Schult, Benjamin Spaeth, Michael Herrmann

The concept of the Hexastone Pavilion is based on the principle of stereotomy. This construction method aims to realise arches and vaults through the use of carefully cut stones. In this way, any type of reinforcement is avoided, achieving a balance under the forces of gravity. Vaults are constructions composed of individual, wedge-shaped elements that transfer the forces to the supporting structural parts under vertical loads. The hexagon serves as the geometric base element with the construction capability for curvatures on multiple axes.

Historically, vault stones were made from massive stone blocks. Through the approach of more efficient material usage and digital manufacturing, a cross-

section-optimised base element is being developed. The plate at the top forms a shell, which is reinforced by ribs for stiffening. The reinforcement supports the concrete to absorb the occurring loads and reduces surface cracking.

Historically, vault stones are manufactured using a subtractive process, resulting in unusable waste. In additive manufacturing, only the material for the final shape is needed, allowing for cross-section optimisation. Compared to concrete casting, no formwork is necessary, which is particularly advantageous for many individual components. The construction is reusable through dry assembly without binders, enabling it to be assembled and disassembled repeatedly.



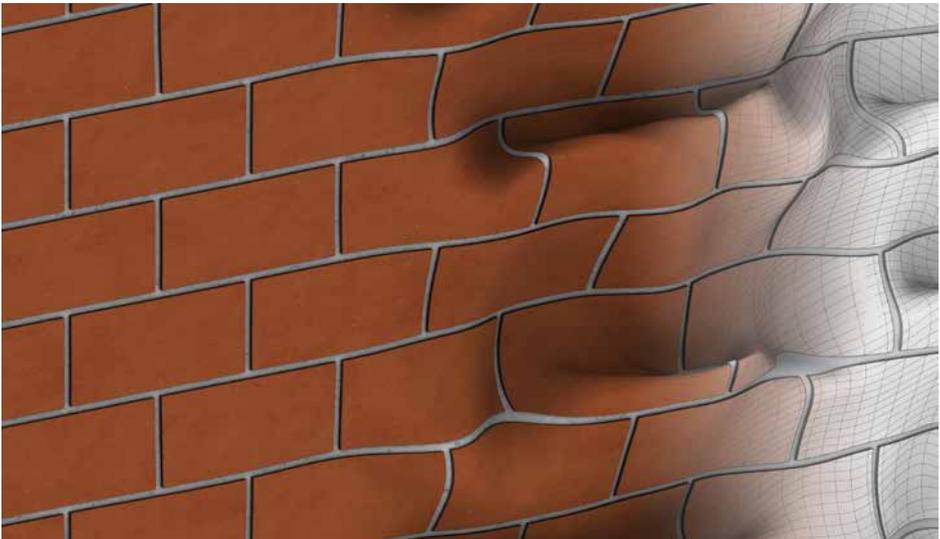


WALLFLOWERWALL

Technical University of Darmstadt, Institute of Structural Mechanics and Design (ISM+D)
Simon Bauer, Alexander Wolf

In contrast to other technologies, the additive manufacturing of ceramics is bound to take place in workshops and factories, as the process of a subsequent firing in a kiln is indispensable to achieve the favoured material properties. Therefore, the application of AM ceramic building components is limited to handy, transportable objects, than rather the in-situ production of full buildings. On the other hand, a vast majority of ceramic components, i.e. bricks or roof tiles, are already producible in high-yield processes like extrusion. To compete with such output-rates, adding distinct features appears as the only justification to produce such components through 3D printing.

While previous projects in this field put an emphasis on unique design solutions by exploiting the processes' geometrical freedom, this research aimed to add value by enhancing the functionality of such constructions. To achieve this, a generatively designed wall was equipped with undemanding crops like mosses and wallflowers to serve as a low-maintenance greened façade. Its contemporary, undulating design provides grooves filled with nutrient soil for the plants to grow in, expecting fast accrual. The bricks additionally manufactured using this methodology are compatible to widely used masonry sizes and bonds, enabling an inclusion of greened areas in common double-shell masonry constructions.





CONTEMPORARY CERAMIC COLUMN

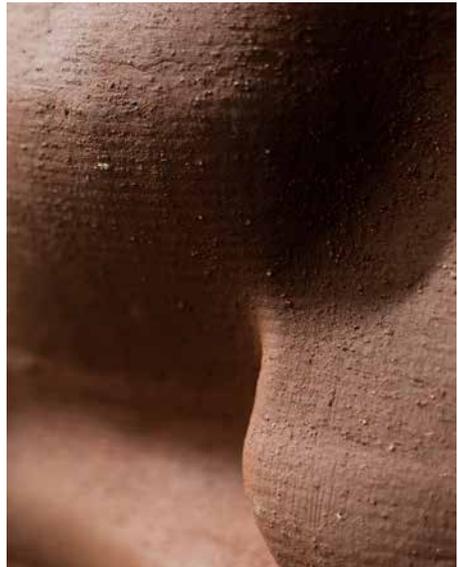
Technical University of Darmstadt, Institute of Structural Mechanics and Design (ISM+D)
Alexander Wolf

When AM is used in order to fabricate design-driven geometries, the process-inherent layered appearance is often accepted as a process characteristic or even presented as a design-feature. In some cases, this is even exaggerated to produce an even more articulated design by creating surfaces with undulating layers or protruding loops.

Contemporary Ceramic Column approaches this issue from the opposite side. By evaluating several strategies to post-process a geometry printed from clay and fired into ceramics, a comparative set of measures to flushly include AM ceramic surfaces into conventional systems is presented. By this, it is envisioned to enable the industry to provide ceramic building systems mainly

consisting of commonly produced elements, which may be complemented by AM-components, whenever there is a need for more geometric freedom or the addition of functionalities, which are not producible the common way.

Each of the column's segments displays a different strategy to smooth the appearance of a printed component, enabling a direct comparison in its vertical direction. Further, an untreated segment is included to showcase the benefits of the researched processes. The respective segments feature a planar, a tessellated and an undulating NURBS-surface, representing contemporary ornamental aesthetics, as often found in digitally created designs.





BIOPOLYMER PAVILION

Technical University Lübeck, computational methods in Design and Engineering (coDE), Robotic Fabrication Laboratory (RoboLab)

Anton Brodmann, Anna Prell, Efstathios Damtsas, Christoph Schult, Benjamin Spaeth, Michael Herrmann

Productivity development and resource scarcity are among the most important topics in the construction sector. Through digitalisation and new construction processes, the construction sector aims to advance and increase productivity growth. Guided by the aspects of sustainability, modularity, and flexibility, a construction system has been developed that enables the realisation of freeform geometries with additively manufactured biopolymer segments. The sustainable certified material, which has a 50% lower CO2 footprint compared to petroleum-based polymers, forms the elements of the pavilion. The concept follows an approach of simple, quick, and

reversible assembly by horizontally and vertically connecting the segments. The demonstrator consists of two parts. One part is the double-curved freeform geometry with overhangs, demonstrating the system's flexibility in processing complex shapes by dividing them into different segments. The other part consists of single-curved surfaces made only of identical elements, demonstrating the modularity of the system. The project explores the possibilities and limitations that large-scale additive manufacturing (LSAM) of recyclable biopolymers offers. Through the flexible application range of the segment form, new spaces, structures, and facades can be created.





TOR ALVA

ETH Zurich, Digital Building Technologies, D-Arch
Ana Anton, Che Wei Lin, Michael Hansmeyer, Benjamin Dillenburger

Project Credits:
Nova Fundaziun Origen

ETH ZÜRICH

Architektur
Prof. Dr. Benjamin Dillenburger, Digital Building Technologies (DBT)
Michael Hansmeyer

Baustoffe und Tragwerk
Prof. Dr. Walter Kaufmann, Institut für Baustatik u. Konstruktion (CSBD)
Prof. Dr. Robert Flatt, Institut für Baustoffe (PCBM)

Supported by:
NCCR Digital Fabrication
Partnership Council for Sustainable Construction
ETH Foundation

Industry Partners:
Conzett Bronzini Partner AG - Structural Design
Zindel United - General Contractor
MESH – Rebar
Saeki – 3D Printed formworks

Tor Alva, the tallest 3D-printed modular tower with load-bearing, fully reinforced printed concrete, showcases a scalable building system. Architectural-scale 3D concrete printing typically involves non-structural, low-resolution formwork for conventional structures. In contrast with the state of the art, Tor Alva demonstrates the possibilities of digital construction technology to revolutionize long-term the building industry. The tower uses less resources: the digital printing process reduces material and does not require formwork. The modular

design allows for easy assembly and quick dismantling. In Tor Alva, the printed concrete is used for the first time as load-bearing, and the necessary reinforcement is inserted in the robotic production process, which is a significant milestone in the development of 3D concrete printing. To ensure structural strength of the thin 50 mm shells, the 3D-printed columns are reinforced horizontally and vertically with reinforcing steel. All project data is stored in a digital twin, enabling the coordination, simulation, evaluation, and construction without conventional plans.

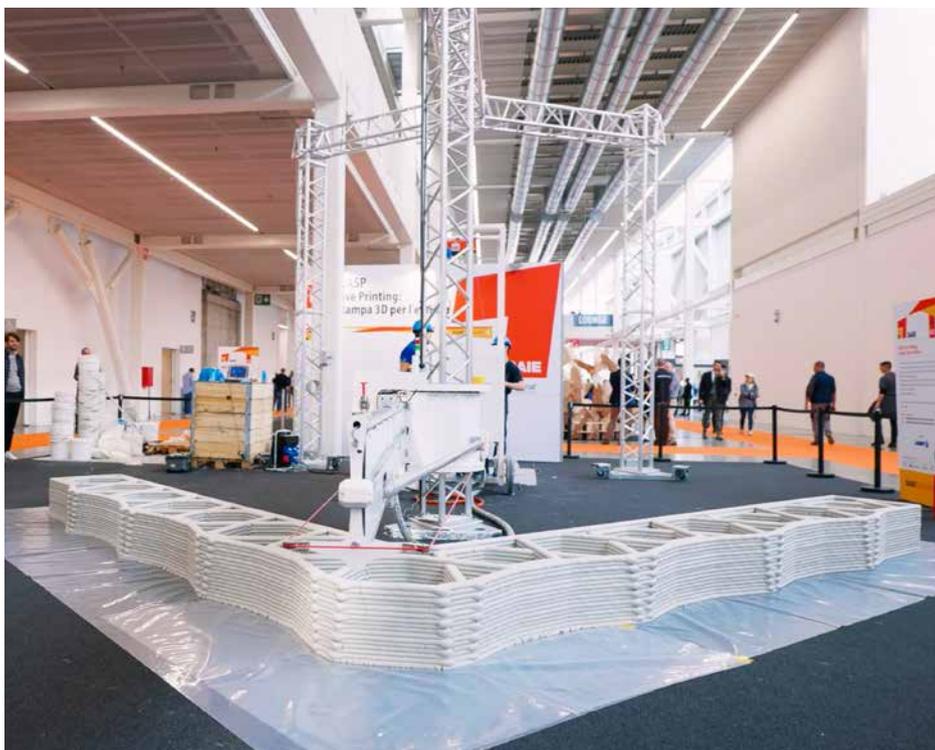


ITACA

WASP Srl
WASP TEAM

Since its inception ten years ago, WASP's goal has been to provide a Home as a birthright for every human being while respecting the environment around us. The ITACA project represents the achievement of this objective. A low impact self-sufficient house that combines knowledge from the past and innovative technologies to provide sustenance for a group of people working together to live in harmony with the planet. ITACA constitutes

the first prototype of a model that is expandable and adaptable to different geographical and social contexts. The construction of the building will take place thanks to Crane WASP, the architectural printer developed by WASP, already the protagonist of several internationally renowned projects, including the experimental TECLA project in collaboration with Mario Cucinella, and the two Dior pop-up stores currently operating in Dubai.





WILLOWWEAVE

Karlsruhe Institute of Technology (KIT), Professorship Digital Design and Fabrication (DDF)
Moritz Dörstelmann, Daniel Fischer, Fanny Kranz, Vincent Witt, Erik Zanetti, Eszter Olah

The presented prototypes showcase the development of an additive digital prefabrication process for structural willow-earth hybrid building components. The work emerged from research-oriented teaching and was subsequently tested in a series of 1:1 scale research demonstrator projects culminating in certified and application ready additively prefabricated earth-willow-wood hybrid ceiling components. The underlying digital prefabrication technology emerged from a series of research projects conducted in interdisciplinary cooperations at the Karlsruhe Institute of Technology (KIT) which pioneer willow reinforced clay as a natural composite of clay as compression bearing infinitely recyclable material in synergy with willow as fast regrowing tension reinforcement for structural building components. Its application as horizontally spanning ceiling component expands the traditional compression-based design and construction

repertoire of earth structures and allows for a scalable and societally relevant contribution towards a digitally enabled sustainable transformation of the construction industry by expanding and diversifying the range of regrowing and recyclable building materials through digital design and fabrication methods. An additive three-stage digital prefabrication system was custom developed for low emissions, waste free and fully circular construction with inhomogeneously grown materials through adaptive digital prefabrication. First, the machine splices individual willow twigs and jute yarn into a continuous „macrofiber” which is in a second step additively deposited into a three-dimensional willow rebar basket by a custom developed two-axis extruder and subsequently filled with a clay mixture by a modified plastering machine, additively pressing the clay into the spaces between the willow structure.





EPHECELIUM

The Bartlett School of Architecture, University College London (UCL), Bio-Integrated Design Lab
Natalia Piórecka, Rita Morais, Jennifer Levy

Ephecelium redefines sustainable architecture with its robotically 3D-printed, cellulose-based envelope designed to support mycelium growth. This innovative approach combines the precision of 3D printing with the stability and porosity of organic fibres, creating a semi-sacrificial shell that fosters growth and responds dynamically to environmental conditions. Given the construction industry's significant environmental impact, there is a need to reconsider materials. Mycelium, known for its closed-loop biomaterial production, offers a sustainable solution. Ephecelium leverages the fibrous porosity of wood PLA to integrate mycelium-based composites, overcoming the constraints of direct mycelium printing. This novel technique paves the way for biohybrid structures that

are both architecturally significant and ecologically integrated. The prototype, printed with a wood filament high in cellulose fibre content, nurtures mycelium growth within a semi-sacrificial shell. This method maintains the precision of 3D printing while providing stability through the PLA content, eliminating contamination risks as opposed to cold extrusion of mycelium paste. Designed with Swarm Intelligence algorithms, the structure responds to environmental factors such as wind flow and rainfall, optimizing moisture regulation for mycelium proliferation. By exploring various cellulose sacrificial molds, Ephecelium advances sustainable manufacturing techniques, creating a biohybrid multi-materiality that aligns with nature's logic in material distribution and ecosystem integration.





AXISYMMETRIC COLUMN NO. 1

University of Virginia, School of Architecture
Ehsan Baharlou

Axisymmetric Column No. 1 exemplifies a novel approach to large-scale robotic additive manufacturing, utilizing curved-layer fused filament fabrication (CLFFF) on a pre-stretched textile. It explores how patterning affects CLFFF printing to develop a lightweight hybrid shell structure. The cross-ply $[0^\circ/90^\circ]$ and quasi-isotropic $[0^\circ/60^\circ/90^\circ]$ patterns, inspired by composite engineering, enhance the mechanical properties of SCF-PLA. The final unit, including the shell structure and the base, has a height of 2300mm with a span of 900mm, and is reinforced by 10 kg of SCF-PLA pellets. The developed

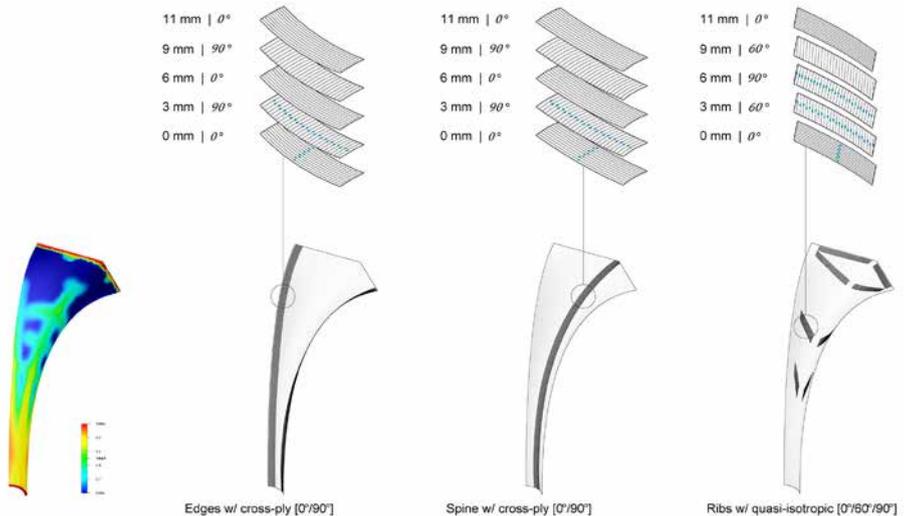
nonplanar robotic 3D printing technique was applied in reinforcing an individual axisymmetric column, which is one column out of three-column vault structure.

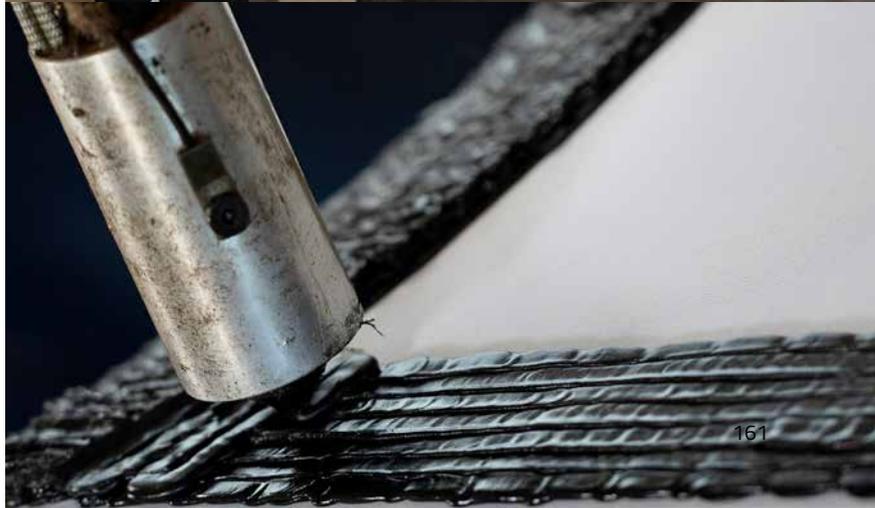
| Place/Date: University of Virginia, 2023

| Dimensions: 2300mm high, 900mm span

| Material: Short Carbon Fiber-reinforced Polylactic Acid (SCF-PLA), Flexible Textile Formwork, E-glass Fabric and Epoxy Resin

| Project student research assistants: Avery Edson, Juliana Jackson, Eli Sobel, and Tabi Summers



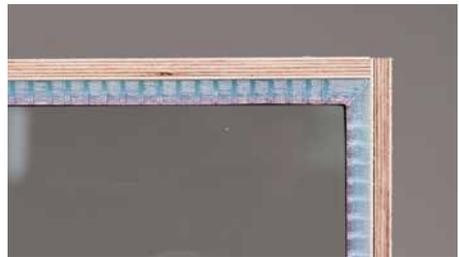


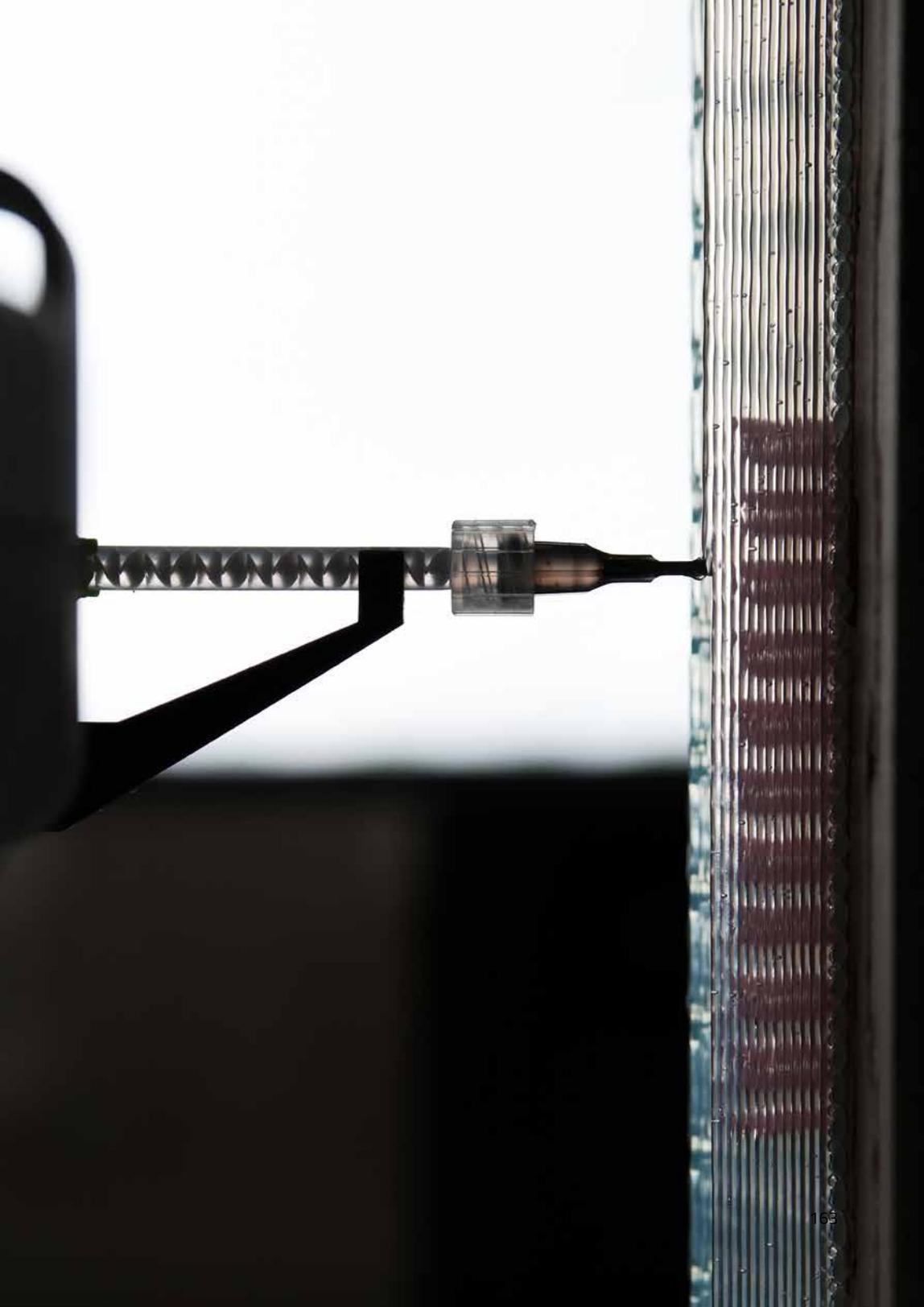
IN-PLACE 3D-PRINTING

FH Muenster, Architecture - Department for digital design and construction
Adam Pajonk

In-place 3D-Printing introduces a novel method for integrating additive manufacturing into building construction. Building upon prior research in additive manufacturing with varying material properties of thermosetting reactive polymer, this project utilizes this process within a construction environment. By using the thermoset reactive polymers polyurethane, this approach enables robotic additive manufacturing without the need for a specific build chamber or plate. Furthermore, the adhesive properties of the polyurethane allow for adhesive bonding to underlying surfaces. Additionally, the flexibility provided by a 6-axis robotic arm enables 3D-printing on complex or non-horizontal surfaces. A fixed glass window frame serves as a case study to test and demonstrate the capabilities of this process.

Therefore, the in-place 3D-Printing approach was embedded in a workflow, starting with the digitalization of the window reveal and the collection of essential data, such as the dimensions and positioning of the insulated glass unit. This data forms the initial parameters for the parametric design of the window frame geometry, and the following fabrication data for the 3D-print. This seamless digital construction approach allows for the integration of printed elements within existing architectural components, streamlining the construction process and its supply chain by effectively combining manufacturing and installation of a building component. The proposed prototype for the BE-AM 2024 exhibition is a full-scale fixed glass window frame with an insulated glass unit installed, 3D-printed in-place using additive manufacturing with varying material properties.





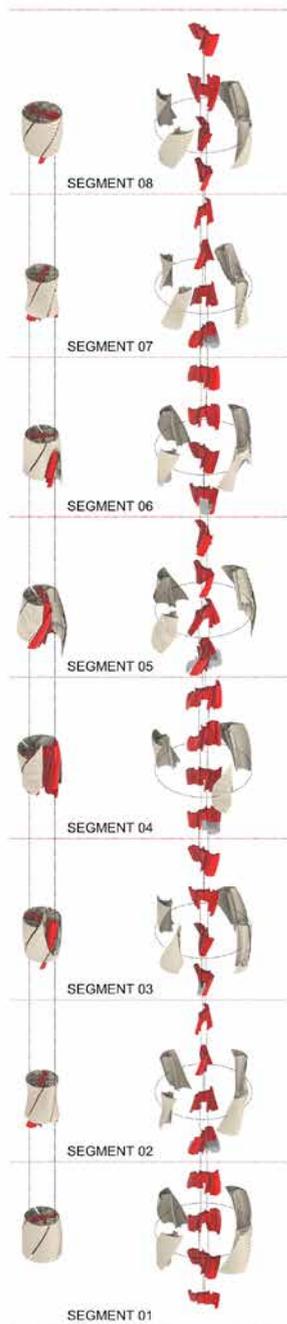
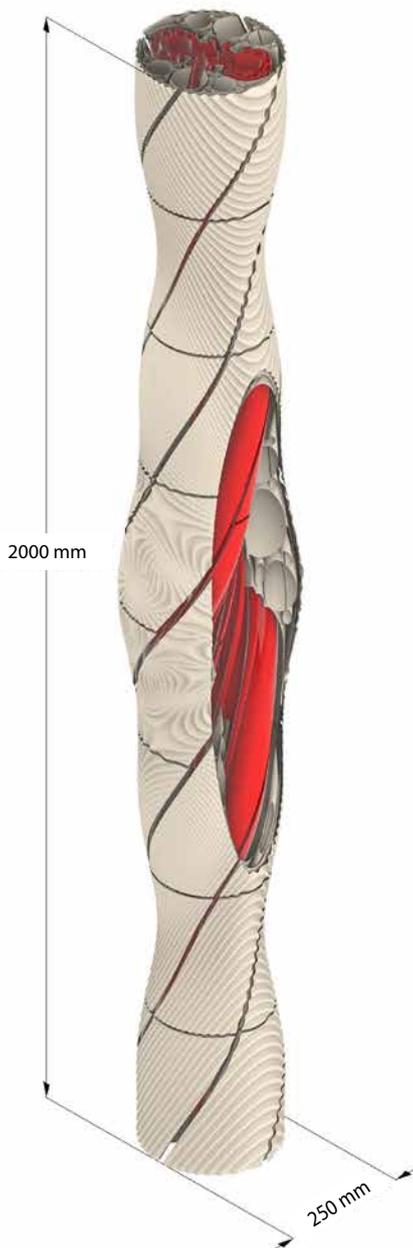
3D CONCRETE PRINTED INTERLOCKING COLUMN

Eindhoven University of Technology, Department of the Built Environment
Cristina Nan, Mattia Zucco, Vertico (company) & Lanxess (company)

This project presents a different conceptual approach and robotic fabrication strategy for additive manufacturing showcased through a fundamental architectural element, the column. The Interlocking Column is treated as double system made out of core and skin, both fabricated with 3D concrete printing. The underlying principle is the spatial self-interlocking of the two subsystems, core and skin, thus eliminating the need for a substructure or fastening. A particular emphasis is placed on the infill beyond its stabilizing function. Expressive and ornamental value is not only assigned to the skin but also translated to the infill. Based on a conceptual strategy of unwinding, the infill is punctually exposed, showcasing it to the viewer and amplifying the ornamental aesthetic and digital materiality of the computational design strategy and robotic fabrication

logic. By exposing the core with its self-interlocking system, the tectonic expressiveness of the column as an architectural archetype is amplified. The research discusses the computational workflows, material experimentation, the interlocking and assembly logic, fabrication strategy as well as the concepts of digital craft and digital materiality. Additionally, the column is printed with an embedded gradient pigmentation. The applied methodology is based on research-through-design. No prioritization is given to form over material and process of production. The knowledge derived from analog and robotic material experimentation as well as concrete's specific material behavior relating to drying, shrinkage and warping are used to inform the design, production sequence and fabrication logic. Concrete column is currently in production.





REGROW

FibR GmbH

Moritz Dörstelmann, Julian Fial

The presented prototypes showcase recent developments of coreless robotic filament winding as an additive fabrication method for fast regrowing flax fibers, combining the material efficiency of load adapted spatial arrangement of anisotropic fiber composite materials with the utilization of fast regrowing resources for architectural load bearing structures. Coreless robotic filament winding for architectural lightweight structures was explored through a series of research demonstrators at the University of Stuttgart starting from 2011 and commercialized at industrial scale since 2017 through the foundation of FibR GmbH as robotic construction company. FibR enables the exploration of a novel design and construction repertoire for resource efficient architectural load bearing structures, facades, and interiors using computational design and robotic fabrication methods. Robotic filament winding allows for an additive placement of complex spatial

fiber structures, enabling societal relevant solutions for resource efficient manufacturing and architectural construction through load adaptive and waste free material usage. The process, initially developed for a wide range of technical materials to realize expressive luminous glass fiber structures, high-performance carbon components and non-flammable basalt fiber reinforced structures, has recently been adopted for sustainable and material efficient building components reinforced with natural fibers. Leveraging adaptive online control of computational fabrication enables to process naturally grown fibers in an automated process at industrial scale. The presented prototypes showcase the fully weather exposed and safety relevant application of robotically fabricated flax fiber biocomposite components as a certified permanent bridge handrail in Almere, Netherlands as well as a façade substructure developed for point held glass facades.



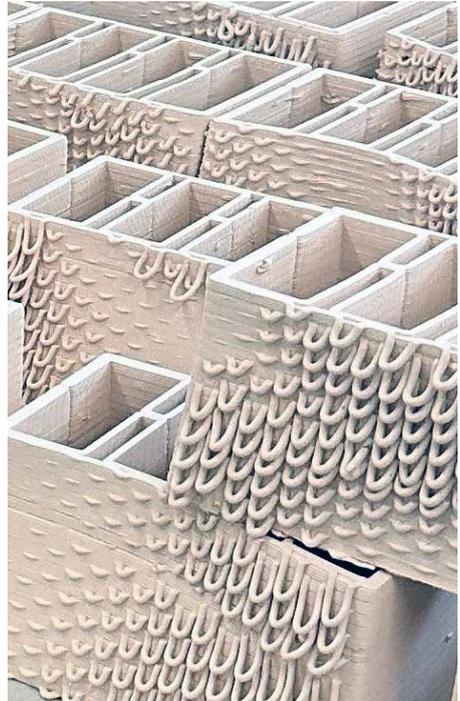
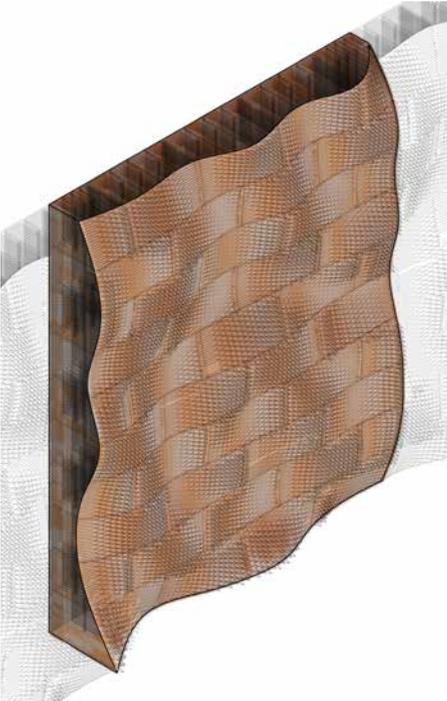


ENTANGLED ENCLOSURE

Washington University in St. Louis, College of Architecture
Kelley Van Dyck Murphy

In Entangled Enclosure, clay bodies in various textures and colors from different regions throughout the United States were manually loaded into the printer and extruded layer by layer to form bricks. Through the clay deposition process, the Potterbot became co-author, defining the final composition of the column. The undulating printing path produced differentiated textural loops and color gradients within the entwined layers of clay, suggesting the unseen subsurface conditions of the earth. The prototype wall utilizes textural loops and the natural porosity of terracotta as a means to sustain plant life.

“Pockets” for roots and soil are scattered throughout the wall, and textile-like loops cover the brick face, entangling exposed roots and securing them to the wall. The bricks were formed by the creation of a single printing path (a line) that oscillated between straight and undulating on the exterior and shaped the interior cellular structure. This code produced differentiated fields of depth similar to the soil and mineral patterns common to a boring. The fields of depth create a woven texture, weighted by gravity, reminiscent of a loosely knitted textile.





IBEX PROJECT

Erratic, R&D
Massimo Visonà

We are excited to introduce a novel approach to single-wall 3D printing using fluid-dense materials like clay, lime, and cementitious mortars. For this first prototype we are using our proprietary technology that features a custom Feeder and Extruder operated by a KUKA robot, allowing us to print a uniquely formulated natural lime mortar that blends Italian tradition with modern innovation. The printing process involves layering the mortar on a 70-degree surface, which supports the material as it hardens. We also integrate a plastering mesh to improve adhesion between the mortar and the wooden substrate. The panels produced, weighing approximately 20kg, are lightweight and easy to handle for installation. It measures 57x84x6 cm, with an extrusion width of 20 mm, and was printed in just 45

minutes. This innovative method is especially beneficial for 3D printing wall coverings, as traditional techniques typically involve printing self-sustaining structures that result in thick and heavy coverings. Our lightweight approach reduces wall covering thickness and preserves indoor space, effectively addressing the challenges of renovations focused on maximizing interior space and minimizing floor loads. Moreover, our technique is also ideal for creating ventilated walls or green façades by designing the printed structures to incorporate plants. This not only enhances the aesthetic appeal of buildings but also promotes environmental sustainability. We believe our approach marks a significant advancement in 3D printing for architectural applications, providing innovative solutions to modern construction challenges.





ratio

WILLOWPRINT - BIODEGRADABLE 3D PRINTING FROM WOOD WASTE

Willowprint / RWTH Aachen University
Federico Garrido, Joost Meyer

Willowprint is a spinoff startup from RWTH Aachen dedicated to sustainable innovation in manufacturing. Our focus is on creating eco-friendly products using advanced technologies and circular materials. An example of our efforts is the Willowprint Chair Collection, a series of algorithmically designed chairs that highlight the potential of sustainable design and production. The Willowprint Chair Collection exemplifies our commitment to sustainability. These chairs are 3D printed using Willowpaste, a sustainable and circular material. Willowpaste is central in our process, it is composed primarily of wood flour sourced from industry waste and fast-growing trees from certified forests. One of the key advantages of Willowpaste is its biodegradability and recyclability. Unlike traditional 3D printing materials, which often rely on resins, cement or non-renewable plastics, our material can be re-ground and reused

or composted at the end of a product's lifecycle. This ensures that products made with Willowpaste contribute to a closed-loop system, reducing environmental impact and waste generation. Willowpaste's local sourcing and production approach also enhance its sustainability. By using wood waste and fast-growing trees from nearby sources, Willowprint reduces transportation emissions and supports regional economies, promoting sustainable resource management. The goal of Willowprint is to revolutionize manufacturing by producing eco-friendly objects, furniture, and, in the near future, entire houses. We aim to merge sustainability with advanced 3D printing technologies to minimize waste, utilize renewable materials, and promote sustainable resource management. We seek to set new standards for environmentally conscious production and inspire broader adoption of sustainable practices in the industry.



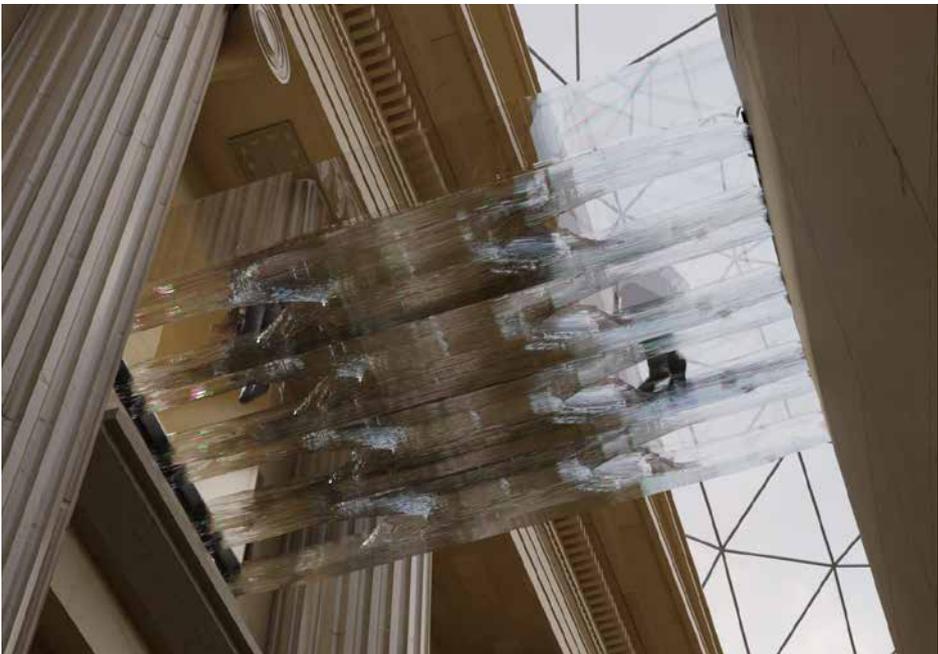


TO3DPGS - THE FUTURE OF GLASS, DEVELOPMENT OF AN ALGORITHM FOR TOPOLOGY OPTIMIZED 3DP GLASS STRUCTURE

TU-Delft, Building Technology
Pim Brueren

This thesis investigates the use of topology optimization for large-scale glass structures in architecture, focusing on overcoming the limitations of traditional casting methods by utilizing 3D printed glass. Previous studies highlighted the lack of transparency in topology-optimized cast glass, prompting this research to explore the unique properties and manufacturing techniques of 3D printed glass. The study addresses challenges such as the brittle nature of glass and differences in tensile and compressive strengths. A thorough literature review underpins the research, examining glass properties, manufacturing techniques,

and topology optimization principles. The study advances the SIMP methodology, adapting it to 3D printed glass constraints like overhangs, path continuity, and nozzle size. Specific adjustments include layer-to-layer overhang filters and advanced computing techniques for path control. The implementation details and testing within a predefined design domain validate the proposed solutions, leading to the selection of a feasible design for 3D printing. The results emphasize the need for further research, especially on the anisotropy of glass layers. Two physical glass models were produced through casting and waterjet cutting.





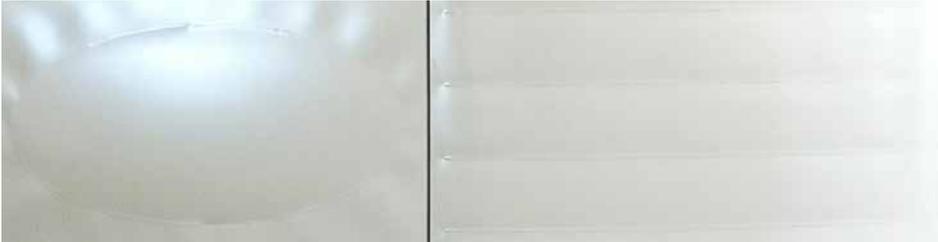
FORMLIGHT

TU Darmstadt, Institute of Structural Mechanics and Design (ISM+D)

Juan Ojeda, Ulrich Knaack, Philipp Rosendahl, Jörg Lange, Philipp Grebner, Jochen Hölscher, Martin Manegold

The use of freeform sheet metal panels in architectural facades is a growing trend that impacts both building technology and aesthetics. However, these panels are often handmade, costly, and require high thicknesses due to structural demands. To overcome these challenges, architects and engineers are using digital fabrication as a mean to integrate aesthetics, strength, sustainability, and circularity into building processes. Wire Arc Additive Manufacturing (WAAM) is a cost-

effective metal 3D printing process that enables to produce unique components efficiently, reducing material waste and manufacturing time, providing design flexibility and productivity advantages. The presented panel is the result of an innovative workflow that combines robotic fabrication, depth cameras, computer vision and WAAM, to scan, analyze, shape, and stiffen thin steel sheets for free-form facades.





3D-PRINTED EARTH-FIBER PATTERNS INSPIRED BY TRADITIONAL BASKETRY

GSAPP Columbia University, Natural materials Lab
Lola Ben-Alon, Olga Beatrice Carcassi

This research explores earth-fiber composites in textures resembling rope- or yarn-like aesthetics that echo traditional basketry elements. It incorporates weaving techniques for locally sourced clay-rich soils and natural plant fibers of grain, bast, and leaf origins, such as straw, banana, kenaf, and hemp. Integrating digital fabrication with traditional weaving, this work asks us to reimagine ancient materials to foster a deeper connection between constructed forms and our relationship with earth. The methodology embarked in this research includes three steps: (1) Developing and testing the printability of natural mix-designs that are rich in plant fibers for reinforcement within a clay-biopolymer paste; (2) Characterizing the processing parameters for each

successful mix-design in terms of nozzle size, layer height, extrusion and flow rate, and clogging prevention; and (3) Examining a range of basketry typologies for surface curvature threshold (vertical, convex, and concave profiles) and contour craft demonstrations as final texture results. The final appearance of the textures generated in this work was shown to be affected not only by the angle accentuation, curvature used, and layer and nozzle size but also by the type of material recipe used. Baskets printed with "light straw clay" mixtures exhibited better resolution and precision given their shorter fiber lengths. The resulting artifacts showcase novel fusions of material surface patterns crafted through line deposition, embodying traditional inspirations in sustainable digital design.

	CONTOUR	GEOMETRY	FINAL RESULT	TEXTURE	PARAMETERS	
CONVEX PROFILE	#CX1					E: 40% F: 150% NS: 6mm LH: 3mm M: Light Straw Clay H: 240mm PRINTER: DELTA WASP 40100
	#CX2					E: 75% F: 90% NS: 4mm LH: 3mm M: Light Straw Clay H: 350mm PRINTER: DELTA WASP 40100
	#CX3					E: 80% F: 120% NS: 6mm LH: 3mm M: Light Straw Clay H: 200mm PRINTER: DELTA WASP 40100
	#CX4					E: 70% F: 80% NS: 4mm LH: 3mm M: Light Straw Clay H: 140mm PRINTER: DELTA WASP 40100
	#CX5					E: 80% F: 50% NS: 6mm LH: 3mm M: Light Straw Clay H: 150mm PRINTER: DELTA WASP 40100
	#CX6					E: 85% F: 120% NS: 6mm LH: 3mm M: Light Straw Clay H: 200mm PRINTER: 3DPotterBot 10 Pro





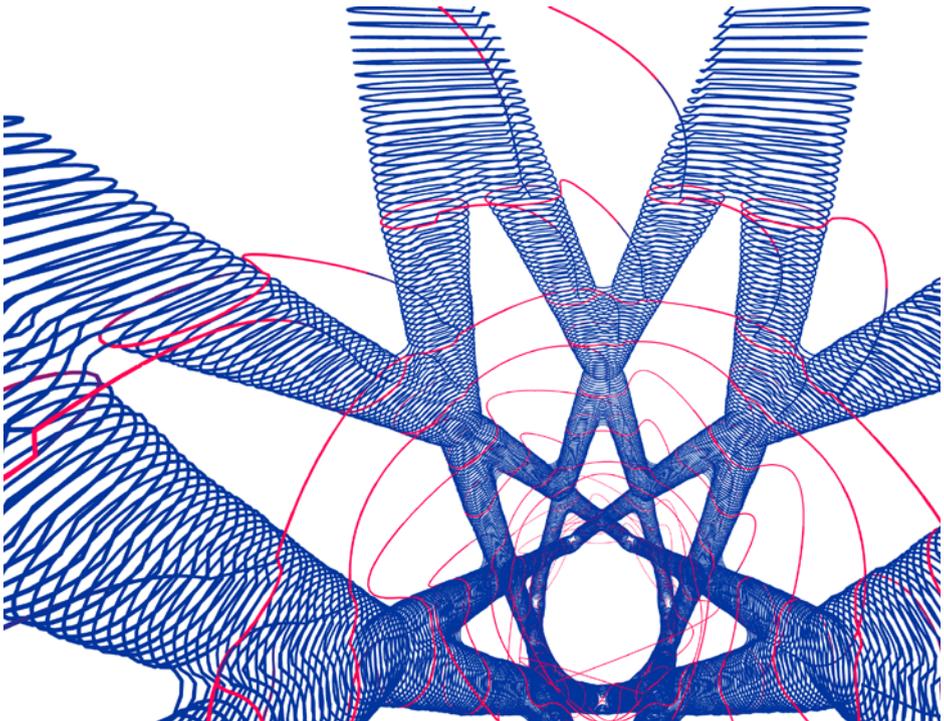
KRYPTON 2024

XtreeE

Felipe Penagos, Taha Bouizargan, Nicolas Ducouloubier, Romain Duballet

Krypton pillar was the first large scale project of XtreeE in a real architecture and construction context. Installed in 2016, it was the first load-bearing structure in Europe to be made with large scale 3D printing of cementitious materials. At the time it was fabricated following a building system limited by the printing capabilities and structural capacities. Today thanks to enhanced performances of XtreeE printer, this type of structures can be quickly and easily fabricated. Indeed, very high productivity,

variable flow rate, and accurate control of material composition are a must for industrialized manufacturing of high-end prefabricated constructive elements. Today, Krypton-type structures are used as maritime biodiversity enhancers like artificial reefs, taking advantage of their porous topology, and are envisioned as topology optimized high performance pillars for large scale infrastructure.



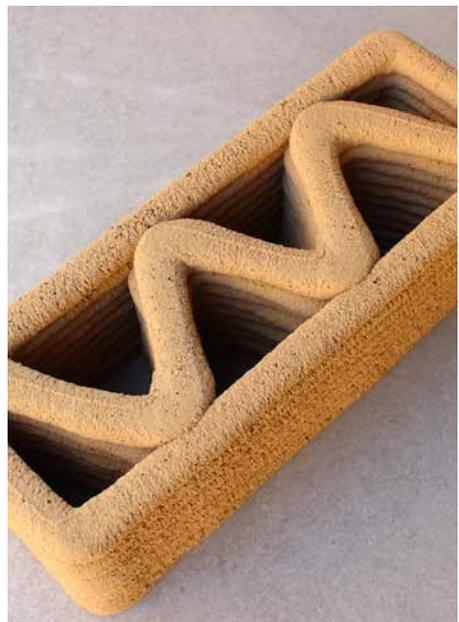


ADDITIVE MANUFACTURING WITH EARTH-BASED MATERIALS

Technical University of Dresden, Institute of Construction Materials
Leonie Gleiser

As part of my doctorate, I am focusing on additive manufacturing with earth-based materials. This integration of traditional circular construction materials with digital production techniques presents a promising construction technology. However, the additive manufacturing with earth-based materials also brings challenges, particularly related to shrinkage-induced deformations and stability. To address these, the project explores the impact of print and material parameters, such as strategic printing paths and adjustments to the clay, silt, and sand content. Alongside improving mechanical properties, ensuring material recyclability is essential. Thus, this project exclusively examines

recyclable admixtures for stabilizing earth mixtures in additive manufacturing to ensure the circularity of the earth. Additionally, material parameters are optimized to minimize the need for additives. To understand the fundamental behavior of earth in additive manufacturing, small elements were initially produced, which can be scaled up by our knowledge advances. The 3D printed element presented consists only of clay, silt, sand and water and was produced using a KUKA KR 240-2 2000 equipped with a six-axis controller. Subsequently, the element were placed in a climate chamber of 25 and a relative humidity of 60% to ensure uniform and gradual drying.



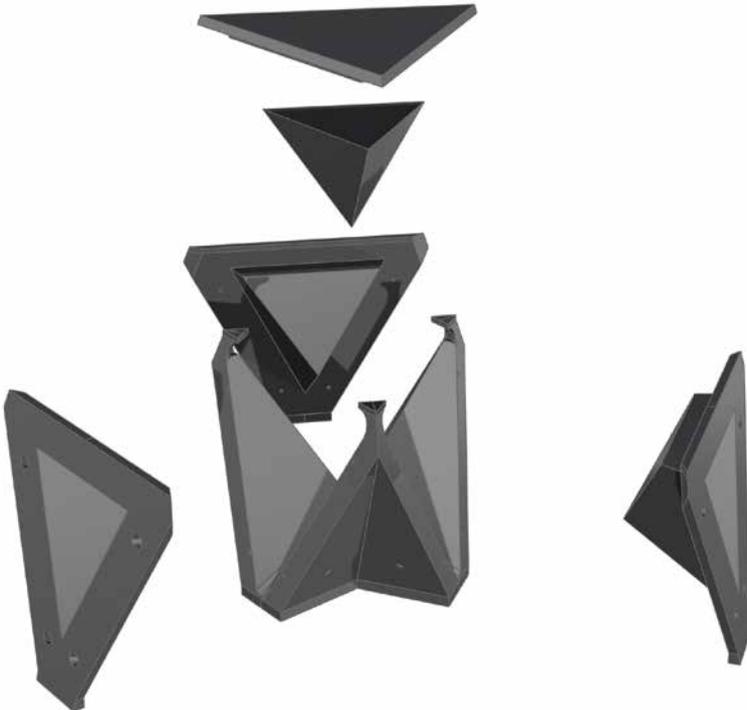


COALYMER STOOL

TU Darmstadt, Institute of Structural Mechanics and Design (ISM+D), NDC
Emanuel Nowak, Jörg Petri

What if building components could store CO₂ permanently instead of emitting it? This is the innovative approach of the Generative Design Lab at TU Darmstadt and New Digital Craft in Heidelberg. Together, they've developed a geopolymer mixture incorporating biochar, a substance produced by pyrolysis of plant material, which can store large amounts of CO₂. Biochar has been recognized by the UN as key to achieving the Sustainable Development Goals (SDGs) and is certified with CO₂

Removal Certificates (CORCs). When combined with low-carbon geopolymer, building components can be created with a positive CO₂ balance, storing CO₂ permanently. New Digital Craft manufactures these components using 3D printed formwork technology, enabling the creation of complex components with high precision. One example is the „Coalymer Stool“, a lightweight outdoor furniture piece designed by NDC for both public and private spaces.





ADDITIVE DESIGNS ON GLASS PLATES

TU Darmstadt, Glass Competence Center / Maple Glass Printing
Emanuel Nowak, Dylan Vlahopoulos, Philipp Amir Chhadeh, Nick Birbilis, Matthias Seel

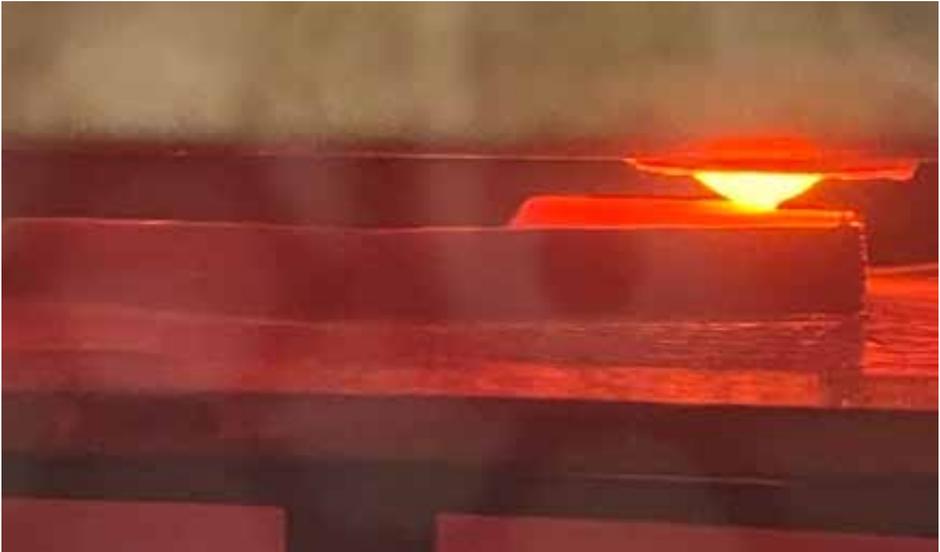
Glass 3D printing can be used to reinforce glass panels or provide them with customised designs.

Glass 3D printing reaches a new level

In cooperation with Maple Glass Printing and its latest glass 3D printer, the Glass Competence Centre (GCC) of TU Darmstadt is presenting 3D-printed glass structures applied to flat glass sheets made of soda-lime silicate glass for the first time at glass technology live. The Maple 4 printer was used for manufacturing, applying the desired structures to the glass plate using FDM technology (Fused Deposition Modeling).

New dimension for structural glass design

Flat glasses in facade applications can be stiffened, which, according to a case study by the Glass Competence Center (GCC) at TU Darmstadt, can lead to material savings of up to 70% compared to the use of conventional glass. Insulating glass with a 3D glass structure in the interlayer can also be produced, as well as 3D lettering/patterns or, for example, shelves and door handles. The range of colors and design possibilities is (almost) unlimited and offers not only aesthetic benefits but also economic and ecological advantages.





BRIDGE THE GAP

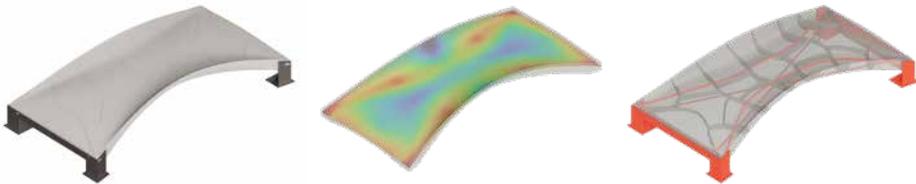
Technical University of Munich, Professorship of Structural Design, Professorship of Digital Fabrication, Chair of Structural Analysis, Chair of Materials Science and Testing

Sebastian Dietrich, Philip Schneider, Christiane Richter, Reza Najian Asl, Alexander Straßer, Thomas Kränkel, Kai-Uwe Bletzinger, Christoph Gehlen, Kathrin Dörfler, Pierluigi D'Acunto

Technical University of Braunschweig, Institute of Structural Design (ITE)
Harald Kloft

The initial 'Bridge the Gap' design concept was conceived for the courtyard of the Munich branch of the German Federal Bank and was developed using computational tools for structural form-finding in combination with digital fabrication technologies for additive manufacturing. In this context, structural form-finding allowed for the effective use of material resources by taking advantage of the interplay of form and forces. For the structural design of the bridge, graphic-statics-based form-finding approaches such as Combinatorial Equilibrium Modelling (CEM) [1] were employed. Moreover, the geometry of the bridge was specifically optimised to take advantage of the innovative 3D-printing method Selective Paste Intrusion (SPI) [2]. As a result, the primary structure of the bridge was designed as a thin, vaulted geometry made of 3D-printed concrete segments under compression. To comply with the

constraints imposed by a historical building context – i.e., the inability of the existing structures to accommodate any horizontal support reactions – the concrete structure was supplemented with a system of unbonded post-tensioning cables beneath the 3D-printed concrete segments of the bridge. The clear differentiation between compressive and tensile elements in the construction highlights another significant advantage in terms of the recyclability and reusability of the printed components. Unlike conventional reinforced concrete structures that require a time-consuming procedure of crushing and sorting for recycling, the SPI-printed parts can incorporate specially designed channels and voids, thanks to the inherent flexibility in form. These features allow for the inclusion of constructive details like post-tensioning elements while avoiding a permanent bond between the steel and concrete components.



[1] Ohlbrock PO, D'Acunto P. "A Computer-Aided Approach to Equilibrium Design Based on Graphic Statics and Combinatorial Variations", Computer-Aided Design, 121; 2020.

[2] Weger D. "Additive Fertigung von Betonstrukturen mit der Selective Paste Intrusion – SPI", PhD dissertation, Technical University of Munich; 2020



I3DCP BRIDGE

Technical University of Braunschweig , Institute of Structural Design (ITE), Institute of Building Materials, Concrete Construction and Fire Safety (iBMB)

Yinan Xiao, Norman Hack, Dirk Lowke, Harald Kloft

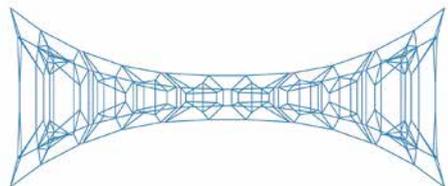
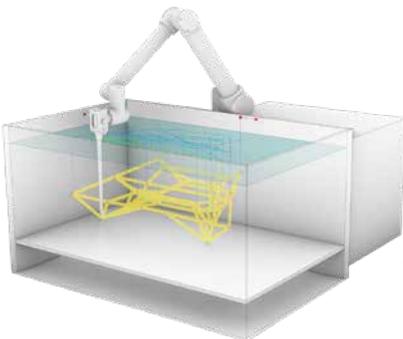
Technical University of Munich, Professorship of Structural Design
Pierluigi D'Acunto, Patrick Ole Ohlbrock

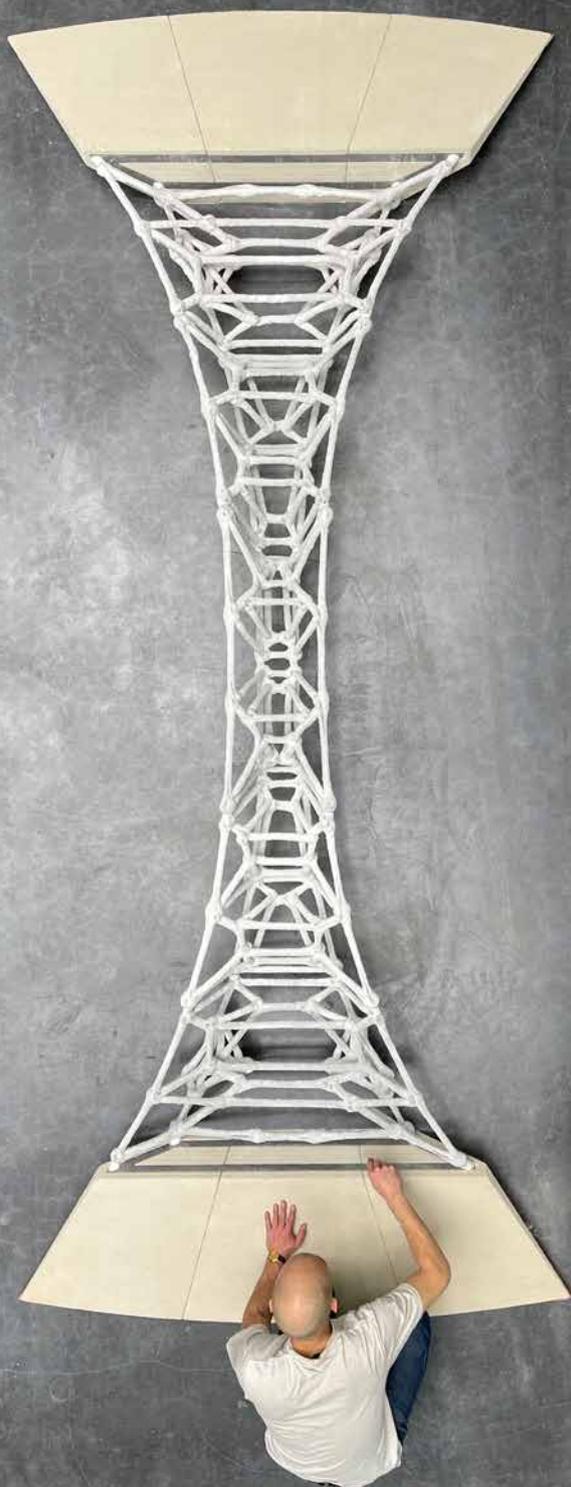
Technical University of Berlin, Professorship of Robot-Assisted Manufacturing of the Built Environment
Inka Mai

The novel approach of Injection 3D Concrete Printing (I3DCP) is a technique that challenges the layered build-up and enables complex spatial printing trajectories. This technology involves the robotic injection of concrete into a non-hardening carrier liquid that supports the printed strands. With this technique, we can create intricate and filigree lightweight structures, which are today completely unknown with concrete as a construction material. Furthermore, the use of I3DCP allows the print path to be aligned with complex spatial frames in the design phase, using equilibrium-based methods such as Vector-based Graphic Statics (VGS). VGS is a geometry-based approach to the analysis and design of structures in static equilibrium that is particularly effective for designing spatially complex, lightweight, and material-efficient structures. VGS uses the form diagram

to model the geometry of a structure with its applied loads and the force diagram to represent the equilibrium of the forces applied to the nodes of the structure. By combining VGS and I3DCP, the geometry of the lattice structure can be optimized in the early design phase to meet the static requirements and constraints of the I3DCP manufacturing process. The goal is to make 3D concrete printing more efficient, sustainable, and cost-effective, and to explore new possibilities for design and construction that were previously unimaginable.

The constructed 3-meter span bridge prototype measures 4.2 meters in length, 0.5 meters in height, and 1.8 meters at its widest point. Its overall weight, including the abutments, amounts to 312.5 kilograms, while the five components manufactured through I3DCP have a combined mass of 50 kilograms.





REINFORCED WALL SECTION MANUFACTURED BY SC3DP

TU Braunschweig, Institut für Tragwerksentwurf, Institut für Baustoffe, Massivbau und Brandschutz, Institut für Werkzeugmaschinen und Fertigungstechnik

Robin Dörrie, Niklas Freund, Martin David, Klaus Dröder, Dirk Lowke, Harald Kloft

This research object presents a case study on additively manufactured concrete construction elements utilising the Shotcrete 3D Printing (SC3DP) technique, focusing on interlayer- and short rebar reinforcement. To demonstrate the potential benefits for an automated reinforcement integration and to uncover further challenges and research questions, a wall segment was produced using a unique combination of Interlayer Reinforcement (ILR) and Short Rebar Insertion (SRI). By incorporating these methods, it was possible to

generate three-dimensional continuous reinforcement structures within the wall. The innovative approach showcased takes full advantage of the SC3DP technique, enabling the integration of reinforcement during the printing process itself, thus utilising the geometric freedom, the fast build up rate and the kinetic energy during application. This eliminates the need for premanufactured reinforcement structures, enabling a more efficient and flexible manufacturing process.





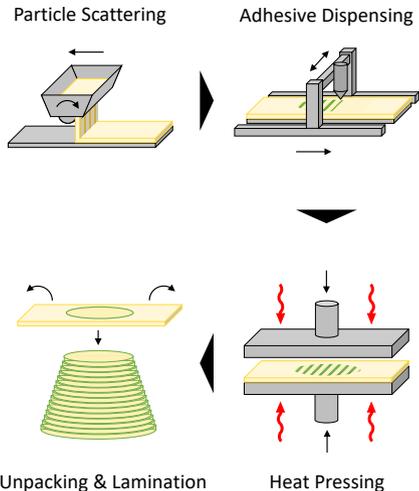
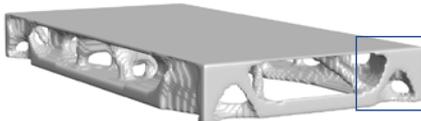
CORNER CUT DEMONSTRATOR

TU München, Chair of Timber Structures and Building Construction
Birger Buschmann, Daniel Talke, Klaudius Henke, Carsten Asshoff, Reza Najian Asl

Individual Layer Fabrication (ILF) is a novel additive manufacturing process that was developed to create objects with high wood content and high mechanical strength. Here, thin and individually contoured wood composite panels are created via Binder Jetting and subsequent mechanical pressing. Like in Sheet Lamination, these panels are then laminated onto each other to create a three-dimensional object. With wood contents and mechanical properties on par with other engineered wood products like particle boards and plywood, the produced objects are well suited for the construction and furniture industry. The general scheme of the ILF process can be divided into four main steps. A thin layer of wood particles is scattered and bound by locally dispensing adhesive according to the target geometry of the object. After dispensing the adhesive, the

wood particle layer is pressed. In doing so, the amount of required adhesive is drastically reduced while at the same time the mechanical properties of the wood composite are increased. Finally, the unbound material is removed and the contoured layer of bound material is laminated onto the stack of previously produced layers.

The displayed demonstrator is a section of a topology optimized design. A ceiling element with the size of 3.6 m by 1.8 m by 0.4 m was designed under the following constraints: Uniform load of 10 kN/ m² and Volume fraction of 25 % (compared to massive block). Because of size constrictions of the printer, only one section (one 0.5 m by 0.5 m corner) of the design was printed. The final object is a wood composite with over 85 mass percent of wood particles.





ROBOTIC FRAME WINDING: PREFABRICATED FIBRE STRUCTURES AS FORMWORK AND REINFORCEMENT FOR DIGITALLY FABRICATED SHELL-LIKE CONCRETE ELEMENTS

TU Braunschweig, Institute of Structural Design, Institute of Mechanics and Adaptronics
Stefan Gantner, Philipp Rennen, Fatemeh Salehi Amiri, Tom Niklas-Rothe, Christian Hühne, Norman Hack

This exhibit demonstrates an innovative method for creating complex reinforced concrete structures using robotics. Instead of adapting to the limitations of layer-based concrete printing, we explored a new approach where the reinforcement is the starting point, serving as a framework that stays in place and allows for more intricate shapes than conventional methods. By combining two advanced robotic techniques – Fiber Winding and Shotcrete 3D Printing (SC3DP) – we

developed a process to fabricate double-curved concrete elements with precise thickness and even concrete distribution. This approach reduces concrete waste and eliminates the need for traditional formwork. The exhibit is a section of the full-scale demonstrator, a shell segment of a pavilion, which was cut into specimens to assess the mechanical properties. At this point, only one side has been concreted, offering a glimpse into the process and the potential of this technology.





INFO

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Institute of Structural Mechanics and Design
Institut für Statik und Konstruktion

xchange
for innovation



Generative
Design
Lab



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