BE-AM

BUILT ENVIRONMENT

ADDITIVE MANUFACTURING

2023

BE-AM 2023 SYMPOSIUM

TECHNISCHE
UNIVERSITÄT
DARMSTADT

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Digital Design Unit — Digitales Gestalten

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Institut für Statik und Konstruktion

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INTRODUCTION

PREFACE

BE-AM has become over the years a platform of exchange of knowledge and resources, providing through its symposium, exhibition, publications, website, and research cluster a space for all practitioners interested in the developments of additive manufacturing in the built environment – architects, designers, engineers, constructors, material scientists, computer scientists and more. The contributions this year show not only the relevance of additive manufacturing for the Architecture, Engineering and Construction (AEC) industry, but also how the technology is making its way into it through an ever-expanding range of possibilities.

Contributions demonstrate among other how additive manufacturing can now be combined to existing building techniques, deepening links to the existing industrial fabric of construction. Research also provides more reliable processes for materials such as glass, and access to novel formulations for biomaterials to be shaped with additive manufacturing. Such developments in turn allow for lower energy spendings, for the resort to local materials and waste streams in fabrication. As the whole AEC industry, additive manufacturing now faces the challenge of sustainability in construction, and the contributions to the 2023 edition show not only this preoccupation, but also how it is gradually integrated not as a main research and development focus, but as a base requirement. Finally, not only the technical and the sustainable expand: the creative and aesthetic dimension of additive manufacturing and its uses in design and architecture make it a craft in itself. Exhibition and symposium contributions demonstrate this craft, from intricate forms and textures to novel assemblies, diving into still unexplored potentials of additive manufacturing for our disciplines.

Nadja Gaudillière-Jami

ESSAYS

Fig 1: Detail of the porous pattern of 3DLightBeam+.

STRESS-BASED DESIGN FOR 3D CONCRETE PRINTED HORIZONTAL STRUCTURES

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Abstract

This research delves into an integrated design-to-fabrication approach, merging robotic extrusion-based 3D Concrete Printing (3DCP) with stress-based computational logics to enhance the carbon efficiency of horizontal reinforced concrete structural elements. Focusing on the design, fabrication, and structural testing of beams and slabs, it explores the potential of combining 3DCP with structural optimisation techniques. The research emphasises the development of design-to-fabrication workflows specific to the fabrication technology, seamlessly integrating material considerations and fabrication constraints to reduce translation, post-processing, and discretisation steps. The outcome is a digital design approach that accommodates the trajectory-based extrusion process of 3DCP while integrating Finite Element Analysis (FEA) and Principal Stress fields to optimise the material placement. This approach yields proof-of-concept reinforced concrete beams, known as 3DLightBeam and 3DLightBeam+, characterised by a stress-based porous infill structure with a 100% higher strength-to-weight ratio than non-optimized 3DCP beams. Additionally, it extends to the development of a ribbed slab, 3DLightSlab, with toolpath-based stress-optimized rib layouts. Structural testing and a comparative Life-Cycle Analysis (LCA) validate the efficacy of this approach, indicating its potential to impact the construction industry significantly. This research demonstrates the intrinsic connection between design, fabrication, simulation, and validation, highlighting the need for their integration into a tailored workflow to harness the potential of 3DCP for structural applications fully.

Introduction

Concrete is a foundational component of the construction industry and by far the most employed construction material in the world [1], carrying the burden of being a significant contributor to anthropogenic CO2 emissions, accounting for approximately 8% of annual worldwide emissions [2]. Of particular ecological interest are horizontal structural elements within buildings, which, in the context of conventional three- to eight-story constructions, account for over 40% of the concrete volume [3], exercising substantial influence over the ecological footprint and structural robustness of the built environment. Efforts were made to reduce material use and increase the structural efficiency of slabs by integrating computational design and digital fabrication through cast concrete [4, 5, 6, 7]. However, formwork production still brings an increase in used material, budget and time spent for manufacturing horizontal structural elements

The increasing interest within the construction sector and the concrete industry for digital fabrication techniques [8, 9] has 3D Concrete Printing (3DCP) emerging as a high-impact technology within the industry, progressively raising interest both in the academic environment and in the sphere of commercial projects [10]. 3DCP holds the potential for unparalleled construction flexibility and precise material allocation, presenting a prospective avenue for curtailing the environmental footprint of the construction sector. However, a number of challenges need to be faced for its widespread adoption [11], encompassing the intricacies of 3DCP's printing techniques, quality assurance and standardisation, a comprehensive understanding of the structural behaviour of 3DCP structures, and the necessity for comprehensive economic and environmental assessments [12].

The paradigmatic shift in manufacturing and 3DCP's additive layered nature calls for a shift in design and engineering methods able to exploit the geometric flexibility and embed the constraints of the technology [13]. To unlock the full potential of 3DCP, the development of fabrication-aware models and comprehensive design-to-simulation-to-fabrication workflows that tightly link geometry to material characteristics and manufacturing features, ensuring minimal data loss and geometry rationalisation [14], emerge as a crucial step towards efficient adoption of additive processes, particularly of 3DCP, in the construction sector [15].

Aim and Methodology

Traditional design workflows based on NURBS 3D modelling and conventional Finite Element Analysis (FEA) approaches fall short of capturing the intricacies of 3DCP. Visualising and predicting the 3DCP process is challenging due to its unique layer-by-layer deposition, demanding real-time tools for design feasibility, issue identification, and performance optimisation. Moreover, the absence of reliable structural simulation models tailored for 3DCP presents a significant obstacle. These models should encompass material properties, deposition strategies, and structural design parameters. Overcoming these challenges with material developments, visualisation tools, efficient digital workflows, and reliable structural models will empower designers to explore innovative, material-efficient, and sustainable solutions. The ongoing research project presented in this essay aimed at formulating an integrated design-to-fabrication strategy that harmoniously combines robotic 3DCP with stress-based computational design principles to enhance the carbon efficiency of horizontal concrete structural components. This work bridges the gap between 3DCP potential and practical implementation, contributing to the advancement of the construction industry with a focus on precast reinforced horizontal structural elements.

The devised workflow was developed through an iterative experimental campaign which encompasses (i) the development of digital tools for the design and optimisation, prediction and simulation of 3DCP elements [16, 17], (ii) fabrication and material testing [18] and (iii) building-scale proof-of-concept prototypes of horizontal structural elements [19, 20, 21, 22](Fig. 3).

The 3DCP fabrication was done at the CREATE Lab's robotic facility, located at the University of Southern Denmark. The laboratory facility featured a six-axis ABB IRB 6650S robot with a maximum reach of 3.3 meters and a Vergumat P06 continuous mixing cavity pump with a capacity of up to 56 litres per minute and a maximum aggregate size of 8 mm, along with a printing head equipped with a 25 mm diameter cylindrical nozzle. The setup included three fabrication areas, enabling the

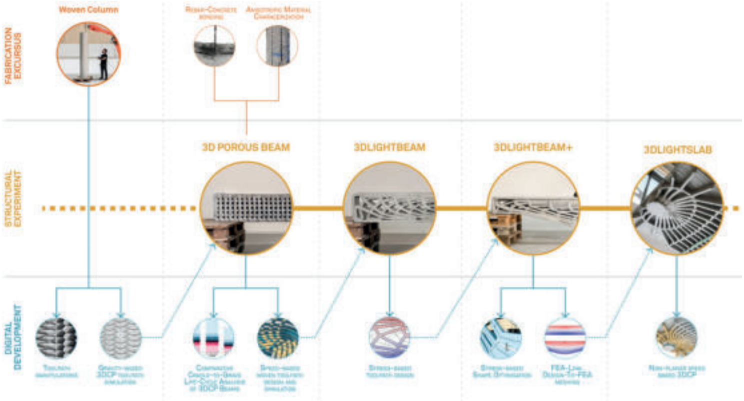

Fig 2: Adopted experimental methods exploiting 3DCP

Fig 3: Robotic 3DCP fabrications in the CREATE Lab at the University of Southern Denmark.

Scenario 1: Towards shape- and -infill optimised beams

The devised workflow for the fabrication of horizontal structures was developed through the design and fabrication of three incremental proof-of-concept reinforced concrete 3DCP beams: GridBeam, 3DLightBeam, and 3DLightBeam+.

GridBeam is a 3 m x 0.3 m x 0.16 m beam that introduces the concept of porosity in the design of horizontal structures, reducing the amount of concrete utilised in concrete beams (Fig. 3) [19]. This approach strategically utilises a grid-like orthogonal structure and employs, for the first time, a developed woven approach to toolpath planning and fabrication. This entails the subdivision of the grid design into longitudinal and transversal lines and the use of these two groups as consecutive layers in an alternated fashion. Moreover, the quantity of material is modulated by controlling the motion speed of the robot and consequently achieving a set target width of the layer. The devised method makes possible the fabrication of multiple voids in the printed objects and provides an enhanced bonding between consecutive layers in the intersections between the two perpendicular directions. Finally, following material testing, a series of 6 mm reinforcement bars were inserted during the printing process. The results of the first prototype suggest a potential for substantial environmental and material efficiency improvements in the realm of 3DCP by optimising the internal material layout in beams. GridBeam resulted having a substantial reduction of material usage, approaching 25%, while maintaining structural integrity and a higher strength-to-weight ratio compared to an equivalent 3DCP element with full section.

Building on the developments of GridBeam, a second beam design iteration, i.e. 3DLightBeam, was designed, manufactured and tested (Fig. 3) [20]. The design-to-fabrication workflow was integrated with an optimisation of the material placement by integrating FEA in the design process and optimising the infill, characterised by an orthogonal grid, following the stress intensities and direction output of the structural analysis. The core principle of this design approach was using stress isostatic curves, optimising structural elements for minimal bending stress. Pre-bent 6 mm reinforcement bars in the same volume ratio as in the GridBeam were inserted along the printed trajectories corresponding to the isostatic

Fig. 4A: prototype of GridBeam, a three-metre porous slab with a grid pattern and a woven layered extrusion;

Fig 4B: outlook of 3DLightBeam, a 3DCP lightweight beam that integrates FEA-generated PSL as a design driver.

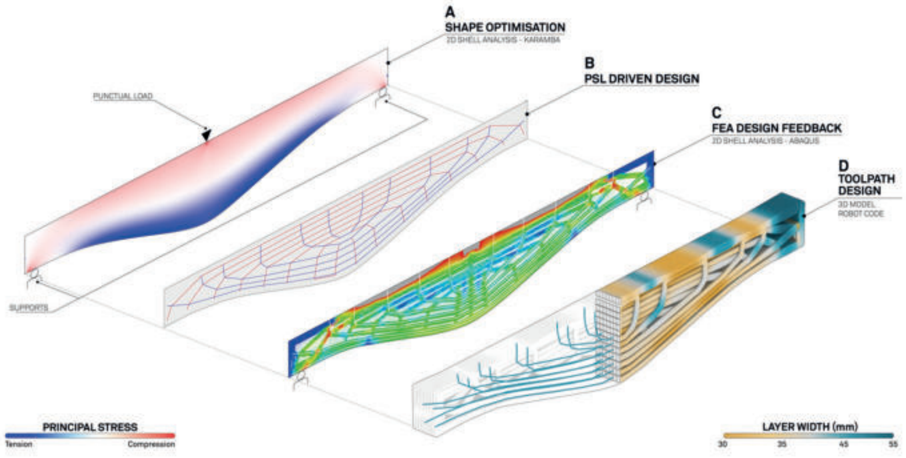

Fig 5: From Principal Stress Lines (PSL) to Toolpath Preview

curves that act in pure tension, maximising the efficiency of the bars. The 3DLightBeam specimens demonstrated a structural capacity of 79.5 kN in three-point bending tests, signifying an 85% improvement in strength-to-weight ratio over GridBeam and an impressive 178% increase compared to a 3D-printed beam with full section. The proposed approach of infill-optimised beams not only allows for the creation of bespoke, structurally efficient components but also results in a significant enhancement of the strength-to-weight ratio, a significant metric marking a more efficient use of material and the potential reduction of carbon footprint for beam elements using this design and fabrication strategy.

3DLightBeam+ represents the final step of the ongoing research project (Fig.7) [21]. In this phase, the design-to-fabrication methodology was integrated with a routine of optimisation of the shape following stress results from a linear FEA (Fig. 4). Moreover, the workflow proposes and integrates a method of FEA and of seamless data transfer from the design environment to a commercial FEA package, which includes the definition of in-layer and intralayer interactions. This ratio demonstrates substantial improvements in strength-to-weight ratio over previous design iterations, exceeding them by a significant 200% when compared to solid 3DCP beams, surpassing GridBeam by 120%, and achieving a noteworthy 20% enhancement compared to an infill-optimized beam with a rectangular cross-section, such as 3DLightBeam. This progression underscores the evolving nature of the developed workflow, enhancing the role of structural efficiency and optimisation of material use with 3DCP.

Fig. 6. Outlook of 3DLightSlab, a 3.5 m x 1.6 m ribbed slab with two punctual supports and optimised through PML and non-planar 3DCP extrusion

Scenario 2: stress-based ribbed slabs

The stress-based workflow developed for the realisation of 3DLightBeam+ was adapted and implemented for the design and fabrication of a prototypical ribbed slab. While the presented beam is characterised by an optimised layout of the infill in the longitudinal section, the designed slab was optimised in the layout and depth of its ribs. The proof-of-concept 3DLightSlab was developed with the aim of creating a lightweight yet structurally efficient concrete horizontal structure with a high strength-to-weight ratio and the ultimate goal of saving material and reducing the carbon impact deriving from its manufacturing (Fig. 6). The slab was realised by implementing in the workflow the use of Principal Moment Lines (PML) to generate an optimised bi-directional rib grid and compute their variable depth based on resultant shear and moment derived from FEA [22].

The prototype is a 3.5 m x 1.6 m rectangular slab supported by two 0.25 m diameter circular columns. It features a series of ribs with variable depths ranging from 0.08 m to 0.16 m. The design of these ribs was directly informed by the structural analysis results, particularly the magnitude of bending moments identified at each analysed location of the ribs. Fabricating the varying ribs' depths was possible by integrating non-planar and variable filament heights in the 3D printing process. Moreover, exploiting the programmed adjustments in robot printing speed and material width modulation, guided by the FEA results, ensured that more material was placed where shear stresses were most significant. 6 mm rebars three-dimensionally pre-bent with the aid of Mixed Reality (MR) were inserted along the ribs, and further rebars were inserted in the top of the slab to counteract punching shear. In testing, the slab demonstrated remarkable structural integrity. Subjected to a distributed load of 1680 Kg, it exhibited minimal deflection, meeting European standards. Furthermore, two specimens of 3DLightSlab withstood concentrated loads to an average failure load of 17.8 kN, far exceeding the standard's design load of 4 kN.

The successful design and fabrication of 3DLightSlab marks a significant milestone in overcoming the economic constraints that have historically limited the use of stress-optimised ribbed slabs, tracing back to the works of Nervi in the mid-twentieth century. By fusing the knowledge of architectural precedents with computational design tools and the layer-based approach of 3DCP, a new aesthetic dimension emerges in ribbed concrete floor construction.

Conclusions

The essay demonstrates the practicality of the approach developed for prefabricating carbon-efficient reinforced horizontal structural elements using robotic 3DCP. While some refinements are needed to meet industry standards and regulatory requirements, the structural outcomes and the efficiency of the proposed workflows indicate that 3DCP, combined with stress-based toolpath design strategies, shows great promise for reducing carbon emissions in the construction industry. The adopted methodology for design and fabrication detailed in the essay streamlines the manufacturing of beams and slabs through prefabrication, reducing the reliance on traditional formwork and minimising material waste (Fig. 1). Importantly, this approach's adaptability makes it universally applicable, regardless of specific material properties. It is well-suited for large-scale implementation, adaptable to various geographical contexts, and flexible in accommodating diverse loading scenarios, fabrication setups, and standards.

The presented SDU CREATE's research showcases 3D Concrete Printing's potential to reduce carbon emissions and improve structural efficiency in construction. Ongoing developments include tailored concrete mixtures for enhanced performance and sustainability, integration of sensors for real-time monitoring, and the improving economic viability of 3D printing, offering cost-effective construction methods for builders and developers.

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Fig 7: 3DLightBeam+, proof-of-concept 3DCP prototype of a shape- and infill-optimised beam

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Fig. 1: Adaptive Space Lattice Manufacturing

ADAPTIVE SPATIAL LATTICE MANUFACTURING AS AN EFFICIENT ALTERNATIVE TO 3D PRINTING

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Abstract

Lattice structures are well-known as geometrically optimal material structures, providing unparalleled lightweight mechanical performance across various fields of application. The evolution of these structures has been significantly propelled by breakthroughs in additive manufacturing technology in recent decades. However, the full industrial integration of lattice structures has been impeded by a multitude of bottlenecks inherent in conventional additive manufacturing, such as environmental footprint, supply chain issues, spatial resolution, or scalability. Adaptive spatial lattice manufacturing (ASLM) is a new processing route for lattice structures, based on AI-driven robotic laser welding applied to solid rods, making lattices within reach of any industry. Remarkably resource efficient, ASLM directs energy solely towards connection nodes during welding, making it much more frugal than any other available additive manufacturing process. This new process paves the way for innovative material designs tailored for specific applications.

Introduction

Architectured materials mark a significant departure from traditional materials, with their microstructures meticulously engineered to yield properties that are superior to those of their base constituents [1,2]. Lattice structures, a prominent category within architectured materials, capitalize on geometric optimization to deliver unparalleled mechanical performance with minimal material expenditure [3]. These structures, however, face considerable fabrication challenges, especially at an industrial scale, due to the constraints rooted in traditional additive manufacturing processes. In response to these challenges, Adaptive Spatial Lattice Manufacturing (ASLM) has emerged as a groundbreaking alternative. This innovative technique, which marries AI algorithms with robotic laser welding, is tailored for the construction of lattice structures using solid rods. ASLM distinguishes itself in its approach to resource efficiency, focusing energy application solely at the welding point, thereby reducing the environmental and material costs associated with more traditional methodologies.

What is ASLM?

ASLM diverges from conventional additive manufacturing by eliminating the typical complications related to powder management and layer-by-layer construction. Instead, it utilizes solid rods, joined through precise laser spot welding at specific connection nodes, see Fig.2. This process, governed by advanced AI algorithms, ensures exceptional accuracy in node creation, a critical aspect for maintaining the structural integrity and desired mechanical properties of the lattice structure.

ASLM stands out for its resource efficiency. By focusing energy application at specific points, the process significantly reduces energy consumption, contrasting with the high energy demands of traditional additive manufacturing. Moreover, by employing solid rods, ASLM avoids the complications of powder-based methods, including material waste, contamination risks, and logistical hurdles. The adaptive nature of ASLM comes from the variable length and rod diameters handled by the process, making it industrially scalable, i.e. the build time is not linearly proportional to the size of the final product but to the number of lattice struts. Intricate structures with a dense lattice mesh are longer to produce than bigger structures with simpler inner architecture.

Prospects of ASLM

ASLM's introduction represents a substantial industrial and environmental advancement. Its precision-oriented, AI-enhanced process allows for extensive customization of lattice structures, catering to specific application demands. This adaptability is crucial in sectors with rigorous material performance criteria such as aerospace, defense, automotive, construction and infrastructure. Furthermore, ASLM's compact and energy-conservative operational nature holds significant promise for space applications, such as on-orbit manufacturing, where logistical and environmental constraints necessitate innovative production methodologies. ASLM is thought to be a key enabling technology for the new space economy, and space logistics in particular. As illustrated in Figs.3 and 4, ASLM is enabling redesign of conventional infrastructure through automated large-scale manufacturing of potentially hierarchical lattice structures.

Multidimensional Challenges in ASLM

Despite its transformative potential, ASLM confronts a spectrum of challenges that require comprehensive investigation and resolution.

Metallurgical Challenges

The laser welding central to ASLM introduces complexities analogous to those in spot welding, including the emergence of defects like porosity, cracking, and microstructural irregularities within the weld zone [4]. These imperfections, if unaddressed, can undermine the structural integrity and performance consistency of the lattice structures. Addressing these metallurgical challenges demands a holistic strategy that encompasses several facets:

(1) Laser Parameter Optimization: The laser parameters, including power, speed, and focal point positioning, directly influence the weld pool dynamics and, consequently, the microstructural evolution within the weld zone. Optimizing these parameters is crucial to mitigate weld defects, ensuring a stable weld pool with minimal thermal gradients and solidification rates conducive to a refined microstructure [5].

(2) Real-Time Welding Monitoring: Implementing real-time monitoring techniques, such as high-speed imaging, can provide immediate feedback on weld pool stability, material flow, and defect formation. This real-time data is invaluable for adjusting laser parameters on-the-fly, correcting anomalies that could compromise weld quality.

(3) Predictive Modeling: Developing computational models that predict weld pool behavior, microstructural evolution, and defect formation based on laser parameters and material properties can significantly enhance process reliability. These models, leveraging machine learning algorithms, can facilitate a predictive understanding of weld outcomes, guiding parameter selection.

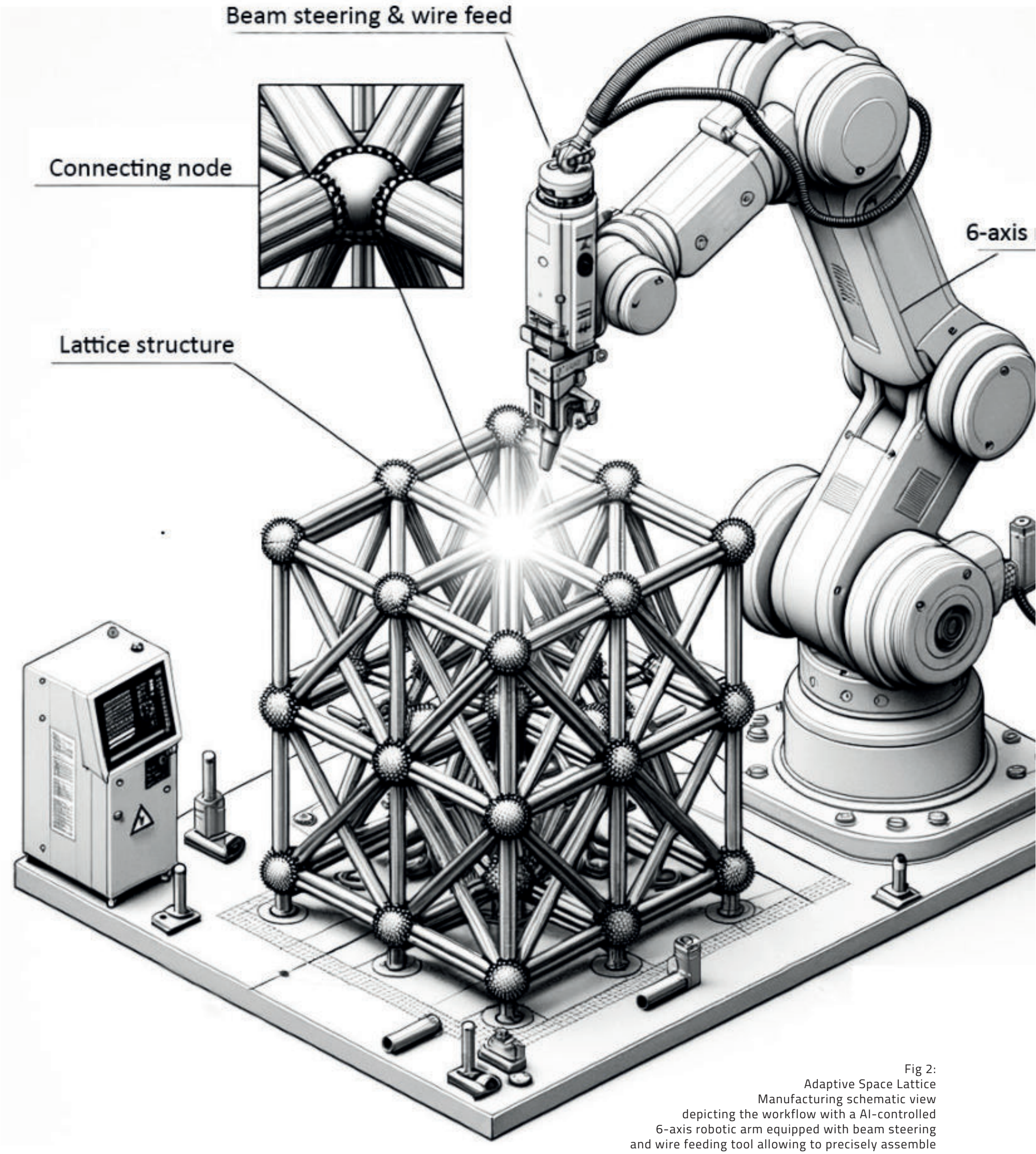

Fig 2:
Adaptive Space Lattice
Manufacturing schematic view
depicting the workflow with a AI-controlled
6-axis robotic arm equipped with beam steering
and wire feeding tool allowing to precisely assemble
solids rods by laser spot welding to form a lattice structure.
This image was created with the assistance of DALL·E 3.

Fig 2: Illustration of ASLM process for in-situ bridge building. This image was created with the assistance of DALL·E 3.

Truss Topology Optimization

Topology, or the geometric configuration of lattice structures, is pivotal for their mechanical performance. However, topology optimization in ASLM is a complex endeavor due to the delicate balance between geometric design, material distribution, and manufacturing constraints [6]. Achieving effective optimization necessitates advanced computational methodologies capable of resolving this intricate interplay, ensuring the final structure manifests the desired mechanical properties without exceeding material or fabrication thresholds.

This optimization process involves several critical considerations:

(1) Material Distribution: The optimization algorithms must effectively allocate material within the lattice structure, adhering to load-bearing requirements while minimizing material usage. This balance is crucial for structural efficiency and resource conservation.

(2) Geometric Complexity: Lattice structures can exhibit extreme geometric complexity, with features at multiple scales. The optimization process must accommodate this complexity, ensuring manufacturability without compromising structural performance.

(3) Multi-Objective Optimization: Often, lattice design involves trade-offs between competing objectives, such as stiffness versus density, or strength versus damping. Advanced multi-objective optimization techniques are required to navigate these trade-offs, identifying solutions that best meet the overall design criteria.

(4) Manufacturing Constraints: All optimization efforts must be grounded in the realities of the manufacturing process [7]. Constraints related to welding (e.g., accessible angles for the laser welder, minimum feature sizes) must be integrated into the optimization algorithms to ensure the designed structures are viable for ASLM.

Sustainability and Life-Cycle Analysis

The environmental sustainability of manufacturing processes, including ASLM, is increasingly under scrutiny. Conducting a thorough life-cycle analysis (LCA) is essential for assessing the environmental impact of ASLM across all stages, from raw material extraction to end-of-life scenarios [8,9]. This LCA should encompass a broad spectrum of impact categories, including energy consumption, greenhouse gas emissions, material utilization efficiency, and waste generation.

Key considerations in this analysis include:

(1) Energy Footprint: The LCA must quantify the total energy consumption associated with ASLM, considering both the direct energy used in the welding process and the indirect energy associated with material production, system maintenance, and auxiliary operations.

(1) Material Efficiency: Material utilization efficiency is a critical factor in the environmental footprint of ASLM. The LCA should evaluate material sourcing, and inefficiencies in material usage due to over-design or conservative safety factors.

(3) Emissions and Waste: The analysis must account for all emissions produced during ASLM, including greenhouse gases, particulates, and any hazardous by-products. Similarly, the generation and management of waste materials, including solid waste, effluents, and gaseous emissions, must be thoroughly assessed.

(4) End-of-Life Scenarios: The LCA should explore various end-of-life scenarios for lattice structures produced via ASLM, assessing the environmental impacts of different disposal, recycling, or repurposing strategies. This assessment is crucial for understanding the long-term sustainability implications of ASLM-produced materials.

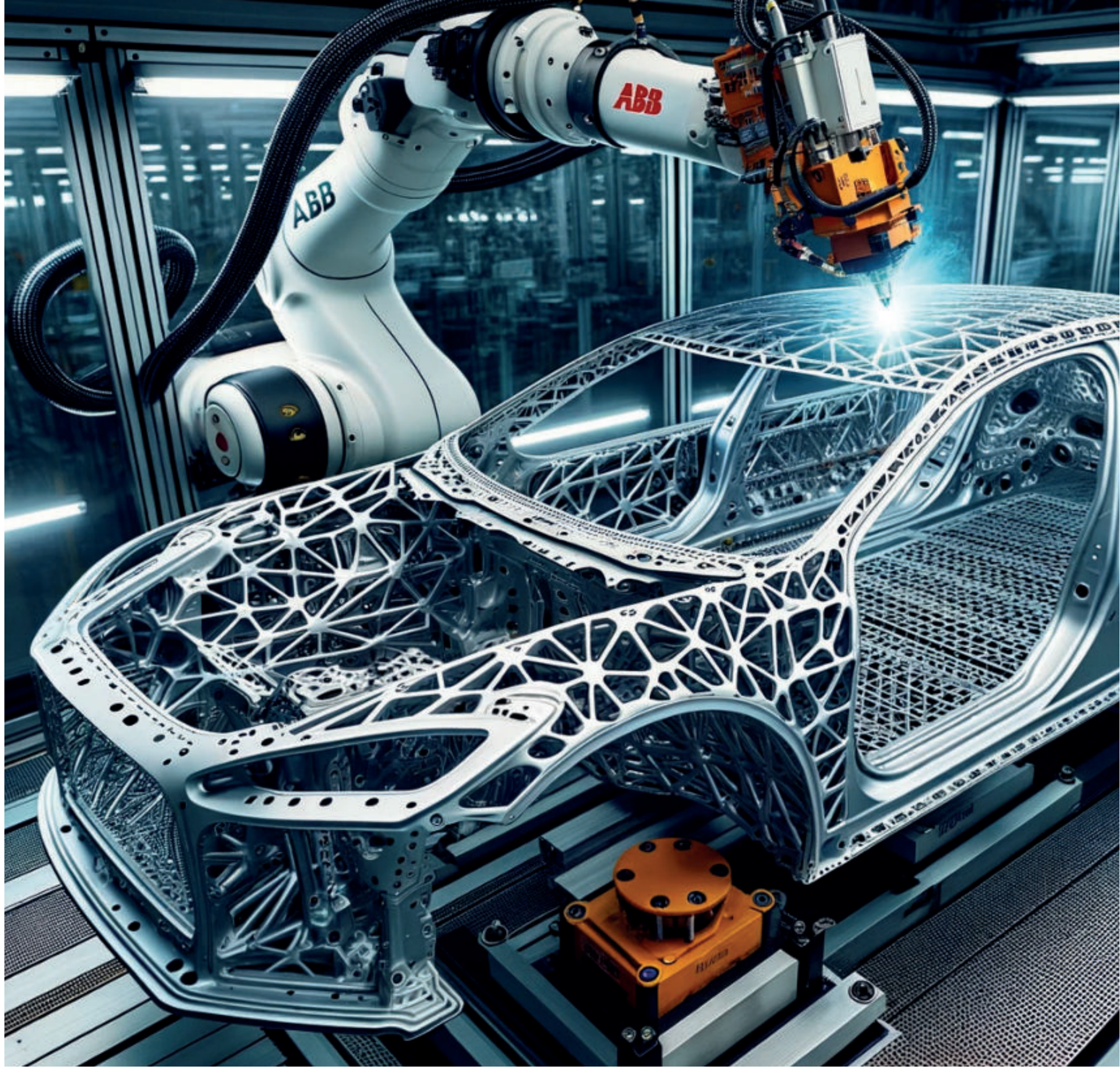

Fig 3: Illustration of ASLM process for lattice car manufacturing.
This image was created with the assistance of DALL·E 3.

Conclusion

ASLM signifies a considerable stride forward in the realm of architectured materials, offering a pathway that circumvents the drawbacks of conventional additive manufacturing. While it introduces remarkable resource efficiency and customization capabilities, ASLM's full industrial realization hinges on addressing its inherent challenges.

These encompass not only metallurgical and technological considerations but also the environmental sustainability of the process. A concerted, multidisciplinary research effort is essential to navigate these challenges, optimizing ASLM for robust, consistent, and environmentally responsible production of lattice structures.

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Figure 1: Underside view of the weight-reduced slab in Nördlingen

LIGHTWEIGHT REINFORCED CONCRETE SLABS WITH INTEGRATED 3D PRINTED FORMWORK

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Abstract

3D printing with concrete intergrated in common casting processes, allow for a renaissance of complex load-bearing structures like introduced by Nervi and Favini in the 1960s and 1970s.

3D printed concrete formwork as voids in combination with in-situ concrete in slabs gives this typology a second go. Tailored design for lightweight slabs and roofs has been developed and implemented in construction projects in progress. To test the load-bearing capacity and serviceability of the design, a prototype was tested in a large-scale bending test. Further tests demonstrate good fire resistance and the excellent adhesive bond between the printed concrete and the poured concrete. In addition to the design aspects the positive effects on the global warming potential of concrete structures compared to the current construction method is highlighted.

The presented building projects stand for a sustainable approach to reinforced concrete, which, among design aspects, relies on economic and logistic issues, resource-saving and digital manufacturing methods.

Introduction

Planners and the construction industry have been using reinforced concrete as a material for building structures for over 150 years. The robust composite material has proven itself over many decades due to its versatility; building physics and fire protection advantages round off the range of uses. The shift in cost shares between materials and working hours has changed the appearance of supporting structures over the years. In the early days, cost-intensive materials and comparatively cheaper working hours favored slim and delicate designs. Nowadays, the desire to save costly working time while at the same time accepting more use of the inexpensive building material leads to more voluminous, thicker-walled components.

Ribbed ceilings as well as generally delicate reinforced concrete elements, such as those planned by engineers such as Pier Luigi Nervi or Aldo Favini and architects such as Angelo Mangiarotti in the 1960s and 1970s, were not only material-saving, but at the same time important design elements of buildings such as: the Palazetto della Sport or the church of Mater Misericordiae. But above all, countless anonymous material-saving rib constructions from this time are still hidden behind suspended ceilings or are uncovered again during revitalizations and are silent, mostly aesthetically high-quality witnesses to a material efficiency that has ultimately been lost in the rush for returns of invest in our economic system. Such constructions use 30% to 40% less material compared

Figure 2: Realized building project in Nördlingen with a 170m² material reduced slab

to flat ceilings. If parts of a shell load-bearing effect are also activated, the savings potential can be increased to up to 70%. The optimization of support structures with regard to their Global Warming Potential (GWP) is fundamentally an overdue and urgently necessary step. But the structural planning that would be able to make this important contribution has been subject to such price competition for years that these "optimizations in the standard case" are the last thing that is even asked for or for which there is time. The comeback of ribbed ceilings can be expected for the reasons mentioned above. 3D printed elements, which serve as permanent formwork and are supplemented with conventional concreting methods, represent an innovative and pragmatic method of taking the long-needed step towards a new lightweight concrete construction.

The three projects differ significantly in their genesis. The Ateliere Schloss Seehof project can still be described as an experimental building. The design and implementation, the production of the 3D printed elements, the installation and reinforcement were largely carried out by the innovation friendly client and the Institute for Structural Design The Concrete Lightweight Ceiling, Nördlingen and Climate-Friendly Concrete Ceiling, Bludenz projects showed a more complex project structure. In both cases, the planning was largely completed by an architectural and engineering office. The redesign of the roof structures particularly the rib-design was carried out according to suggestions from the Institute for Structural Design.

The project constellation described, is characterized by a close network of research and industry, as has been maintained by the Institute for Structural Design and Baumit Beteiligungen GmbH for years. The construction companies carrying out the work themselves, operate 3D printing systems from Baumit and are therefore extremely committed to the high-quality implementation into the projects. On the one hand, these construction projects became the ideal form of dissemination and implementation of innovation from the university into practice. On the other hand, valuable in-depth investigations could be carried out in the laboratory, such as mechanical tests, tensile adhesion tests and carbonation tests. Data from the construction site, especially about assembly times and material costs, indicate the competitiveness of this construction method.

Figure 3: 3D printed concrete formwork

Figure 4: inside view of the atelier

Figure 5: 3D printed void bodies placed on the formwork table

Atelier Schloss Seehof, Lunz am See

Site: Lunz am See, Seehof 1

Client: Prof. Hans Kupelwieser

Design and planning, AM strategies and production: Institute of Structural Design

AM facility and material: Baumit GmbH

Masterbuilder: Fa. Gusel

Roof area: 100 m²

AM building elements: 130 individual printed elements

Weight/ element: 4 to 90 kg

Printing time: ca. 18 hours.

Printing material: app. 5,6 to

Construction time: 2 weeks

Construction year: 2021

Design

Hans Kupelwieser, Austrian sculptor commissioned an extension and annex at the lower part of the eastern wing of Schloss Seehof in Lunz am See/Austria. The design of the roof structure was developed by ITE in cooperation with Kupelwieser and it represents a combination of design and structural optimization. The entire process, from initial design to production planning and the production itself, is based on a single, parametric model that has been carried from the beginning to the end of the project.

AM elements

For the project, 130 different voids were produced using the 3D concrete printing system from Baumit in the Robot Design Lab at TU Graz. The individual prefabricated elements are unreinforced and do not perform any structural functions. The box-shaped voids were printed upside down and are assembled from a flat base / lid, and inclined walls. The lid is extended over the side walls to obtain a clean appearance on the inside.

Sustainability

In addition, the selected slope direction favors the ratio of beam heights to the respective spans, so the reinforcement tonnage can be reduced by 30% compared to an equivalent monolithic flat slab. In this comparison, the new construction method also achieves a concrete saving of 40%.

When carrying out a life cycle assessment, however, it must be taken into account that the printing concrete used for the voids has a much higher CO2 eq compared to normal concrete used for the loadbearing structure due to its cement ratio. Therefore the CO2 saving is approx. 30%.

Figure 6: roof construction-inside view

Figure 7: roof construction- building site

Concrete Lightweight Ceiling, Nördlingen

Site: Maria-Penn-Straße 8, 86720 Nördlingen, Germany

Client: Gemeinnützige Baugenossenschaft Nördlingen eG und Stadt Nördlingen

Design and planning, AM strategies and production: Institute of Structural Design, TU Graz

Architect: Lattke Architekten

Structural Engineer: Engelsmann Peters

Masterbuilder: Eigner Bauunternehmung GmbH

AM Fabrication: Eigner Bauunternehmung GmbH

Printing System, Print-Material: Baumit GmbH

Casting Concrete: Märker Transportbeton

Area: 168 m2

Amount of concrete: Vergussbeton: 38,7 m³

Amount of print material: 3,5 m³

Planning

As part of the construction project „Wohnen am ehemaligen BayWa-Gelände" (Living on the former BayWa site), a 168m² roof was implemented as a lightweight reinforced concrete construction over an underground garage in Nördlingen.

In the original planning, a plane-parallel reinforced concrete flat slab with a usual slab thickness of 25cm was planned. The conventional construction method of this component is optimised in terms of costs and construction times, but this approach holds enormous potential for optimisation in the area of resource efficiency and sustainability. This is where the project team came in and developed a weight-optimised design for the single-axis roof with cantilever, with the help of 3D concrete printing technology.

Design

For the lightweight reinforced concrete construction, the Graz University of Technology developed formwork elements consisting of elongated half-shells that vary in height and width and remain in the component as lost formwork. The design of the voids in the ground plan followed the internal forces occurring in the roof structure. The installed reinforcement was laid conventionally and by reducing the dead weight of the roof by approx. 40 %, the reinforcement could also be reduced by the same amount. The roof was cast with in-situ concrete, which has significantly lower emission values due to its low clinker content. By using a binder reduced concrete composition, saving the amount of reinforcement and applying new technology, the CO2 footprint was reduced by 35% compared to the originally planned design.

Figure 8: werkhof Bludenz - Underside view

Figure 9: Werkhof Bludenz – bird view

Klimaschonende Betondecke, Bludenz

Site: Buldenz, Vbg, A
Client: WERIT Handels GmbH Österreich
User: Stadt Bludenz
Masterbuilder: Tomaselli Gabriel Bau
Architect: Atelier Ender
Structural Engineer: gbd Gruppe
Roof-Design, optimization, AM strategies : TU Graz, Institute of Structural Design
AM Fabrication: Concrete 3D
Area: 717 Quadratmeter
Number of elements: 792
Material Savings (concrete/steel): 316 to res. 32%
GHG: 33 to CO2eq res. 25%
Construction year: 2023-2024

Design

In a team with Tomaselli Gabriel Bau GmbH and Baumit GmbH, the goal of the Institute for Structural Design was to design the 717m² roof of the Werkhof in Bludenz as efficiently as possible by using 3D printing with concrete in order to save resources and increase sustainability for concrete construction

In order to be able to optimally design the geometry with regard to the prevailing span and support situation, the trajectory was analyzed in a first step and an optimized and aesthetic geometry was determined. The roof structure for the Werkhof in Bludenz was then predesigned according to applicable standards (EC2 with NAD), the required concrete strength was determined and the level of reinforcement was determined. In addition, the predimensioning using the FEM program Sofistik provided information about the trajectory in the component.

AM - Elements

The predominant forcesflow in the supporting structure was then the basis for the geometry and arrangement of the AM elements. In addition to the force distribution, the dimensions of the AM elements also played a major role, as weight and size correlate and the goal was to choose the weight so that two people can still lift the AM elements on the construction site. The 792 elements were manufactured and checked by the 3D concrete printing company Concrete-3D GmbH.

Sustainability

In the construction project, around 24% CO2eq could be saved through the use of 3D printing technology. In addition to the concrete saved by the AM elements, a portion of the reinforcing steel could be dispensed with by reducing the structure’s self-weight. In total, the original planning caused 135 toCO2eq, whereas the optimized planning was managed with 102 toCO2eq. This means that 33 toCO2eq could be substituted through the ceiling structure alone.

Additional research related to the projects

Figure 10: For the Concrete Lightweight Ceiling, Nördlingen project a one to one acceptance test was executed. The predicted capacity for servicability and the ultimate limit state could could be proved

Figure 11: Carbonation performance for hybrids made from AM elements and casted concrete

Figure 12: Adhesive bond tests showed the perfect compound between printed material and casted concrete

Fig. 1: Final Demonstrator Breuer X AM

ADDITIVE MANUFACTURING IN CONSTRUCTION – THE CHALLENGE OF LARGE SCALE

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Abstract

The construction industry faces challenges associated with resource use and emissions as the global demand for buildings continues to grow. A key solution to tackle this challenge is the adoption of Additive manufacturing, also known as 3D printing, in construction. The collaborative research centre TRR 277 AMC, led by the Technische Universität Braunschweig and the Technical University of Munich, is driving this transformation, bringing together materials, digital processes and architectural innovation for a sustainable and digitally advanced construction industry that is reshaping the way we build.

Introduction

Building is one of the fundamentals of human socialisation and is an integral part of our cultural development. Throughout history, we have utilized the materials provided by nature and the earth to construct buildings and other structures. Just like society as a whole, the construction industry is also at a turning point.' The building sector already consumes 50% of the world's natural resources, and construction is responsible for 11% of CO2 emissions, with the operation of buildings accounting for over 40%. The paradox is that as the world's population continues to grow, we must keep building, both in terms of buildings and infrastructure. So, the question for the future is: How can we build for more people with less material and fewer emissions?

With additive manufacturing, a promising construction technology that contributes towards solving these challenges is emerging at the right time. Additive manufacturing has the potential to shift the focus in the building industry from costs of human labor to the value of materials. Secondly, additive manufacturing processes are digitally controlled, opening the door to the digital age in construction. The digital connection of automated additive manufacturing processes to the preceding planning and subsequent construction site processes enables new digital workflows.

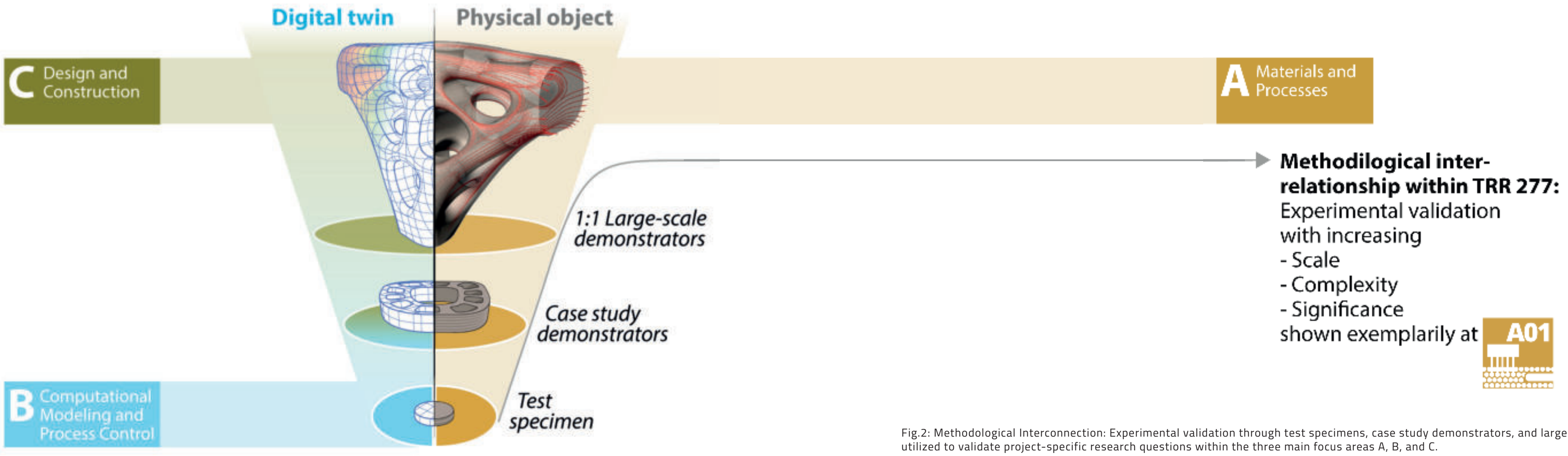

Fig.2: Methodological Interconnection: Experimental validation through test specimens, case study demonstrators, and large-scale demonstrators is utilized to validate project-specific research questions within the three main focus areas A, B, and C.

TRR 277 AMC

The Collaborative Research Centre TRR 277 Additive Manufacturing in Construction (TRR 277 AMC) of the Technische Universität Braunschweig (TUBS) and the Technical University of Munich (TUM) has been researching innovative technologies of AMC across materials and processes since 2020. The researchers of TRR 277 AMC see additive manufacturing as a key digital technology to provide materials with high-performance manufacturing processes for material-appropriate forms and, at the same time, to transform the construction industry into a contemporary productive and environmentally sustainable economic sector. At the dawn of the digital age, we have a great opportunity to use additive manufacturing technologies to pave the way for the unity of material, process and form in construction and fundamentally change the way we build in the future. In the highly interdisciplinary environment of TRR 277 AMC, researchers are working together to investigate the fundamentals of AMC technologies as central drivers of digitalisation, resource conservation, environmental sustainability and productivity in the Architecture Engineering Construction industry (AEC) sector.

At the core of the research work are fundamental investigations of novel AMC technologies in various material and process combinations. This is based on an integrative research approach whereby structural design, material technology and manufacturing processes are considered as an inseparable, digitally networked unit and are subjected to coherent research. In addition, AMC technologies as digital processes are integrated into the prior planning and the subsequent construction site as an interacting digital environment. This holistic approach of digitalisation in construction offers completely new possibilities for the interaction and exchange of data-based information between planning and manufacturing. It also allows integral digital workflows to improve quality and shorten construction time.

To enable a collaborative approach to the research topics from multiple perspectives, the TRR 277 AMC is structured into three main focus areas. In focus area A, Materials and Processes', various material-process combinations are fundamentally investigated from the perspective of different disciplines. The research scope is defined by the established building materials concrete, steel and wood in combination with the particle bed and deposition processes known to date. In future, an expansion to earth-based materials, low carbon footprint materials and graded materials, as well as innovative AMC processes such as Robotic Sprayed Earth and Injection 3D Printing is planned. Focus area B, Computational Modelling and Process Control', systematically enhances the research of focus area A through the accompanying numerical modelling of material and process interaction as well as through the optimisation of control and path planning. Modelling detail, size and time scales are geared to the requirements in defined phases of the additive manufacturing processes. Focus area C, Design and Construction', investigates the interfaces between AMC processes and the preceding BIM-based planning environment as well as the subsequent organisation of the construction site. Structural design in particular will be strengthened with regard to form optimisation and function integration and in terms of the environmental impact of AMC.

The methodological interconnection of the three main focus areas A, B, and C, is based on experimental validation through the production of test specimens, case study demonstrators, and large-scale demonstrators (Figure 2). This provides a platform for the cooperation in interdisciplinary teams of AMC researchers across various fields such as civil engineering, architecture, materials science, and mechanical engineering. The large-scale collaborative demonstrators used to experimentally test and validate the integration of materials and processes (focus area A), computer-aided modeling and process control (focus area B), and design and construction (focus area C) featuring sections of building and infrastructure designs at a 1:1 scale.

The goal is to test, compare, and evaluate the typical characteristics of individual AMC processes, such as resolution and granularity, mechanical properties, and load-bearing capacity, building physics usability, and geometric freedoms in various building and infrastructure applications. Contrary to focusing on a single process, new AMC technologies are examined and explored in terms of their broad applicability and potential in sustainability, productivity, and resource efficiency. As such, the Collaborative Demonstrators aim to transfer research results into technically mature applications outside market mechanisms. In summary, this approach aims not only to make the research findings of the AMC tangible through potential applications of AMC technologies in the construction sector but also to provide conceptual perspectives and drive and motivate future AMC research.

Collaborative Demonstrators

(1) Breuer X AM – Façade element by Particle-Bed 3D Printing

Breuer x AM is a façade element manufactured using Selective Cement Activation (SCA), a particle-bed 3D printing technique. The demonstrator is named after the architect Marcel Breuer. He developed innovative solutions for a novel industrial approach of modular construction methods at the IBM Research Center in LaGaude, France (1960-1962). However, the standardised manufacturing methods at that time were not yet capable of customising building elements to address local requirements within the building envelope or to differentiate the inner structure.

Marcel Breuer's concept served as an initial framework for design explorations of one-component building envelope elements enhanced by AMC, in which the overall design can adapt to local parameters such as sun position and orientation, as well as considering thermal aspects and load-bearing requirements within the inner structure. By utilising the AMC technique of Selective Cement Activation, this design project aimed at expanding traditional industrial construction methods towards non-standard, mass-customised, and resource-efficient alternatives. The Selective Cement Activation technique is fundamentally investigated in a TRR 277 project of focus area A, which focuses on high-resolution particle-bed 3D printing of reinforced cementitious composites as a novel technology in the construction industry.

The collaborative demonstrator was designed and planned to validate (a) the general applicability of the design approach for multi-scale, customized, and site-specific building envelope elements; (b) the functional hybridization of the simultaneous incorporation of thermal aspects and load-bearing requirements, as well as integrated joint details in one building component, and (c) the fabricability via the SCA process of such large-scale components. For this, a south-southeast oriented and functionally hybridized building envelope segment, composed of a full (3 m height, 1.80 m width and 0.75 m depth) and an adjacent truncated building element (1.25 m height, 0.5 m width and 0.75 m depth), was selected to be realised in full 1:1 architectural scale (Figure 3).

Breuer X AM was manufactured at Additive Tectonics GmbH in the Big Future Factory using the particle bed setup with Portland cement and lightweight aggregates as printing material, and the Demonstrator was printed in one piece (Figure 1).

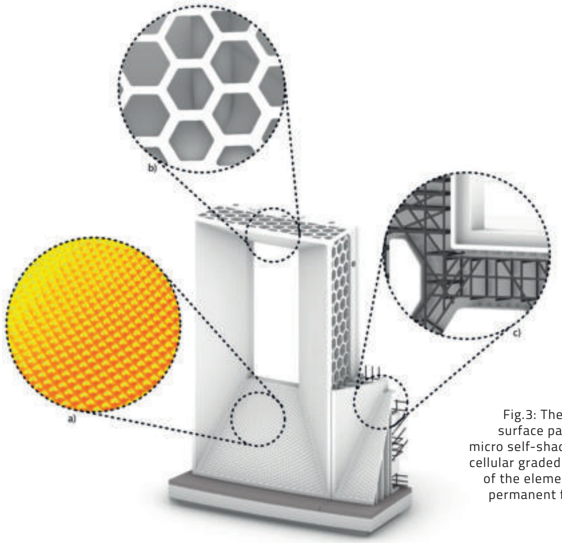

Fig.3: The element featured (a)geometrically differentiated surface patterns on the adjacent glazed surfaces to provide micro self-shading effects reducing the surface temperature, (b) cellular graded cavities contributing to the thermal performance of the element inside a ~50 cm deep insulation zone, and (c) a permanent formwork providing a 20 cm load-bearing zone to cast the reinforcement with grouting mortar

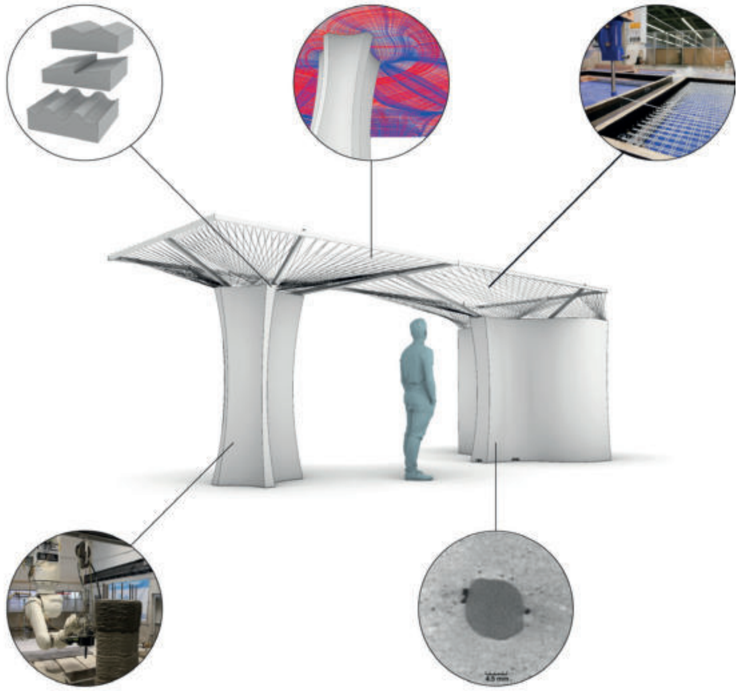

Fig. 4: Shelltonics Demonstrator: AM-Section of building construction; Length 6,35m, Height 2,40m, Width 2,40m

(2) Shelltonics - Integration of Individualized Prefabricated Fibre Reinforcement in Shotcrete 3D Printing

One of the biggest challenges in 3D printing with cementitious materials is the integration of reinforcement. As 3D-printed, unreinforced concrete components can only compensate for limited tensile forces, their range of applications is confined to predominantly compression-stressed components and thus, the structural potential of 3D-printed parts remains unrealized. This is where the 1:1 scale demonstrator Shelltonic steps in.

The Shelltonics Demonstrator is fabricated with Shotcrete 3D Printing (SC3DP) and Fibre Winding reinforcement to achieve the aesthetic quality of a shell structure: a thin and elegant element that transfers bearing loads to the ground in a material-efficient way (Figure 4).

Furthermore, automated horizontal and vertical reinforcement placement, along with robotically wound fibre reinforcement, were incorporated to fabricate a structurally sound concrete component. Additionally, the integration of anchors, conduits, and electrical elements into the printing process was achieved. Finally, precise surface post-processing was employed to emulate architectural concrete-like finishes and prepare the component for transportation. Shelltonics effectively connects three inseparable research domains-design, material, and process- and

serves as a compelling showcase of the SC3DP's and Fibre Windings reinforcement capabilities for manufacturing large-scale reinforced concrete components, thereby fostering a more expedient and sustainable construction industry (Figures 5 and 6).

Fig. 5: Shelltonics set up at Digital Building Fabrication Laboratory at TU Braunschweig

Fig. 6: Final Demonstrator Shelltonics with Augmented Reality;

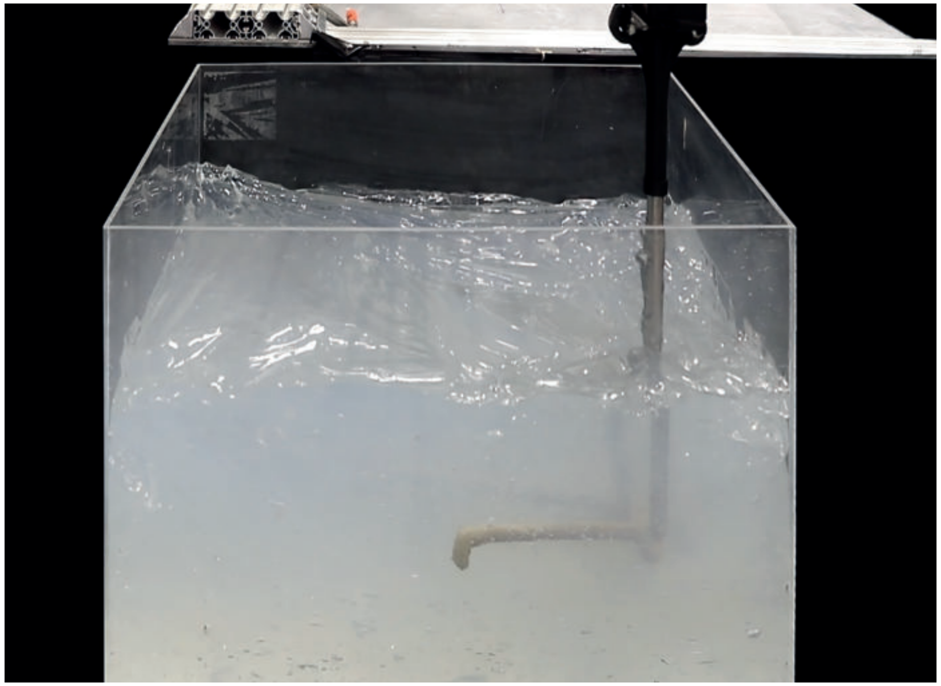

Fig. 7: Robot Setup of the Injection 3D Printing Process

Injection 3D Concrete Printing

The novel approach of Injection 3D Concrete Printing (I3DCP) has been recently introduced to overcome the limitations of layered 3D printing techniques. I3DCP challenges the layered build-up and enables more 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, it is possible to create intricate and filigree lightweight structures that were previously unknown when using concrete as a construction material. (Figure 7).

Furthermore, the use of I3DCP allows the print path to be aligned with complex spatial stress trajectories that can be treated as strut-and-tie networks in the design phase using equilibrium-based methods such as Vector-based Graphic Statics (VGS). By combining VGS and I3DCP, the geometry of the lattice structure can be optimised 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, like the large-scale Demonstrator I3DCP Bridge (Figure 8). The constructed bridge prototype measures 4.2 m in length, 0.5 m in height, and 1.8 m at its widest point. Its overall weight, including the abutments, amounts to 312.5 kg, while the five components manufactured through I3DCP have a combined mass of 50 kg. The bridge's maximum load capacity exceeds 20 times its own weight, demonstrating the potential of the Injection 3D Concrete Printing (I3DCP) technique in constructing lightweight concrete infrastructure (Figure 8).

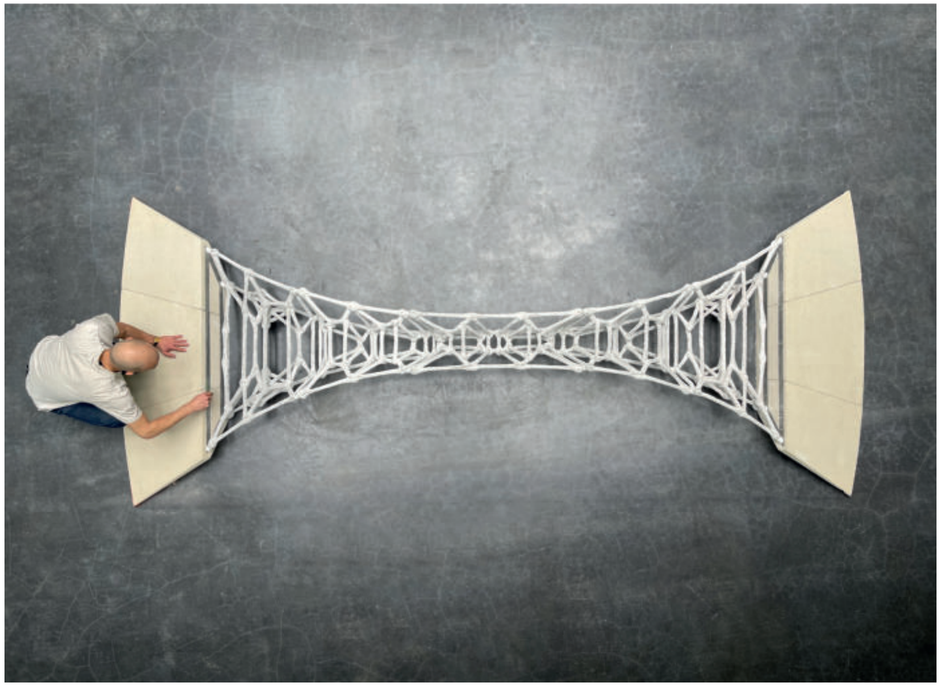

Fig. 8: Injection 3D Concrete Printing Bridge

Conclusion

The Technische Universität Braunschweig (TUBS) and the Technical University of Munich (TUM) share many years of experience in interdisciplinary and cross-location research on additive manufacturing in the construction industry. The excellent research infrastructure present at both universities, coupled with their complementary expertise, serves as the foundation for the research programme and fosters the strategic advancement of both universities. TRR 277 AMC harbours the potential for gaining substantial national and international recognition, and it aims to firmly establish itself as a formidable partner in driving the digital transformation of the construction industry in the years to come. With its promising direction and the dedication of its research teams, TRR 277 AMC is set to become a player that significantly influences developments and innovations in the construction sector.

Acknowledgements

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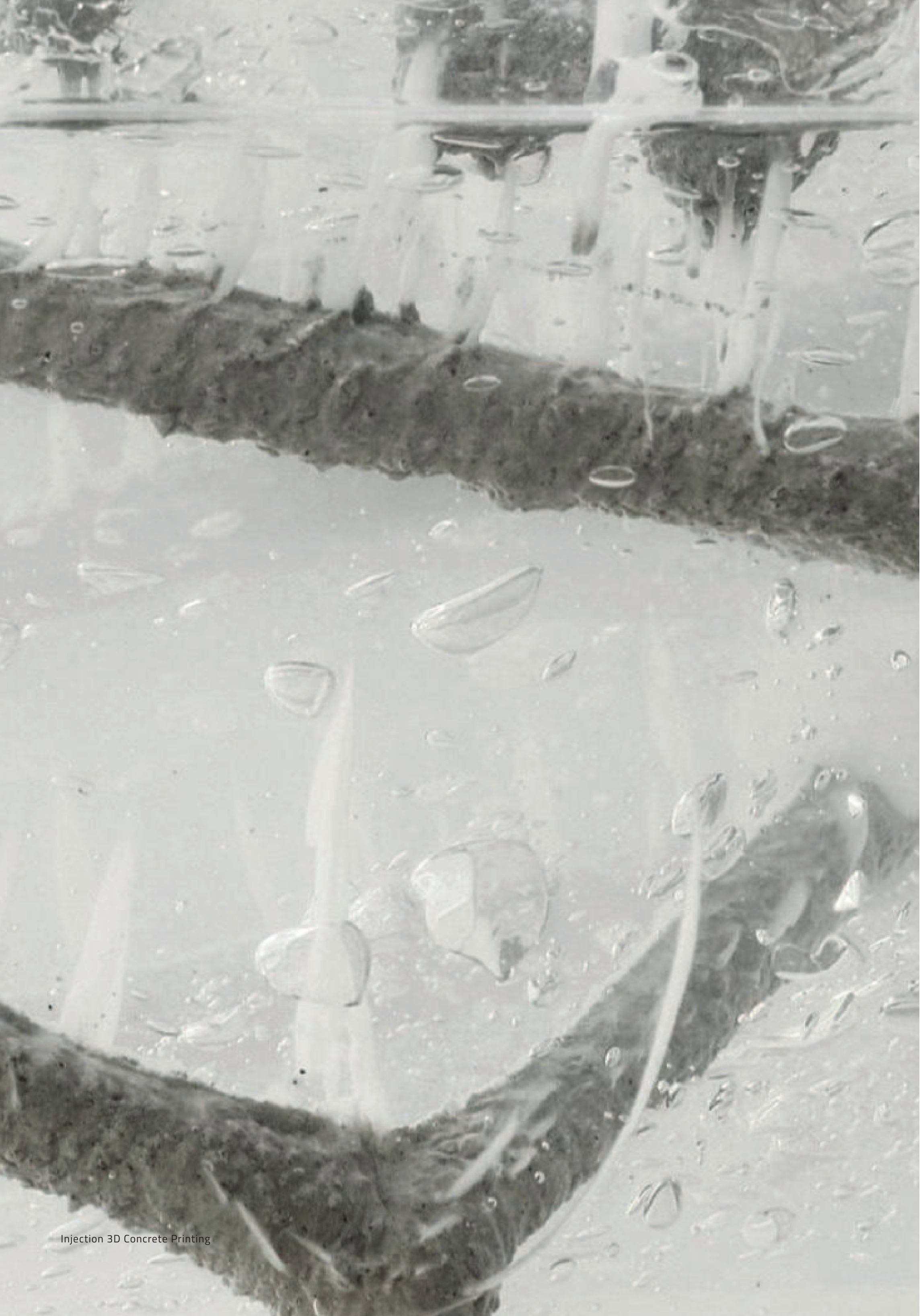

INJECTION 3D CONCRETE PRINTING – EXPLORING NEW POTENTIALS IN CONCRETE 3D PRINTING

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Abstract

The productivity of the construction industry is stagnating over the past decades. By using digital fabrication techniques, such as 3D printing with concrete, costs could be reduced by up to 45% and material usage by up to 70%. At the moment most of the projects in research and industrial applications focus on depositioning concrete via extrusion, particle bed binding or material jetting. Nevertheless, also other 3D printing techniques have their advantages and may even have further ecological benefits. On the example of Injection 3D Concrete Printing a look beyond “conventional” concrete extrusion is taken and potential applications are presented.

Introduction

The productivity of the construction industry is stagnating over the past decades [1]. By using digital fabrication techniques, such as 3D printing with concrete, costs could be reduced by up to 45% [2] and material usage by up to 70% [3]. The majority of research today in 3D concrete printing focuses on one of the three methods: I) material extrusion; II) particle-bed binding or III) material jetting. For all three methods the same principle of production is applied: material is (mainly) applied in horizontal layers. This principle is challenged by the Injection 3D Concrete Printing (I3DCP) technique, which is presented within this article and which enables a new freedom during the fabrication process as intricate concrete structures can be created through printing spatially free trajectories

Basic principle of Injection 3D Concrete Printing

Injection 3D Concrete Printing (I3DCP) is a unique additive manufacturing technique recently developed by researchers at TU Braunschweig [4–6] and in variants by others [7, 8]. The basic principle of I3DCP is that material (A) is robotically injected into a material (B) with specific rheological properties. When mastering the process properly, material A remains in a stable position within material B (4). In general, I3DCP can be categorized into three sub-categories:

1. Concrete in Suspension (CiS): injection of concrete into a non-hardening carrier liquid;
2. Suspension in Concrete (SiC): injection of a non-hardening suspension into a concrete; and
3. Concrete in Concrete (CiC): the injection of a concrete into another concrete with different properties.

With the first sub-category, CiS, a fine grain concrete is printed into a non-hardening suspension with specific rheological properties. Up to now, ultrasound-gel, limestone suspension with additives, limestone-and ultrasoundgel-mortar have been investigated [5, 4]. Using this technique, complex truss structures and filigree concrete space frames that are otherwise challenging or impossible to construct can be created. The basic principle of fabrication with the CiS-method is shown in Figure 1.

With the second sub-category, SiC, the CiS-process is reversed: a non-hardening suspension is injected into a formwork, which is filled with a hardening material such as concrete. After hardening of concrete, the non-hardening suspension is taken out, leaving cavities or channels behind. This can be used for example to grade concrete components by differentiating its density at specific locations. In Figure 2 the schematic SiC-process is shown.

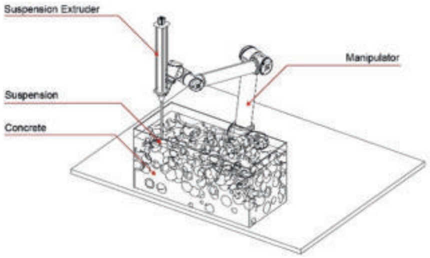


Fig 2: Principle of Suspension in Concrete (SiC) [4]

The third sub-category of Injection 3D Concrete Printing is called CiC. Here, concrete is used as injected material and as carrier liquid. The main benefit is, that the material properties differ according to functional needs making it for example possible to locally strengthen structures. A schematic fabrication process is shown in Figure 3. This sub-category enables – in contrast to the other variants – a permanent (mechanical) bonding between the two materials (A) and (B).

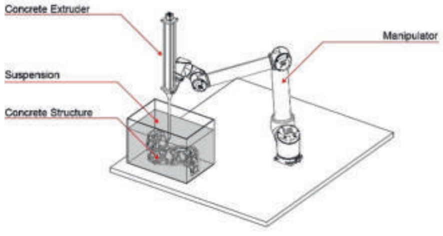


Fig 1: Principle of Concrete in Suspension (CiS) [4]

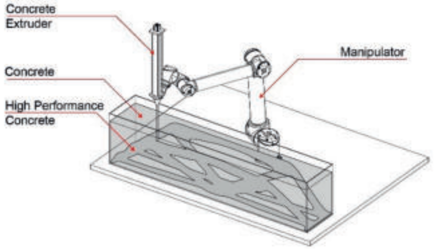


Fig 3: Principle of Concrete in Concrete (CiC) [4]

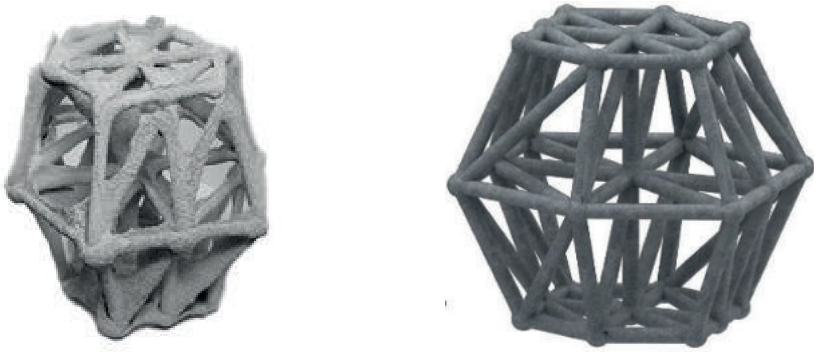


Fig 4: Concrete in Suspension (CiS) demonstrator: design (right) and printed object (left) [4]

Current applications in Injection 3D Concrete Printing

Up to now, first applications of the mentioned techniques are realized and will be presented in the following.

(1) Concrete in Suspension (CiS)

The first small-scale applications in CiS show polyhedral spaceframe structures with a hexagonal base, which were printed in a 50x50x50 cm³ container, Figure 4.

Xiao et al. [6] showed further potential of the CiS-technique, by aligning the spatial stress trajectories, which can be simply treated as strut-and-tie networks in the truss system, with the print path. The fabricated geometry was found by applying Vectorbased 3D Graphic Statics. Graphic statics is a design and analysis method for planar trusses under static equilibrium and provides visual information of the relationship between form and force. With this method, a compression only structure is designed – here a coffee table – which was designed and fabricated in three modules, which were subsequently assembled, Figure 5.

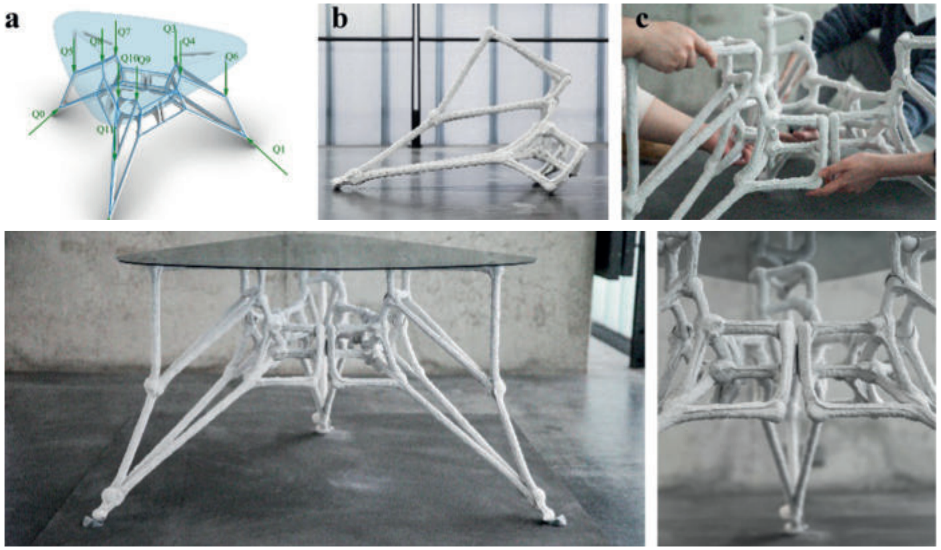


Fig 5: (a) Form diagram of the table; (b) One leg of the table as a segment; (c) The process of assembling the printed segments into a whole table (top); the assembled lightweight concrete table demonstrator (bottom) [6]

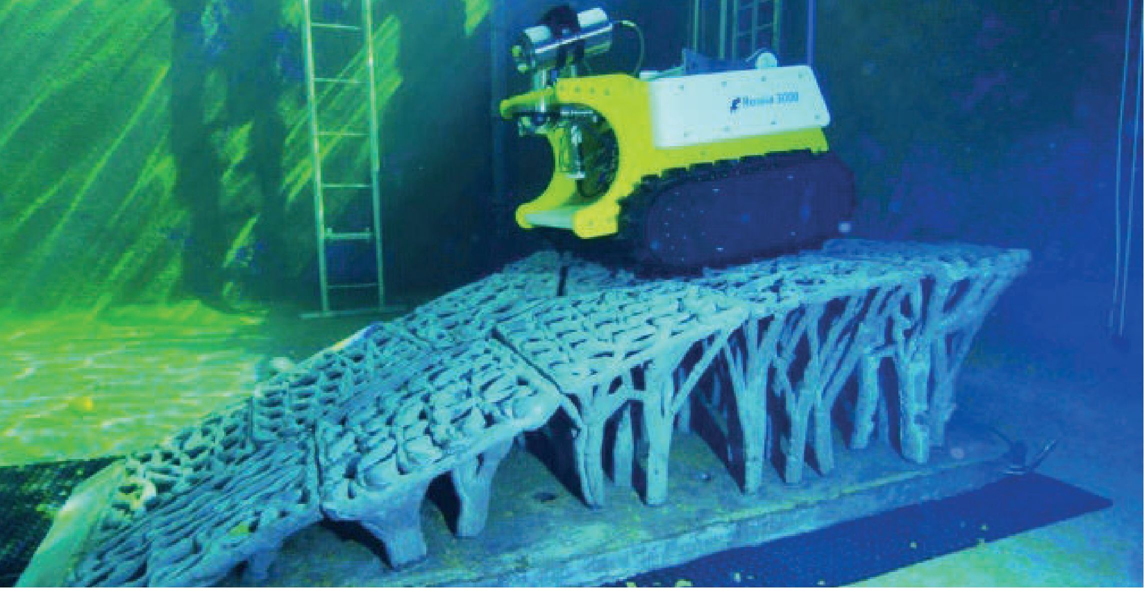


Fig 6: Sampling robot BathyBot on BathyReef structure
(credits: D. Guillemain, CNRS).

A first large-scale application was presented by Soliquid [8], who used the CiS technique in order to print an artificial reef called BatchReef with an industrial robot, which is composed of fifteen 30-120kg modules with a total weight of 2.5 tons, which was submerged in 2022 south of Toulon (France) in 2,550m depth [9], see structure in Figure 6. For this kind of applications, I3DCP offers rapid construction progress, making it possible to design complex parts while saving material.

The BathyReef-project indicates that large innovative lightweight concrete structures have a lot of potential. To further demonstrate the design and structural potential of the I3DCP technology, a large-scale demonstrator for above-ground construction was developed for Time Space Existence Exhibition organized by European Cultural Centre (ECC) during Venice 2023 Architecture Biennale [10]. In an extensive collaboration by researchers at TU Braunschweig, TU Munich, TU Berlin and ETH Zurich an I3DCP bridge was designed (compare rendering of the first concept, Figure 7 and further development of it in [11]) and then built without formwork. It demonstrates the possibility to integrate structure- and fabrication-informed strategies in I3DCP at the early phase of design.

Fig 7: Rendering of the first design of the Injection 3D Concrete Printing demonstrator (bridge with 10m length) based on the principles of graphic statics. Designed by P. D’`Acunto (TU Munich) and O. Ohlebrock (ETH Zürich) [5]

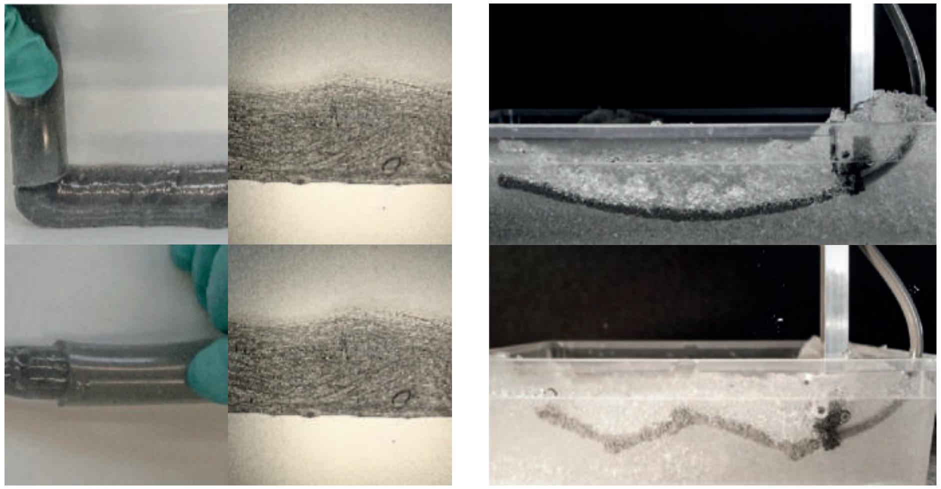


Figure 9: Visualization of fiber alignment for vertical and horizonal extrusion (left) and extrusion with dynamic print head in application (right) (12)

From the shown examples it is clearly visible that the CiS technique allows producing light and complex structures. However, for practical applications where bending and imperfections come into play, the structural quality needs to be improved by implementing reinforcement. First concepts have been presented by Adams et al. [12], who successfully extruded fiber reinforced cement paste to improve the tensile strength and ductility of printed strands. As the fibers' structural effect depend on their orientation in the matrix, they developed a dynamic print head that increases the rotation freedom of a nozzle without harming its robot reachability, Figure 8 and Figure 9. With this, controlled extrusion of the fiber reinforced cement paste was possible, which enables additional axes of reinforcement orientation. This work demonstrates that new fabrication methods require not only an understanding for material but it is also needed to rethink the tools for production to exploit the full potential.

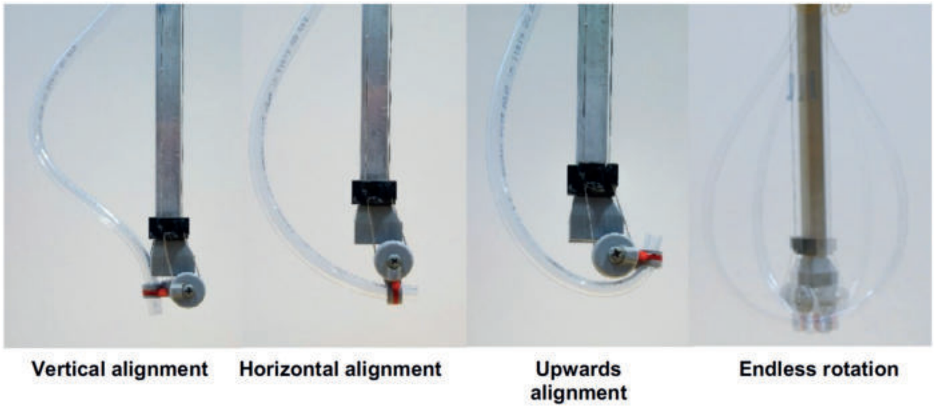


Figure 9: Endeffector for controlled extrusion of fiber-reinforced cement paste [12]

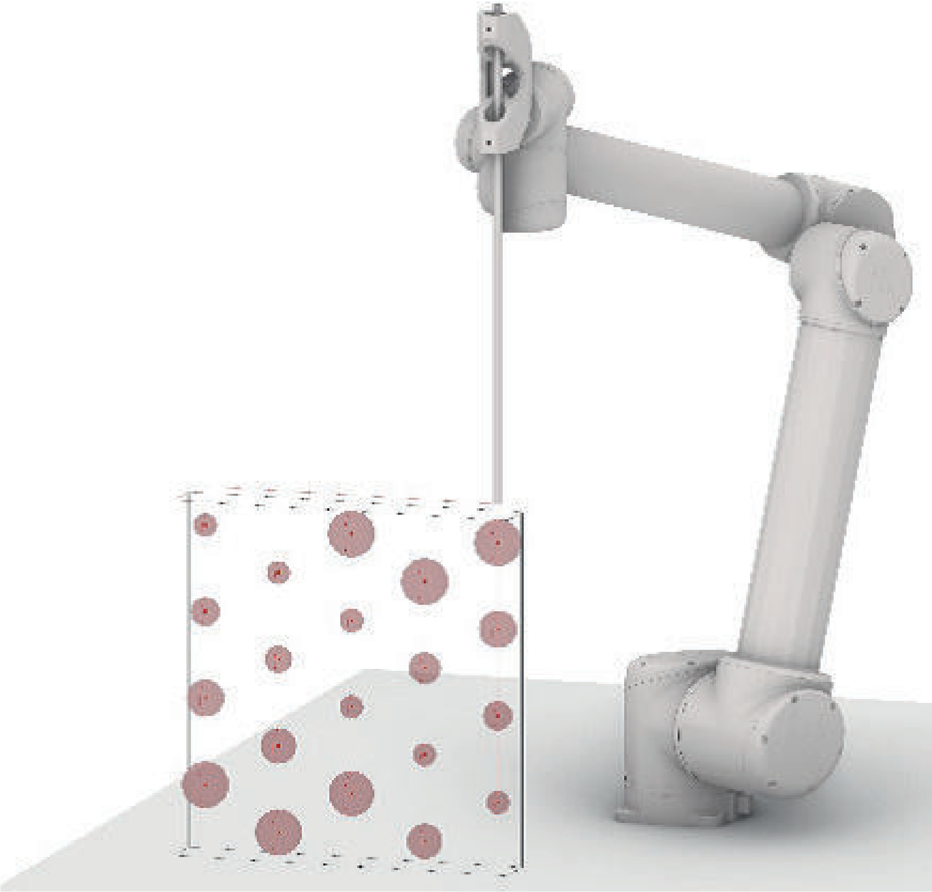


Fig 10: Schematic Suspension in Concrete (SiC) process (top) and 30x30 cm² application (bottom) [4]

(2) Suspension in Concrete (SiC)

The material-process-interaction of SiC is not fully understood yet. However, a perforated façade panel shows potential architectural applications, Figure 4. In a small-scale experiment, displacement bodies consisting of a sand and ultrasound gel, were injected in a fine grain concrete according to a point pattern which is computationally generated [4]. For the designated object "displacement" suspension which differs in volume was injected in concrete. This was realized by varying the duration of extrusion at each point. The printing was realized from bottom to top, so no self-intersection occurred. In this demonstrator the implemented wholes were conceptually used for façade greening elements, Figure 10 right.

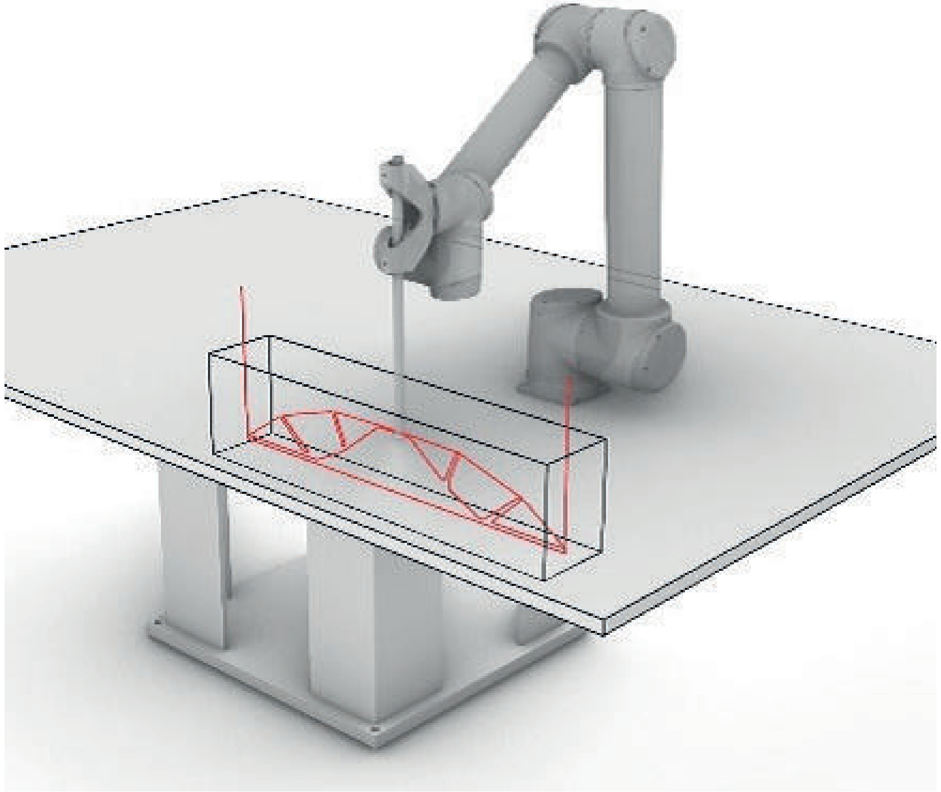
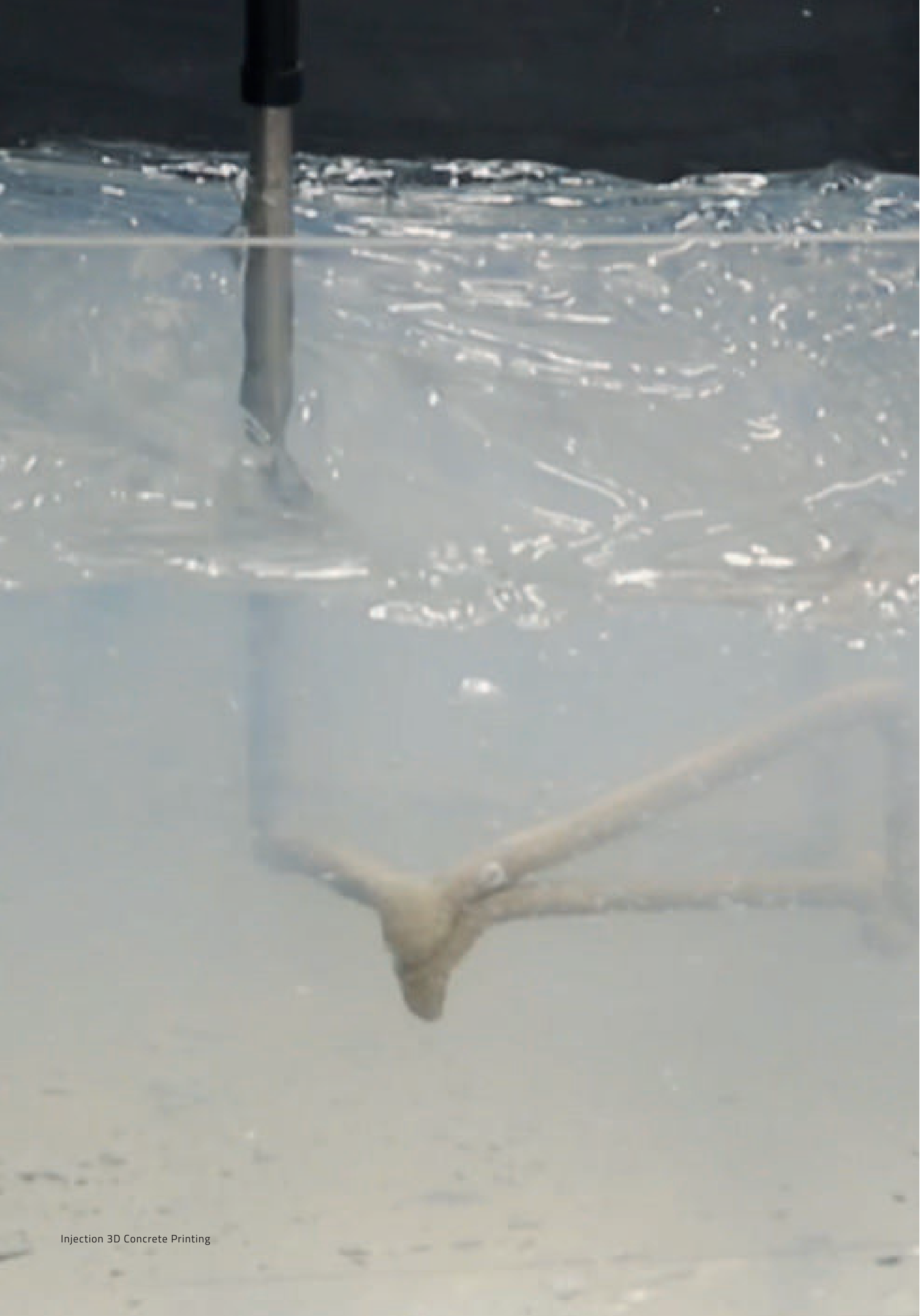


Figure 11: Concept of the Concrete in Concrete (CiC) process (top) and cross-section of one printed sample with two different concretes (bottomn) [4]

(3) Concrete in Concrete (CiC)

As a proof of concept for the CiC-technique, there exists up to now one small-scale concrete beam, which includes an optimized topology with concrete with differing properties, which is printed with one continuous path, Figure 11. In general, the differing properties may result e.g. from incorporating environmental friendly, high performance or very light materials. For larger applications, one of the main challenges will be dealing with the change in rheological properties of the carrier liquid, i.e. concrete, over time, which continuously modifies the boundary condition for a successful print.



Current challenges in Injection 3D Concrete Printing

It became obvious, that it is of utmost importance to control and master the material and process parameters in order to successfully conduct Injection 3D Concrete Printing, see also extensive studies and modeling in [5]. As process parameters, extrusion flow rate, the velocity of the (robot-guided) nozzle and the cross-sectional area of the nozzle have been identified to be relevant for a stable printing result. As material properties, the density and yield stress of the involved materials, i.e. carrier liquid and injected material, have been found to be relevant in this regard. Here, further research is targeted in order to fully understand and master the interaction of these (and potentially further) involved parameters also for longer time spans. Besides, reinforcement integration and 3D pathplanning are topics, which will be further developed in the nearer future.

Conclusion and Outlook

This article provides an overview about a novel concrete 3D printing technology, called Injection 3D Concrete Printing. Three variations of this method were described: A) Concrete in Suspension (CiS): injecting a fine grain concrete into a non-hardening suspension; B) Suspension in Concrete (SiC): injecting a non-hardening suspension into a fine grain concrete; and C) Concrete in Concrete (CiC): injecting a fine grain concrete with specific properties into a fine grain concrete with different properties. The technology readiness level of the CiS technique is the highest, as there are numerous applications already. However, also for the SiC and CiC techniques, first studies demonstrate the feasibility of these approaches. For the future, in depth studies for reinforcement integration, 3D-pathplanning as well as mastering and controlling material and processes for longer periods of time will be central challenges.

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Composite thin glass panel with a 3D printed sine wave core pattern

THIN GLASS COMPOSITED WITH 3D PRINTED POLYMER CORES

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Abstract

Thin glass is currently mainly used for displays on electronic devices, but it also offers interesting characteristics for architectural applications. Due to its high strength and small thickness the glass can easily be bent in architecturally appealing curvatures, while the small glass thickness (≤ 2 mm) offers a significant weight reduction compared to traditional window glazing. Research at TU Delft and TU Dresden focuses on exploiting these beneficial characteristics for the creation of lightweight composite façade panels. More specifically, composite panels are developed that consist of thin glass outer facings which are adhesively bonded to an inner stiffening 3D-printed open-cell polymer core. Besides the benefits of high strength, high stiffness and low weight, the composite panels also offer the potential to influence daylight entry through customisation of the 3D-printed core pattern. The current contribution highlights the current state of the research activities and describes the concept of the thin glass composite panels, their constituent components and the related digital fabrication process.

Introduction

The current contribution focuses on composite panels that consist of thin glass cover layers and 3D-printed polymer core structures that are adhesively bonded to the glass, see Figure 1. The main benefit of such panels is that they are lightweight, strong and stiff. Furthermore, the panels are to a large degree transparent and offer a certain insulating performance through the sealed cavity between the glass layers. These composite panels thus offer interesting characteristics for architectural applications, such as façades (see Figure 2), separation walls, or even floors. Compared to traditional glazing solutions, the use of thin glass with a thickness of less than 2 mm in combination with the stiffening polymer core offers a potential reduction of up to 80% of the glass used. Besides (raw) material and embodied energy savings, this translates into a significant weight reduction of the panels, making transport, handling and installation much more (energy) efficient and convenient. Furthermore, due to the small thickness and high strength of (pre-stressed) thin glass, it can also be easily bent in architecturally

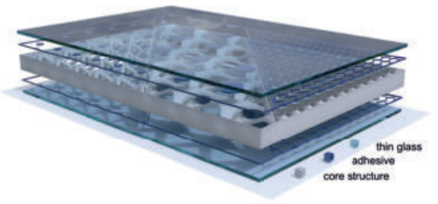

Fig 1: Rendering of the composite panel with thin glass as cover layer, an adhesive bond and a 3D-printed core structure.

appealing curvatures, offering further possibilities for architectural applications.

Research on these composite panels has been ongoing for the past years. While the initial concept was developed at TU Delft [1] and explored on small scale prototypes, the research has now evolved towards large-format prototyping and experimental testing at TU Dresden. Further studies are performed in a joint effort between the institutions and additional R&D projects with industry partners have started.

The subsequent paragraphs provide an overview of the constituent components of the composite panels, their fabrication process, the result of an exploratory wind load test, followed by an outlook into future research. Parts of the current contribution are based on [2].

Fig 2: Rendering of a composite thin glass façade panel with 3D-printed core structure.

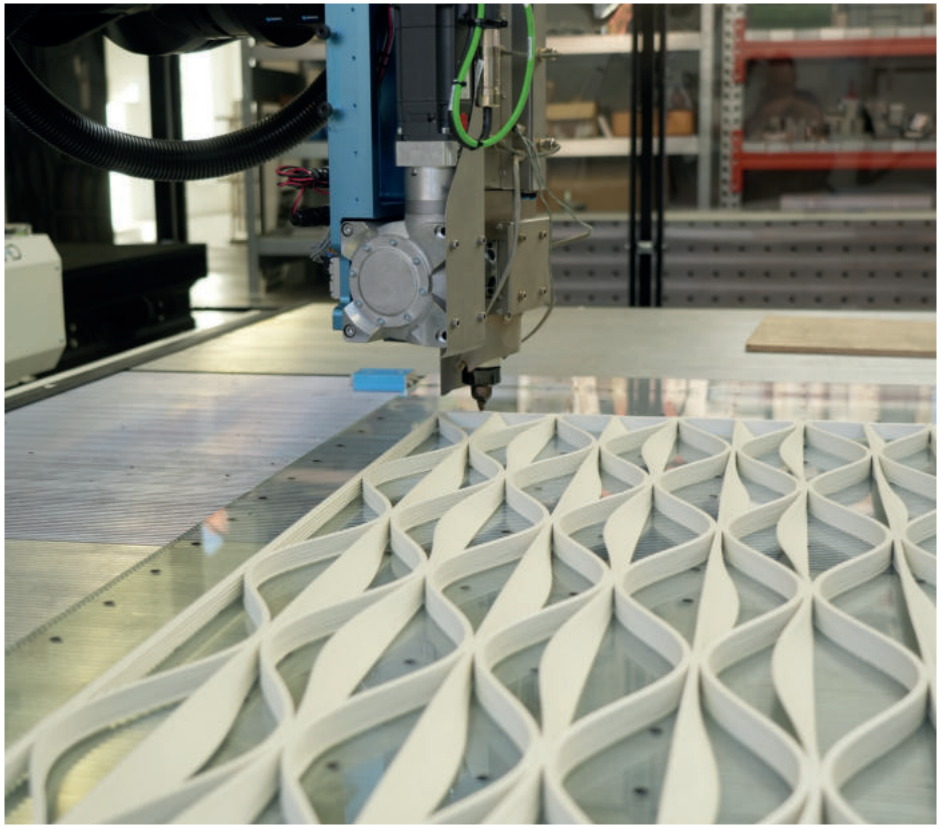

Fig 4: 3D-printing of the composite thin glass panel with a 3D-printed sine wave core pattern

Fig 3: 3D-printed honeycomb core pattern.

Thin Glass Cover Layers

The thin glass that is used usually for displays on devices such as smartphones and tablets, offers promising characteristic for the building industry. Due to its high strength and low thickness, very light and material-efficient façades can be designed. The low geometric stiffness allows a high degree of design flexibility, such as cold bend curved glass panels. Of particular interest for this research is aluminosilicate glass with a thickness in the range of 0.5 – 2.0 mm and a high strength that is obtained through a chemical prestressing process. Additionally, also standard soda-lime silicate glass with a thickness of 3 mm and below is used.

Core Structure

The 3D-printed polymer core structure is an essential element of the composite panel as it provides stiffness to the panel and prevents too much out-of-plane deformation. Besides enhancing the structural performance of the panel, the core structure can also be exploited for daylighting purposes through either blocking or redirecting of incoming light through the shape of the core structure. Moreover, the shape of the core structure also provides a specific aesthetical quality to the panel and can be used for individualised designs.

In preliminary investigations, some core structures were examined for their structural design suitability [3]. From a mechanical point of view, the triple-periodic minimal surface of the Gyroid core pattern turned out to be particularly efficient at a smaller scale. Alternatively, stress line generation could be a possible approach for optimizing the stiffness of the core while keeping weight as low as possible [4]. However, the honeycomb core pattern, which is widely used for sandwich structures, is currently used as a reference core structure in recent research developments, see Figure 3. This basic shape brings rapid progress in manufacturing, especially through simple tool path programming. Its properties in composite panels have been extensively investigated [5–7] and the appearance can be changed in a variety of ways through the use of parameterization and can also be used for initial optimization concepts.

Based on that honeycomb core pattern and inspired from polymer 3D-printed interior wall panels [8], the wave pattern has been developed to open new design perspectives, see Figure 4 and 5. It consist of orthogonal frame lines and inclined function lines, which can be adapted to provide further features like shading and aesthetical preferences.

Fig 5: Composite thin glass panel with a 3D-printed sine wave core pattern.

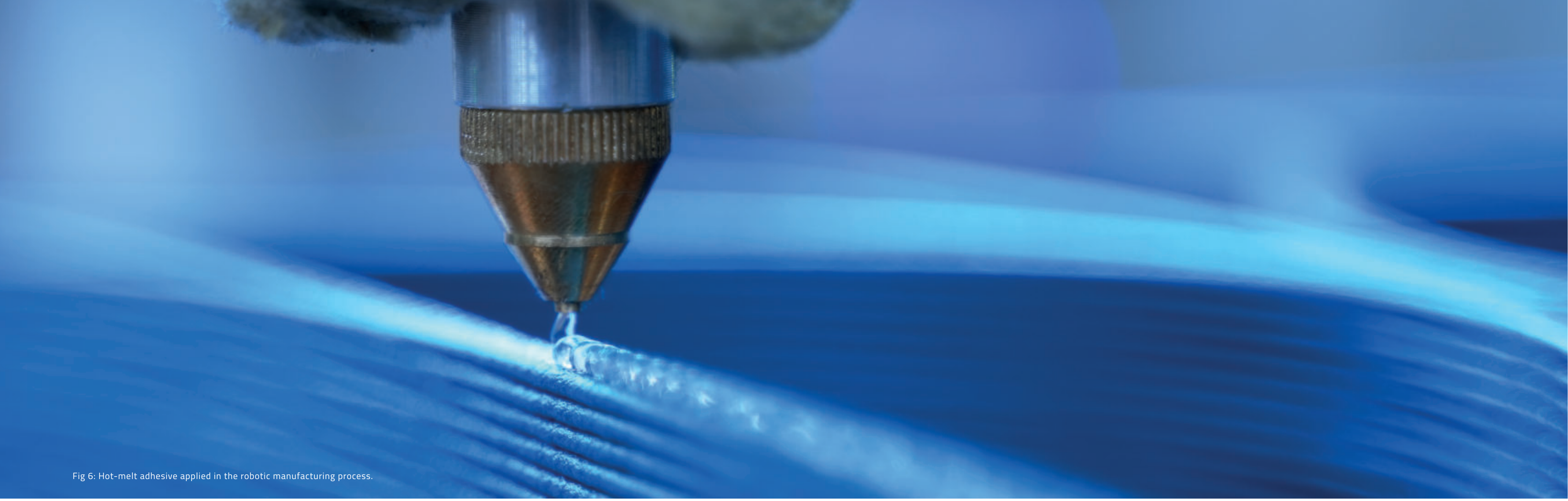

Fig 6: Hot-melt adhesive applied in the robotic manufacturing process.

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Core material

When selecting the polymer for the core structure, a wide range of thermoplastic polymers can be considered with the applied extrusion process (fused deposition modelling). Initial preliminary investigations of small-format materials have already reduced the number of polymers that are considered suitable for use in a façade [3]. Polycarbonate (PC) and Polyamid (PA) is currently most promising because of its heat and UV stability as well as its high stiffness. Due to the additional technical and monetary effort involved in processing PC, glycolmodified Polyethylene Terephthalate (PETG) is being used for the production of the first prototypes. This is particularly straightforward to process at relatively low temperatures and bears a lower risk of thermal stresses and distortion in the component. The prototypes shown in the current contribution are made from a post-recycled PETG with a glass fibre content of 20%.

Adhesive

To join the thin glass with the core structure, different adhesives are investigated [9]. The adhesive provides a mechanical connection transferring loads through the composite panel. When it is exposed to bending moments, the adhesive joint is under shear stress. Therefore, stiffer adhesives are favourable to reduce deflections. Here, UV-curing acrylates have served as a starting point for the research. But to take thermal stresses into account, certain strain levels must be allowed, which benefits the choice of an adhesive with lower stiffness. This led to the choice of hot-melt adhesives, which can be very well integrated into the robotic manufacturing process, see Figure 6. The applied hot-melt cools down and can then be reactivated in a separate lamination process to provide an adhesive bond to the glass.

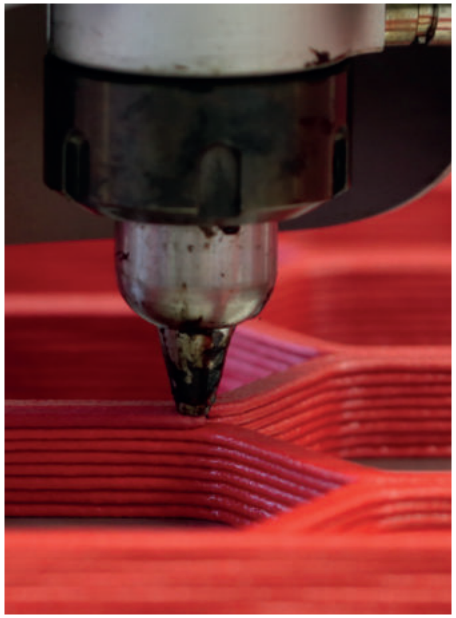

Fig. 7A: 3D-printing process of the polymer core

Fig. 7B: Robotic milling of the core surfaces

Fabrication Process

To take advantage of the possibilities of additive manufacturing and the flexibility of thin glass, the entire process is aimed to function digitally and parametric. Grasshopper is used as a visual programming interface to design a façade as well as the individual panels. Different optimization algorithms are included, to improve various objectives like mechanical and thermal properties, light control or the overall visual aesthetics of the façade.

The program processes the developed core structures in machine readable G-Code and prepares the additive manufacturing, subtractive post-processing and adhesive joining with glass. Figure 7 shows the fabrication steps supported by a robotic arm. In the first step the core structure is 3D-printed onto a heated bed.

In the second step the surfaces of the core structure are milled to allow for an optimal adhesive bond with the thin glass cover layers. In the third step the adhesive is applied. Finally, the glass cover layers are positioned and the adhesive is cured.

Wind Load Test

The structural response of the thin glass composite panels was investigated by means of an exploratory wind load test. For this, a prototype of about 2 m by 1 m was produced and mounted airtight into a façade testing frame, see Figure 8. Within this façade testing an air pressure or suction is created behind the panel, thereby loading the composite panel in out-of-plane direction. The load was applied in steps of 1 kN/m2 until a maximum of 4 kN/m2. During the test, the deformation of the panel was monitored by means of displacement sensors and a Digital Image Correlation system. This exploratory test demonstrated that the panel could resist extreme wind loading. The panel remained intact and the deformations remained within the required limits.

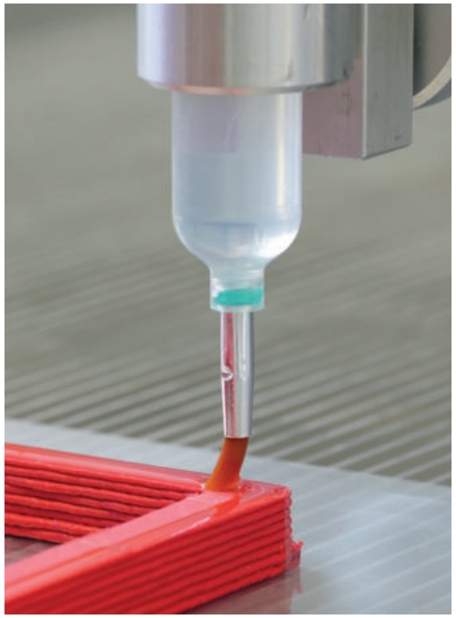

Fig. 7C: Robotic application of the adhesive

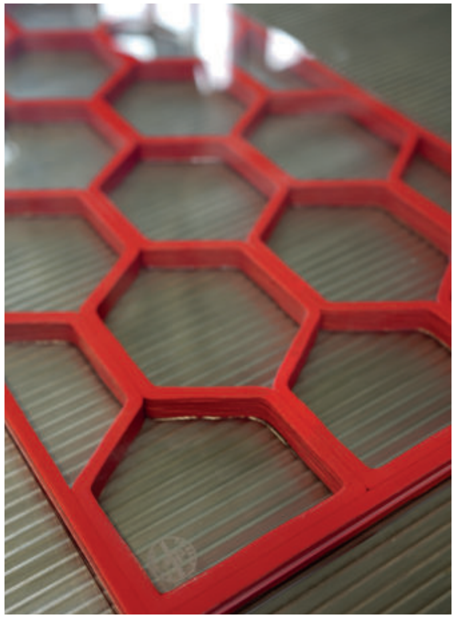

Fig. 7D: Application of the glass cover layers and curing of the adhesive

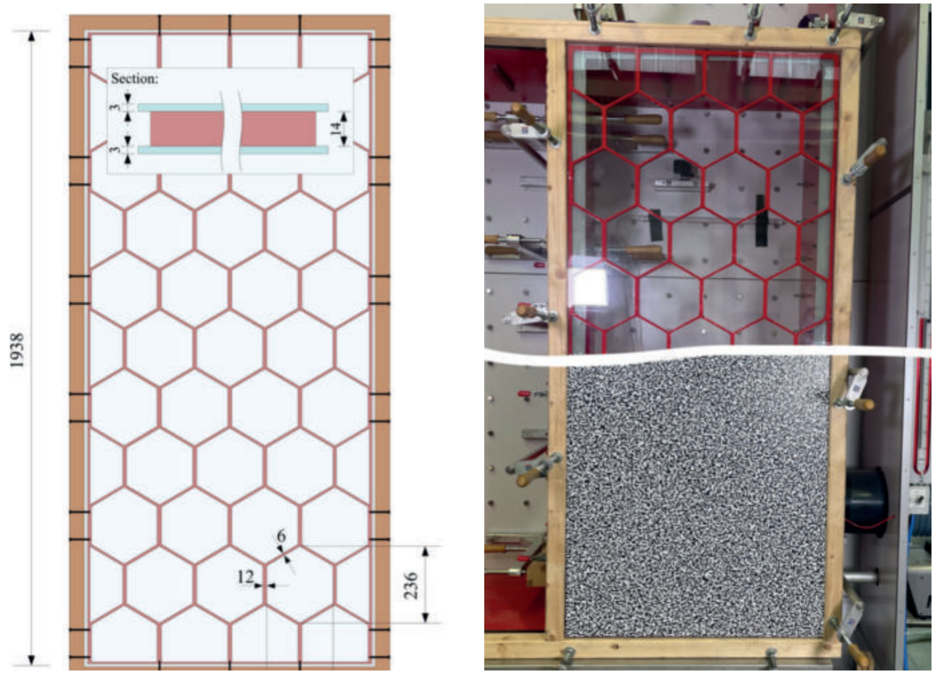

Fig. 8: Composite panel prototype mounted in a façade test rig for investigating the effects of wind loading. The bottom-right image shows a speckle pattern on the glass, which is needed for the digital image correlation system

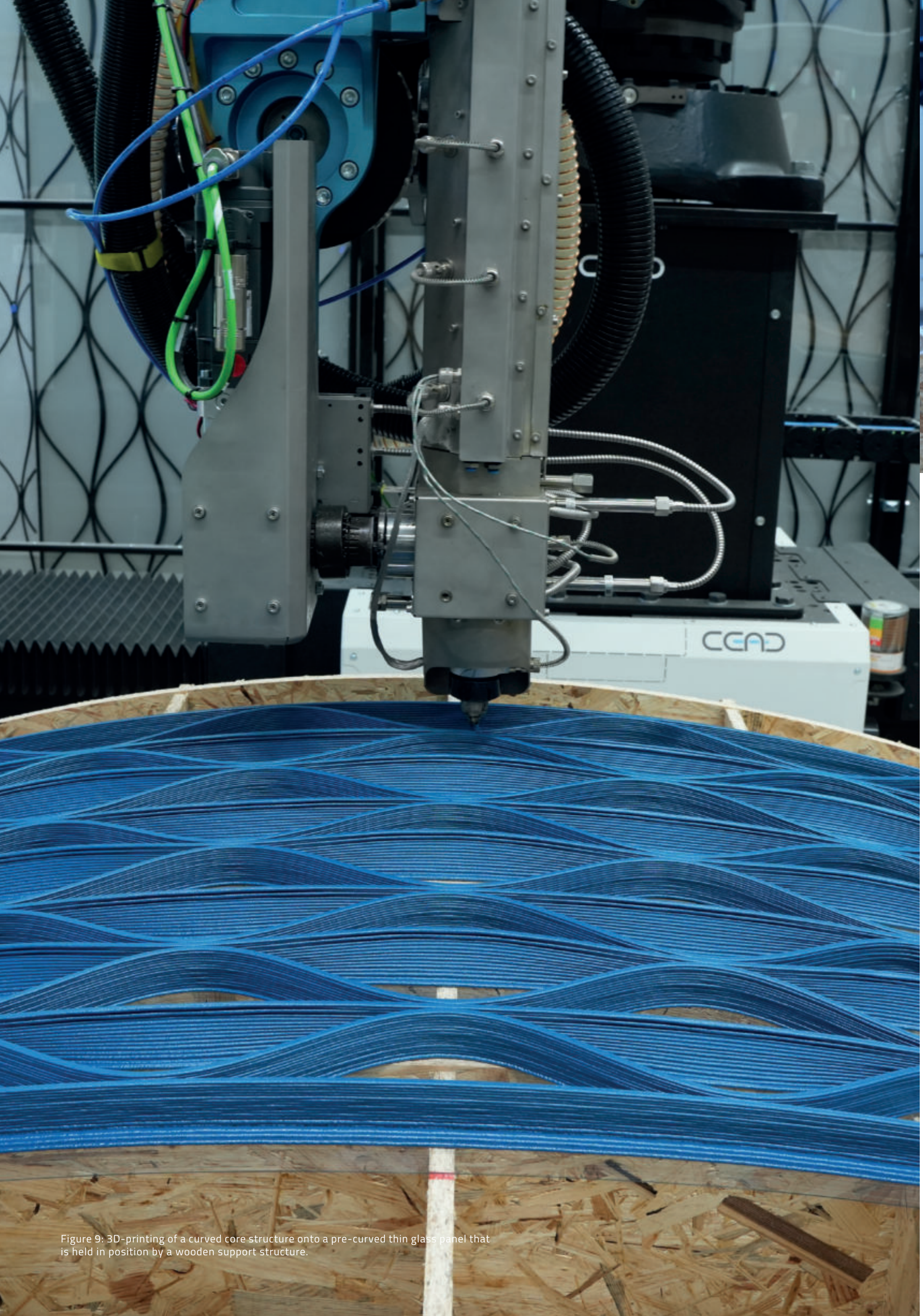

Figure 9: 3D-printing of a curved core structure onto a pre-curved thin glass panel that is held in position by a wooden support structure.

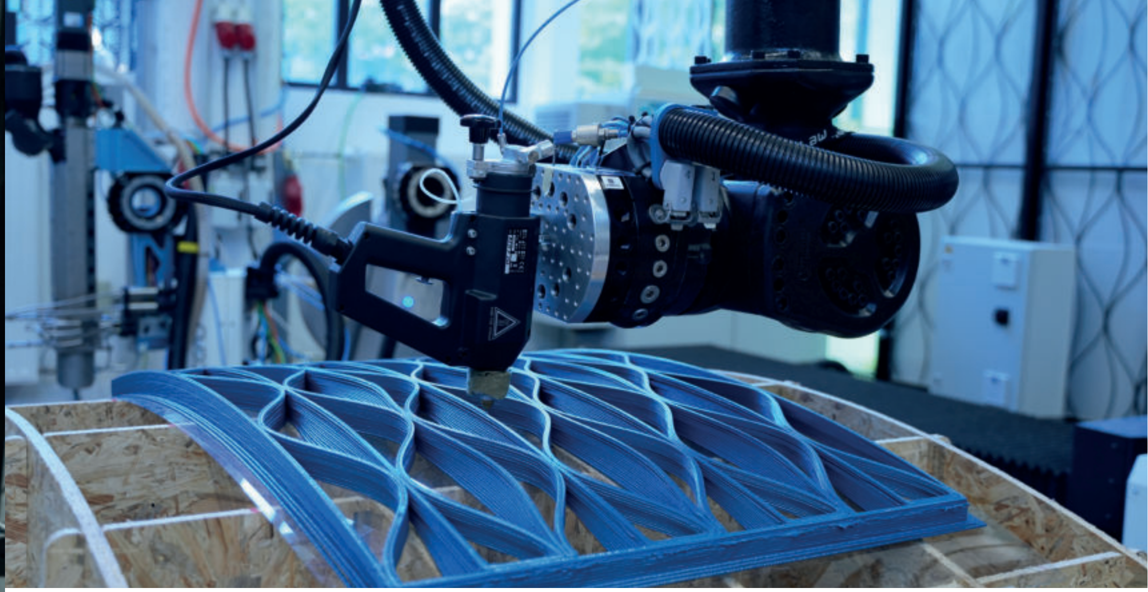

Figure 10: Robotic application of the hot-melt adhesive on the curved core structure.

Outlook

One of the next main challenges in the research is the creation of curved composite panels. This allows to take full benefit of the easy bendability of the thin glass in creating architecturally appealing curvatures. First attempts have revealed promising results, see Figure 11. To avoid the need for 3D-printing of support material, the curved core structure is printed directly on a surface with predefined curvature supported by a wooden support structure, see Figure 9. Afterwards the hot-melt adhesive is applied on the core structure, see Figure 10. The hot-melt is allowed to cool down during this process and is re-activated in a following lamination process. The thin glass is pressed in the curved position onto the core structure. Now it can be reheated to melt the adhesive and provide a load bearing connection after cooling down. The use of physically curing adhesives facilitates possible disassembly after use and offers advantageous recycling possibilities. Further prototyping results and investigations of their structural performance are expected to be published soon.

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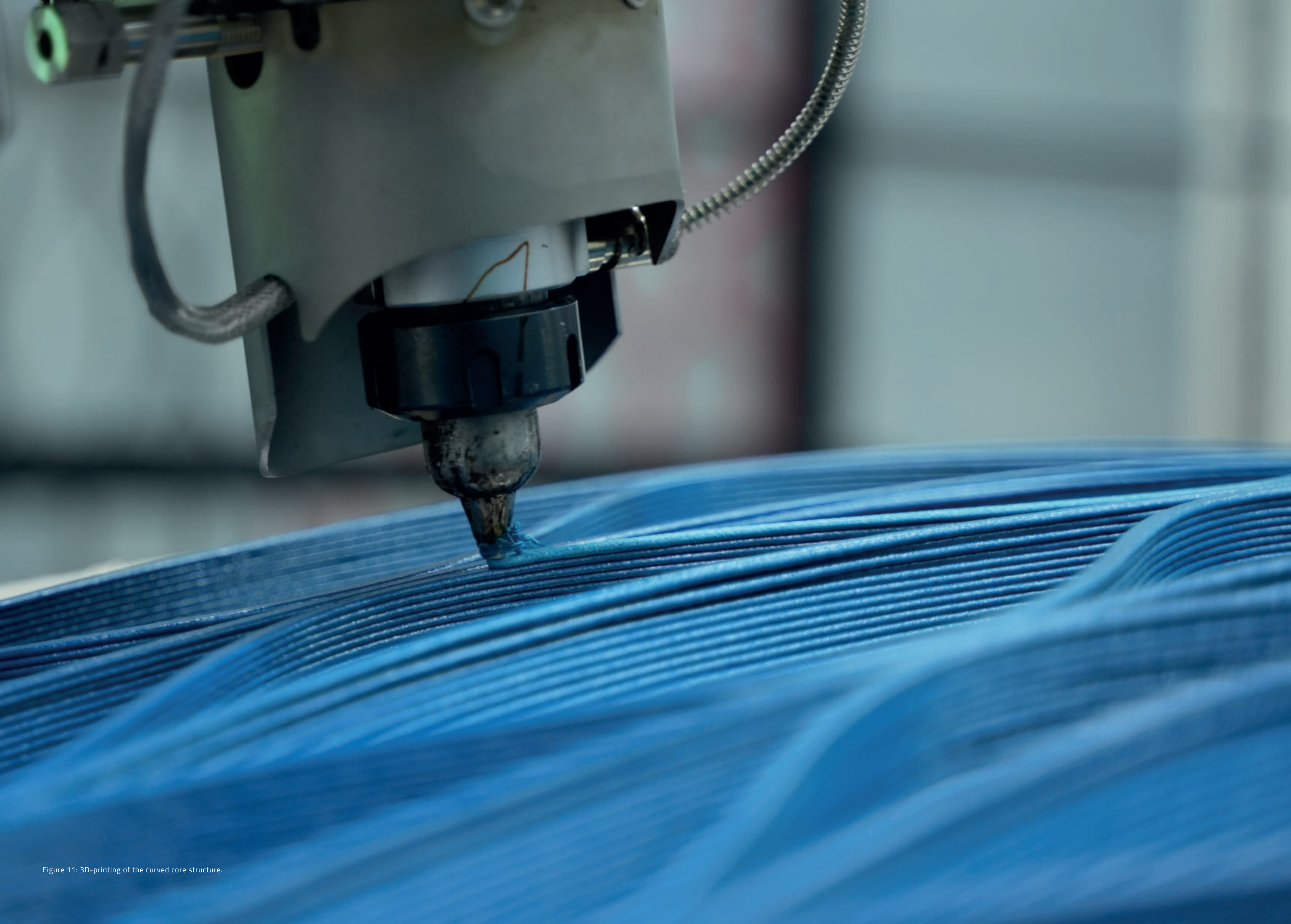

Figure 11: 3D-printing of the curved core structure.

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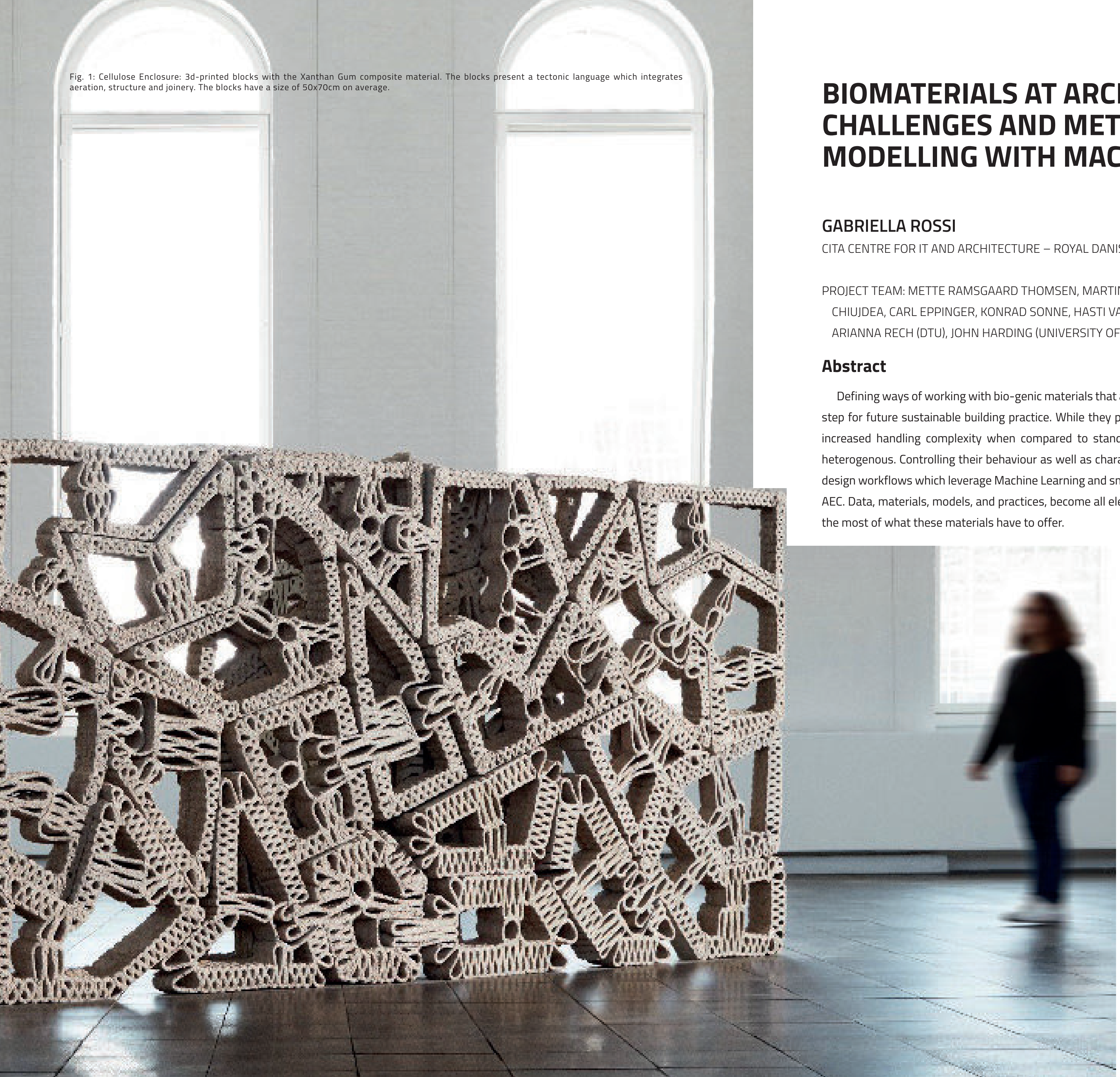

Fig. 1: Cellulose Enclosure: 3d-printed blocks with the Xanthan Gum composite material. The blocks present a tectonic language which integrates aeration, structure and joinery. The blocks have a size of 50x70cm on average.

BIOMATERIALS AT ARCHITECTURAL SCALE: CHALLENGES AND METHODS FOR HYBRID MODELLING WITH MACHINE LEARNING

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Abstract

Defining ways of working with bio-genic materials that are inherently regenerative and biodegradable is an important step for future sustainable building practice. While they provide a smaller embodied carbon footprint, they come with increased handling complexity when compared to standard industrialized materials: they are both anisotropic and heterogenous. Controlling their behaviour as well as characteristics, performance and lifespan through novel data-rich design workflows which leverage Machine Learning and smart fabrication pipelines, can push for biomaterial adoption in AEC. Data, materials, models, and practices, become all elements of design of which the architect orchestrates to make the most of what these materials have to offer.

Urgent need for material shift

The year 2023 has recorded the highest number of climate anomalies ever documented [1]. This escalation in climatic disruptions occurs in conjunction with other socio-economic crises, including the aftermath of a global pandemic, escalating living costs, and ongoing conflicts, thereby spotlighting the inherent fragility and unsustainability of contemporary, post-industrial societies. In this volatile milieu, the Architecture, Construction, and Engineering (AEC) sector occupies a pivotal role, both as a significant contributor to environmental footprint but also as a potential catalyst for achieving Sustainable Development Goals [2,3]. Conventional construction practices, passed-down to us by the Industrial Age, are increasingly under scrutiny for their unsustainable extraction of virgin materials, excessive waste generation, and substantial carbon emissions.

In Europe, a concerted effort is underway among architects, urban planners, and policymakers to steer the AEC sector toward decarbonization and implement more sustainable construction methodologies [4,5]. Two principal categories of non-standard materials are at the forefront of this shift: recycled building elements and natural, bio-based materials. The incorporation of bio-based materials into mainstream architectural applications is especially important for its promise to redefine the sector's approach to resource management and material circularity [6]. These materials, sourced from abundant, renewable, and biodegradable natural elements, present a viable alternative to conventional building materials [7,8] However, their utilization comes with a set of unique challenges, primarily stemming from their inherent dynamic behaviors and complex heterogeneity, factors that differentiate them sharply from industrialized materials [9,10].

Modeling bio-based materials for architecture

Digital modeling, which serves as a cornerstone in architectural design thinking, becomes particularly complex when dealing with these non-standard materials. Traditional modeling practices oscillate between two dominant paradigms [11] : one views material as passive abstract matter, primarily observed in applications of Building Information Modeling (BIM) in industry; the other sees material as an active agent of form, usually confined to academic research settings [12,13]. Existing engineering models, built on long-standing paradigms of classification, standards, and mechanistic representations, fall short of adequately capturing the unique attributes and behaviors of bio-based materials. This is particularly true for biopolymer composites, a category that remains largely unexplored from an engineering standpoint [14].

The absence of a reliable framework for modeling bio-based materials thus poses a significant hurdle to their broader architectural application, calling for the urgent development of a new modeling infrastructure specifically tailored to these materials. This would not only facilitate their integration into mainstream architectural practices but would also significantly contribute to the larger efforts aimed at making the AEC sector more sustainable.

A Data-driven paradigm

There are heightened expectation what role AI and Machine Learning (ML) technology is to play in the AEC sector, mostly due to significant strides in computational power, integrated methodologies, and the digital capacity to generate, represent, and store data in information-rich modeling environments [15,16]. However, the actual integration of ML in architectural practices is confronted with intricate challenges relating to data congruency and quality, where data often exists in a variety of inconsistent formats that do not align with the requirements for effective ML training [17] - a problem often referred to as GIGO (Garbage In, Garbage Out).

This challenge is not restricted the architectural discipline alone. The adoption of ML has experienced noteworthy momentum in natural sciences, specifically within material sciences, where it has spawned a sub-branch known as material informatics. "Data-Driven" is recognized as the fourth scientific paradigm, succeeding empirical science, model-based theoretical science, and computational science [18]. Similar to architecture, material sciences also finds obstacles tied to the specific physicality of data, rendering it time and resource-intensive to collect and curate. Such limitations often make the data non-transferrable across different problem domains [19]. However, there's a growing recognition that the initial sunken costs tied to data curation are justifiable when weighed against the benefits gained from adopting an ML paradigm. This is increasingly evident when compared to traditional methods that rely solely on mathematical modeling or simulations, where the complexity of the process to model would be too high.

In ML, the significance of the dataset used for training is as crucial as the model itself. Two aspects become paramount: Dataset composition, and dataset encoding [20]. Certain rules need to be followed when designing datasets that successfully encapsulate the features and space of the problem they intend to model. Important dataset qualities are that the data should be well distributed, feature signals should be clear, feature representation should be balanced, and the more datapoints, the better the algorithm should perform. Correctly representing the design-space breadth and relevance becomes central. In the case of digital fabrication for example, the datapoints should both be able to embody pertinent fabrication parameters linked to the specifics of a given material system and represent valid designs while the sampling range of the datapoints should allow to interpolate the prediction to future unknown samples. This presents a generalization vs specificity dilemma – where does one draw the line of what the model can or cannot predict. Secondly, Determining the level of abstraction of the problem representation is crucial for a successful encoding of the dataset. This level of abstraction is not obvious. Physical samples can be represented in different ways with more or less direct correlation between the physical object and its datapoint descriptors. This choice is subsequently reflected on the model where one that handles numerical input is not only less complex than a model that handles 3D point clouds for example, but is also less data hungry. Another aspect is the possibility of some data-types to be augmented, therefore making the most out of a small group of physical samples.

Machine Learning applications for biopolymer 3Dprinting

At CITA we have been researching large-scale 3d printing with biopolymer composites over the last 3 years

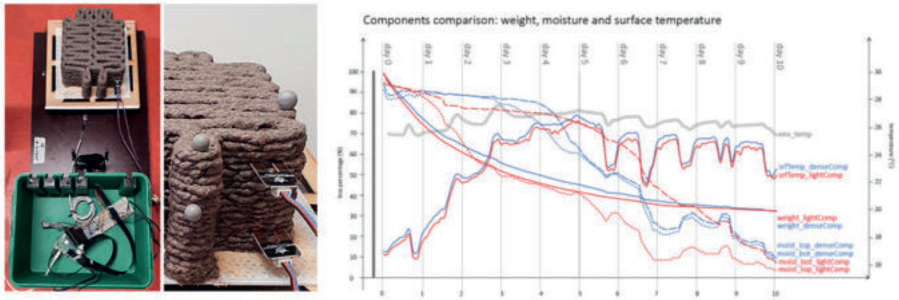

Fig. 2: Material Monitoring Framework. Example of data-gathering from physical samples here a time-stamped recording of the curing of a xanthan-gum biopolymer 3d printed component over a period of 10 days after printing.

Fig. 3: Close-up details of Cellulose Enclosures. The interlocking of the structure is guaranteed thanks to the male-female joinery as well as the component outlines which stack in compression.

Fig. 4: Robotic 3dprinting of the demonstrator components, and subsequent point-cloud tracking of the geometric deformations due to evaporative cooling

through DFF-funded project Predicting Response, ERC-funded project Eco-Metabolistic Architecture and BBSR-funded exhibition Living Prototypes, in collaboration with the Danish Polymer Center at DTU and the University of Reading, and Cobod. Our focus has been on developing robotic 3d printing workflows and material recipes which enable a large-scale high-volume printing. Our recipes focus on biodegradable and waste-stream materials. Biopolymer composites are typically composed of a binder – a biopolymer- mixed into a solvent and reinforced by fibres – the filler. Their attractiveness lies in their designability: the choice of materials and proportions; and how these considerations coupled with fabrication systems give the material its key properties. We have been working with 2 material systems: Xanthan-Gum based biopolymers, and Collagen-Glue based biopolymers.

Below we present two case studies where ML has been integrated prototypical workflows in order to enable design to fabrication with these heterogenous materials. The main contribution concerns data digitization, data formatting, data augmentation and data visualization, in order to compose relevant datasets, and enable the training of ML models.

Cellulose Enclosure: Predicting geometric deformation

Here we use the Xanthan Gum recipe. A gel-like matrix, to which filler and fiber reinforcements are added, for example recycled paper flock, effectively upcycling another waste-stream material into a structural enhancer for our composite [21]. The slurry is extruded through a 3D printing nozzle mounted on a robotic arm and subsequently undergoes a curing process as its water content evaporates, hardening the material. This bio-composite is primarily employed in the fabrication of self-sustaining interior partition blocks. The design of the printing toolpath is engineered to account for the evaporation-driven drying process, incorporating porous geometries that facilitate airflow and expedite water evaporation. Once the blocks are fully cured, they can be manipulated using traditional woodworking tools, and any leftover material can be rehydrated for subsequent printing tasks [22,23].

While our full-scale demonstrator has verified the material's capability for self-support and stacking, it has also served as the base for a dataset to predict the geometric deformation that subsequent prints would undergo. The dataset is therefore composed of datapoints that stem from a real design-scenario. Rather than adopting a deep-learning approach using raw point-cloud data, a feature-engineering based approach is adopted where select geometrical features are encoded numerically. This allows us to perform statistical analysis

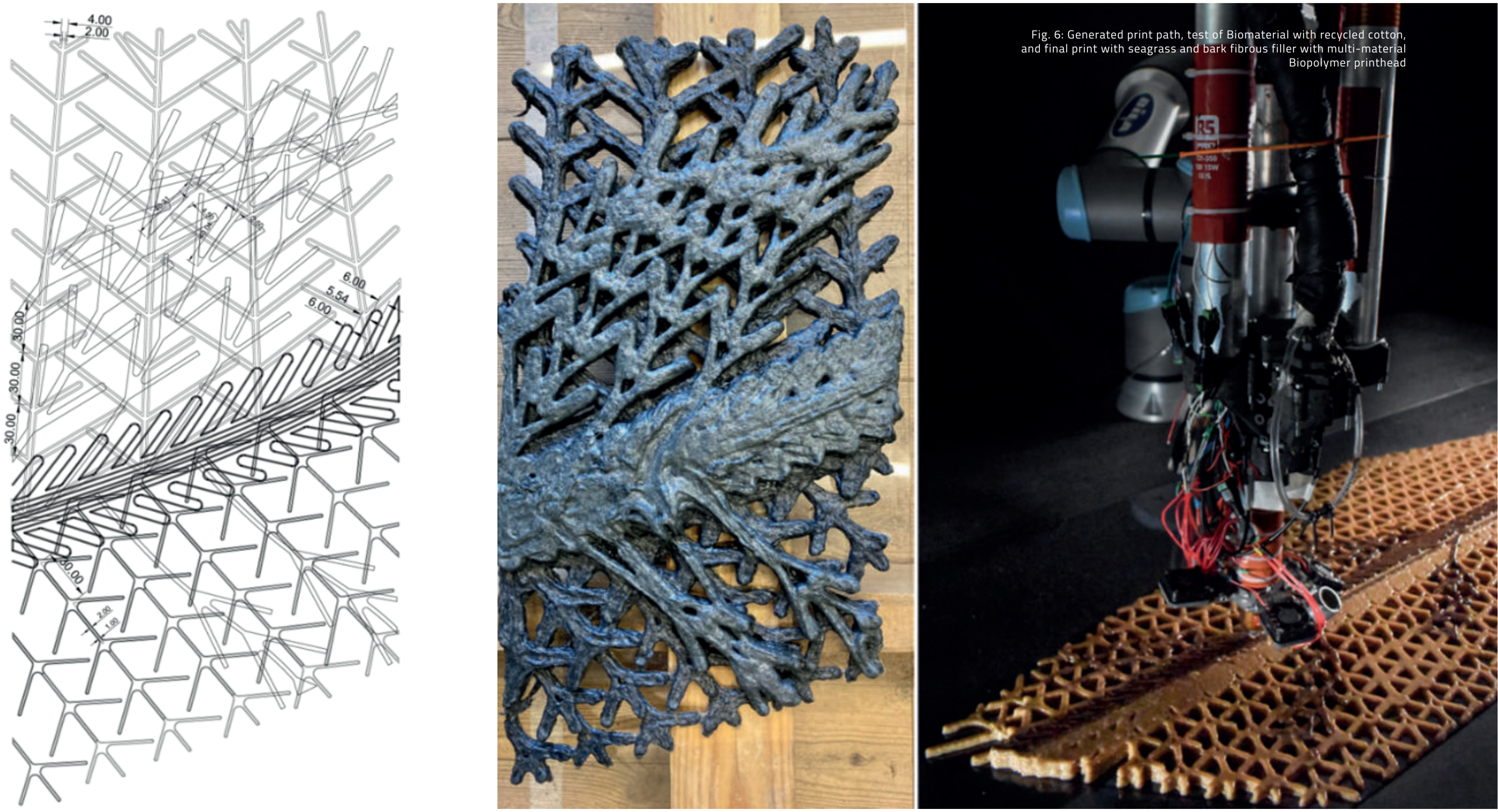

Fig. 6: Generated print path, test of Biomaterial with recycled cotton, and final print with seagrass and bark fibrous filler with multi-material Biopolymer printhead

Fig. 5: Radicant: 3d-printed blocks with the Collagen Glue bio-polymer composite. The panels are composed of interlacing print beads made through material grading, with different fibers and concentrations. The panels size average is 30x50cm

on the data, and to be able to test different types of shallow models and neural networks, which present adequate complexity for the amount of data we have available. The data is collected using a tracking system, it is subsequently compiled and augmented using Tolerance-Informed Gaussian Noise. The dataset is then used to train a Polynomial Kernel Ridge Regressor to predict the vertical shrinkage of the pieces from wet print to dry element [20].

Radicant: Predicting material characterization

Here we use collagen-glue as a binding matrix, and we reinforce the thermally responsive slurry with waste-stream fibers such as wood flour, bark flour, seagrass and recycled cotton fiber. These fibers contribute to the material's structural attributes as well as its aesthetic qualities such as texture, color, and scent. Contrary to the Xanthan Gum-based slurry, which demands a high water content to reach a printable viscosity, the collagen-based composite relies on heat. Within this thermal range, the material is fully recyclable, capable of being remelted and reused with no degradation in structural integrity. In the demonstrator Radicant, we have explored the feasibility of 3D-printing large panels using this collagen-based bio-composite. The project entails the design of complex print patterns aimed at directing the material distribution across a sequence of customized interior architectural panels [24]. Each panel is crafted through varying the fibre content in the base recipe, and this diversification is integrated during the 3D printing process. Our tests have demonstrated that the material can be shaped into double-curved panels when laid on appropriate formwork. At the end of its lifecycle, the material offers diverse disposal options, ranging from reheating and reprinting to granulation for recycling or even biodegradation through composting [25].

The attractiveness of our material system is the capacity to grade the composition of the panels to respond to specific structural performance criteria. However pre-characterizing all possible recipe permutation within the recipe space is an impossible endeavor in terms of time and effort it would entail. In order to overcome this, we develop experimental methodology to predict, with sufficient accuracy, the physical performance of all ingredient permutations within a recipe space, using a very small physical dataset of lab-samples. By leveraging the dimensionality reduction and associative positioning a Parameterless Self-Organizing Maps (PLSOM) we are

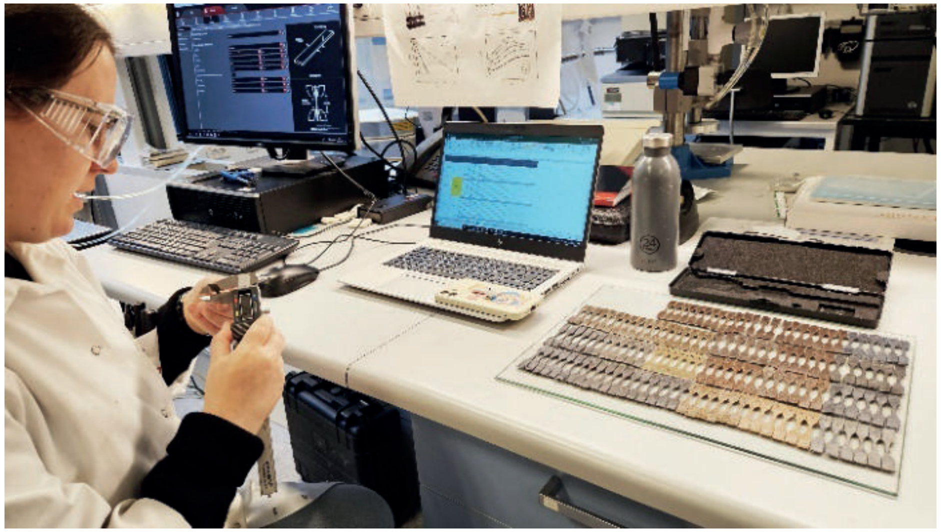

Fig. 7: Dog-bone sample testing at the DPC lab DTU. Six samples of each recipe are produced, hand measured and subjected to stress-strain testing for Training Set compilation.

able to geometrically fit a Polynomial (GPF) model which outperforms state of the art predictive models. The low-dimensional mapping also allows us to develop an intuitive interface to navigate the ingredient-performance response and plugs directly within a computational design workflow [26].

Conclusions

While the presented applications remain prototypical, they showcase great promise to encourage the hybrid modeling of bio-based materials in architecture by integrating Machine Learning workflows within the digital chain. While the main bottleneck to the success of a data-driven workflow is the dataset, we find that through careful consideration with dataset composition and encoding, it can be possible to achieve a useful predictive accuracy using small data and simple ML models. We have showcased how 3D printing presents itself as a unique catalyzing technology, as it fuses material and geometric control. By employing a hybrid ML-aided modeling approach, we are able to prototype the possibilities for the control both of geometric deformation and material characterization, making biopolymer 3D printing a valid alternative as a sustainable material choices in architecture.

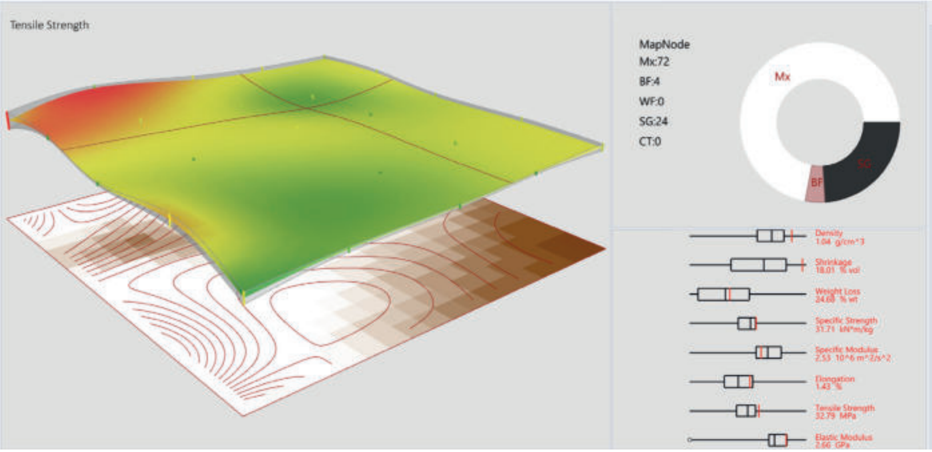

Fig. 8: Recipe Exploration Interface: The recipe base map showing the fiber distribution on which is projected a peformance fitness landscape. The user can navigate the entire recipe composition and understand its perfomance within the recipe space

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Fig 1: Robotic Setup

THE EGGSHELL PROJECT
UN PROYECTO DE HUEVO

DINORAH SCHULTE
MANUFACTURA

Abstract

The need for sustainable practices in multiple industries has led to an increasing demand for circularity, waste reduction, and resource optimisation. This research presents the development and application of an eggshell-based composite material using robotic 3D printing as a potential solution.

The eggshell-based composite material is created by mixing eggshell powder with an organic biodegradable polymer. The result is strong, lightweight, and adequate for 3D printing. This material provides a possible application for byproducts from the food industry, and a cost-effective and sustainable application for other industries.

The project outlines the selection of the fabrication process, development of the material for this process, the geometrical solutions to allow the printability and the digital solutions to optimize these geometries. This ongoing research offers a promising example of the possibilities that exist for creating circularity through innovative approaches and aims to contribute to the advancement of bio-composites as a potential solution for promoting a sustainable future in multiple industries.

Introduction

The generation of food byproducts is inevitable and impacts the environment, economy and society. Environmentally, the disposal of these materials and accumulation in landfills contributes to greenhouse gas emissions, and creates environmental problems due to microbial decomposition and leachate production. The burning of byproducts to remove fungi and parasites releases toxic gasses and increases air pollution. From an economic point of view, the impact of food byproducts arises from the costs related to their handling, transportation, and disposal. (Food waste and byproducts: An opportunity to minimize malnutrition and hunger in developing countries, 2018). The United Nations Food and Agriculture Organization estimates that approximately 17% of all food available to consumers ends up in landfills, which is equivalent to approximately 1,300 million tons per year (Food and Agriculture Organization of the United Nations, 2019).

Additionally, approximately 17% of all food available to consumers ends up in landfills, which is equivalent to approximately 1,300 million tons per year ends up in landfills, according to new UN research conducted as part of global efforts to reduce waste (Food and Agriculture Organization of the United Nations, 2019).

Particularly, Mexico is a country with high levels of poverty that wastes tons of food. Reaching a total waste of 20.4 million tons per year, which means 37.98 percent of what is produced in the country. (El Universal 2018). Mexico is also one of the main producers of eggs worldwide, producing approximately 3% of the hen eggs worldwide (3.02 tonnes). (FAO 2022, 18). In correlation, it is also one of the main consumers globally, with 20 kg per capita, positioning it as the 3rd main consumer (Helgi Library 2020). Additionally, housing regulation in Mexico is affected by two main issues: poor housing development for affordable housing by the private sector, and irregular settlements and construction. Both reflect the necessity not only to build more but also to find new affordable ways to build. Moreover, affordable housing is a crucial issue in developing countries like Mexico, where housing deficits are common.

The utilisation of residues and byproducts has the potential of contributing to a circular economy, generating new products and decreasing the cost of material sourcing and manufacturing.

Fig 2: Material composition: eggshell powder with water

Fig 3: Material source

Methods

(1) Material Basis and Production

As mentioned before, Mexico is among the biggest consumers of eggs per capita at a global level. Considering this, due to the availability and possibility of locally sourcing the byproduct, developing a bio-composite based on eggshell represented great potential.

There are multiple recipes based on eggshell powder as the reinforcement and that can already be applied to ceramics. The matrices for these mixes are usually potato starch, water, glycerin, gelatin, agar agar and other substances that transform from gel to a solid state. Based on the results of the initial testing, the selection of the materials was based on a recipe from the material library of Materiom (materiom.org). This mix contains eggshell, water and xanthan gum.
.

Currently the process is based on:

(1) Cleaning the organic remnants, sanitizing and drying in the oven at a low temperature (100°C)
(2) Grind the eggshells into powder and sieve
(3) Prepare the binder based on xanthan gum and water
(4) Add the eggshell powder
(5) Robotic 3D printing
(6) Drying session

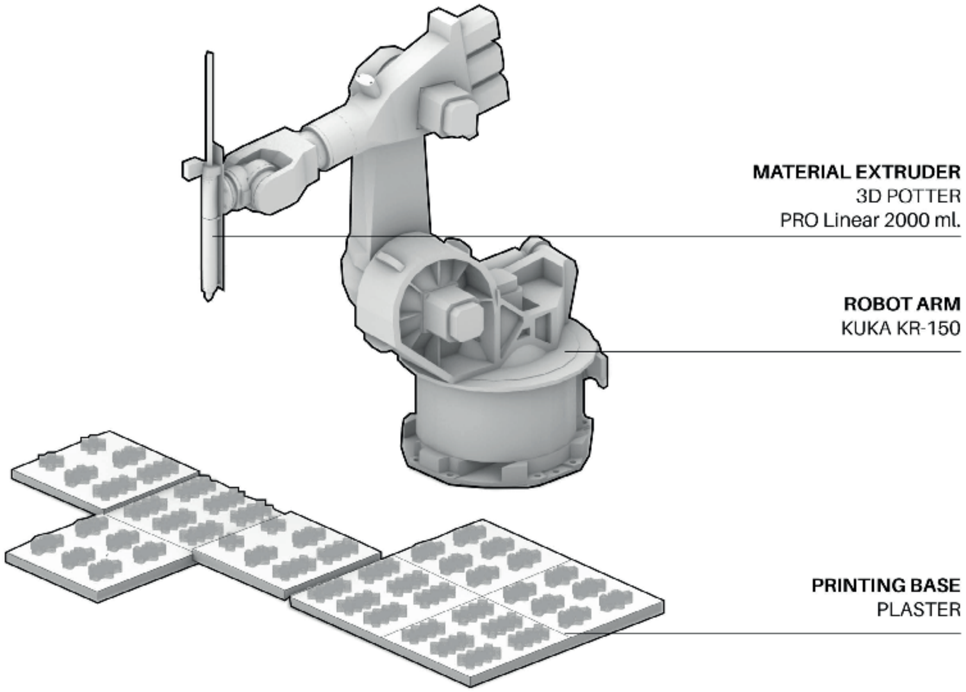

Fig 4: Current fabrication setup

(2) Fabrication setup

Currently the fabrication setup consists of a robotic arm (KUKA KR-150), which provides the positioning of the tool during the extrusion. The extrusion is done using a 3D Potter linear actuator based on a closed loop stepper and an acrylic cylinder, designed for thick materials such as heavy clay and thick dough. The extrusion tool is mounted on a metallic frame using 2 cable ties with raster locking.

The extrusion is done on gypsum bases, which compared to other materials like wood or plastic, allow better adaptation to shrinkage, water absorption, no adhesion during drying, faster drying and better ventilation.

Fig 5: First prototypes based on a PLA 3D printed plastic formwork

(3) Material and Geometrical Characterization

The consistency of the mix informed us of the possibilities of the material. Currently the mix has a high plasticity and requires homogenous and constant ventilation to dry. The possibility of firing the material was discarded as the material undergoes a fragmentation into a powder form when fired in a kiln.

This was corroborated by the first method selected, the first fabrication prototypes were based on using 3D printed PLA molds as a formwork, into which the material was poured and casted, a process similar to one applied in the Eggshell process developed at ETH Zürich. The samples were then left to dry at room temperature for a week and the formwork was removed by cutting. Due to the characteristics mentioned above, the material did not finish drying, leading to breakage, as the solidification of the matrix did not reach completion.

The use of formwork provided geometrical freedom and a higher resolution, nevertheless, as the mold was enclosed without the possibility of ventilation the mix could not finish drying. Added up to this, the process requires a complex demoulding procedure and additional waste production.

Responding to these findings, 3D printing (material extrusion and placement) was an option that could allow thinner walls and self-standing thin surfaces that could dry faster and more evenly. This process also allows fast layering (shorter fabrication times), more geometrical freedom and no need for additional formwork. In order to allow printability, the mix was transformed to be less liquid, allowing it to have a stacked accumulation.

The fabrication configuration has been constant based on:

1. Layer height: 3.0 mm
2. Layer width: 10.0 mm
3. Robot speed: 0.6 m/s
4. Feed Rate: 1.0 ml/s
5. Nozzle diameter: 6.0 mm

These are some of the selected tests that show the characterization of the behavior under certain geometries and the modifications on the mix through time:

Fig 6/7: 3D Printed eggshell section detail
These are some of the selected tests that show the characterization of the behavior under certain geometries and the modifications on the mix through time:

Fig 8: Initial mix
Observations: required infill

Fig 9: Second mix - 0.1% less xanthan gum, 4.2% less water content
Observations: bad stability, mix too liquid

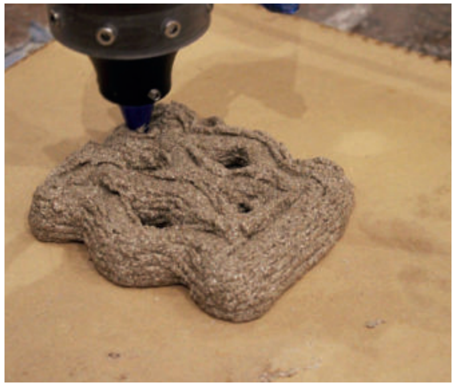

Fig 10: 3rd mix - 0.1% less xanthan gum, scaled in model
Observations: unstable, flat layers, excessive contact between layers attributed to small scale

FIg 11: 4th mix - scaled up model, 0.1% more xanthan gum
Observations: limited rigidity, enlarged scale leads and geometry provides insufficient support and inadequate contact between individual layers

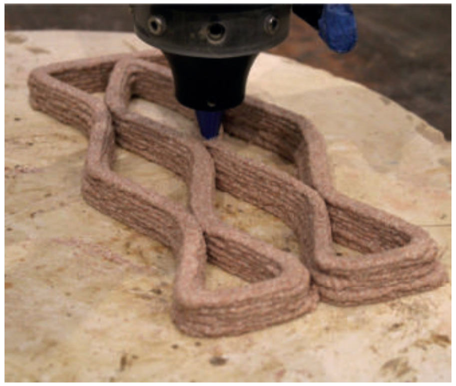

Fig 12: 8th mix - geometry test
Showing allowable height for specific undulating geometry

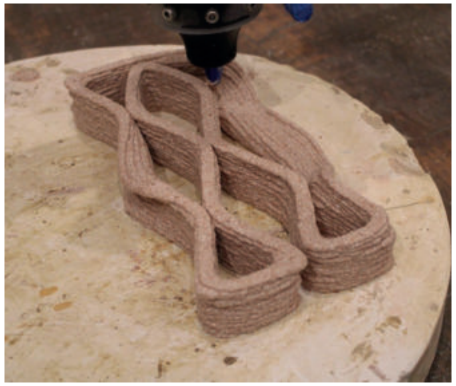

Fig 13: 8th mix - geometry test
Print reaching geometric limit

Fig 14: 7th mix - mid-scaled model
Observations: appropriate scale, material without enough structure

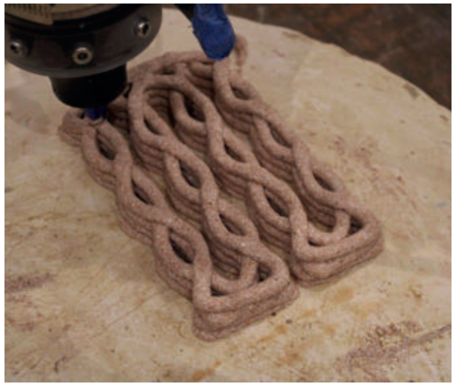

Fig 15: 10th mix - increased layerheight and cross supports
Observations: geometry provides reinforcement, excessive accumulation of material, optimal viscosity

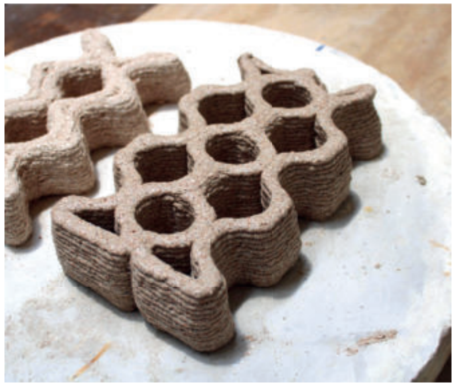

Fig 16: 17th mix - oval squared shaped undulation
Observations: material overaccumulation on the corners

Fig 17: 20th mix - more organic undulation, allowing more stability
Observations: geometry allows more continues printing

Based on these tests multiple guidelines were defined to ensure self support and avoid deformation. This is based mainly on keeping an infill geometry strengthened through inner structure allowing self support; avoiding angles wider than 80°, long straight shapes or arcs without an intermediate support; maintaining a wide base that can allow cross support and low inclination.

Allowing the constant ventilation is necessary for efficient solidification, this can be ensured through enough spread of the material, avoiding overaccumulation. Currently the mix is done manually with natural materials, hence, some tolerance should be considered for the implemented geometry.

The height that can be reached is dependent on the geometrical stability of the shape and on the particular consistency of the mix that is being printed. Nevertheless, the print is rarely able to exceed 7 cm of height before collapse.

In order for the material not to deform or be dragged by the next layers printed, it is important to have enough separation for the expansion of the extrusion and enough closeness for the support to be effective. This height should also be relative to the size of the nozzle, responding to the thickness of the wall.

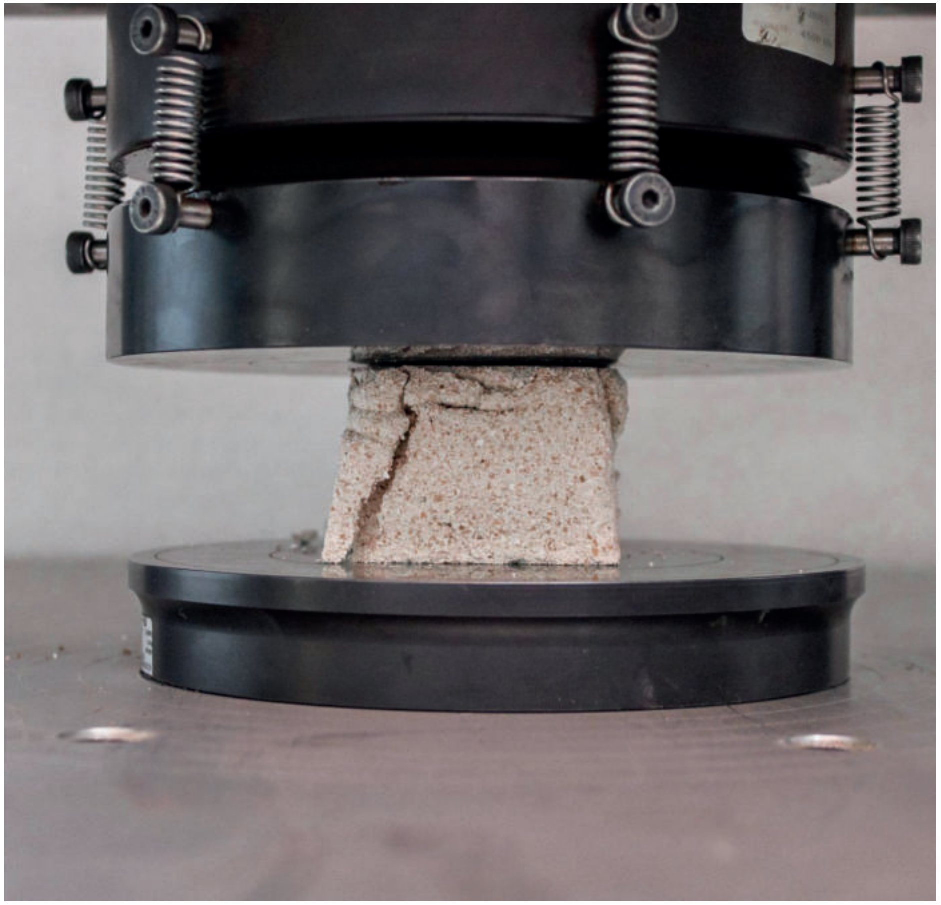

Fig 18: Compression test

RESULTS AND REFLECTION

(1) Material and structural analysis

Currently, an ongoing collaboration exists with Laboratorio Nacional de Vivienda y Comunidades Sustentables (LNVCS) and Laboratorio de Materiales y Sistemas Estructurales (LMSE) from UNAM (Universidad Nacional Autónoma de México - Mexico's Autonomous National University) for the analysis of the material. The material has undergone microscopic inspection and compressive testing.

Under compressive loads the mixture has shown limited flexibility, leading to failure upon reaching fracture point. The maximum average load resisted on the sample is 516 kg and maximum average resistance 15.52 kg/cm2.

In addition to compressive testing, microscopic analysis was conducted on the material. The analysis unveiled the presence of mold growth, which can be attributed to various factors including drying, environmental conditions, cleaning procedures, and the composition of the mixture. The emergence of mold poses a potential threat to the material's application, particularly in terms of meeting sanitary standards.

As a result, further research and development are necessary to address these challenges. Improvements in cleaning methodologies for the eggshells and optimization of environmental conditions are imperative to mitigate mold growth and ensure the material's suitability for safe usage.

(2) Demonstrators: Fabrication and computational solutions

The demonstrators have been featured in two public exhibitions:

(1) Eggshell Bricks, presented in INÉDITO collection by Design Week Mexico 2022,
(2) Eggshell Column, presented in DISEÑO EMERGENTE collection by ZONA MACO 2023.

The raw material for the production was locally sourced from restaurants, farms and bakeries in Mexico City such as Rosetta, Rosetta Panadería, LARDO and Rancho Rio Blanco.

The main characteristics to showcase with the demonstrators have been strength, the possibility of building free-standing structures through geometrical stability and stiffness, and the possibility of creating precise discrete elements that can be easily transported and assembled on-site. The first demonstrator responds to the geometrical possibilities that favor the material, its strength and structural possibilities.

Eggshell Bricks

The first demonstrator Eggshell Bricks consists of a wall with a sine wave base that transitions vertically into a linear top. This geometric configuration allows the creation of self-supporting shapes, eliminating the need for additional adhesives. The 105 custom bricks adapt to a different base geometry in each of the 15 levels.

During the development and testing of the material, the geometries that could maximize height based on stability (as mentioned in the "Material and geometrical characterization" section) were the ones with undulating shapes based mostly on 90° angles, curvilinear shapes and constant supports. The first demonstrator was based on these shapes.

In this instance, the brick is based on a structural configuration that relies on a biaxial displacement, featuring both a central and an elliptical parallel undulation. This provides an additional micro-level support to the macro-level support of the general structure.

The undulation pattern is based on a consistent subdivision of each individual curve, wherein the undulation is derived from each distinct pair of curves using the division and the center of the curve. To achieve the desired elliptical form, the planes encompass a translation of (x - (x/3), y/4, z) within the coordinate system associated with the frames of reference for the curves.

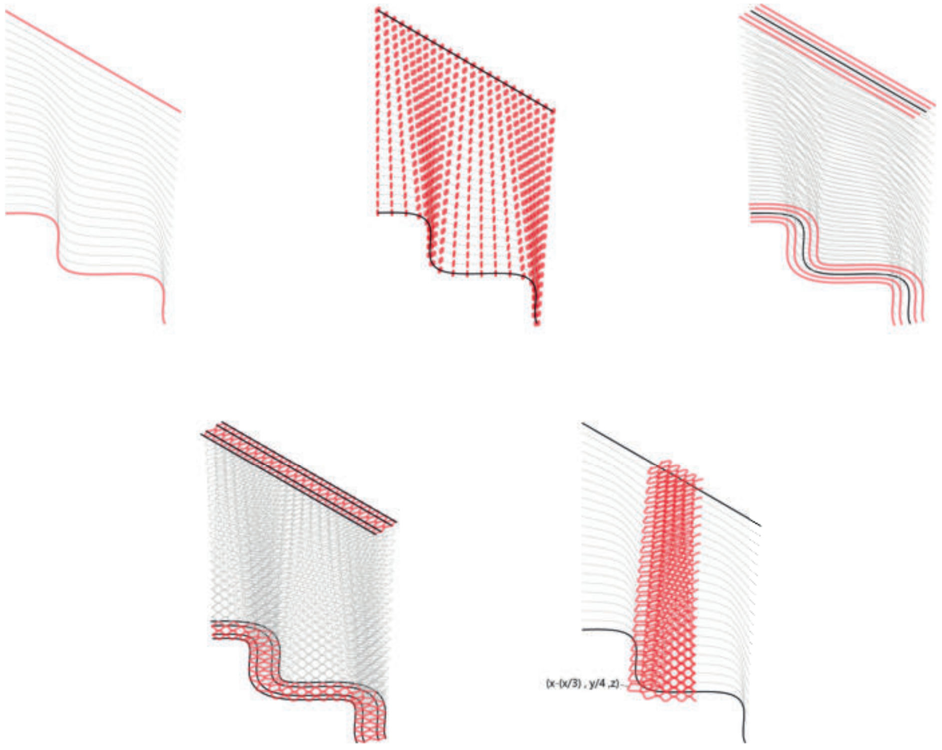

Fig 19: Geometrical process

Fig 20: Model of the Eggshell Bricks wall

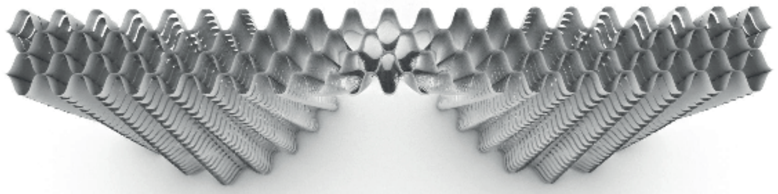

Fig 21: Top view: Model of the Eggshell Bricks wall

Basing the shape of the bricks on the particular geometry of each layer helped keeping a homogenous distribution and taking advantage of the possibilities of the system, by creating discrete elements.

The fabrication setup currently does not allow a constant flow of material, this makes it necessary to divide the shape for printing based on the capacity of the extrusion tube. The split can happen either horizontally (based on layers) or vertically (based on columns). In this case the second was selected mainly for transportation purposes and for the mix variation not to affect the general shape. There are always differences between the digital and physical world based on materiality and the physical reality. In this case, during the fabrication there were irregularities based on the drying stage and mix batch differences reflected in the viscosity (the shape showed more expansion on the bottom compared to the top and some bricks had thicker walls than others) and longer drying time.

These differences made the overall shape irregular and added complexity to the assembly. The angle of confluence between the pieces also made it difficult to mount them next to each other considering the irregularities of the material process. A better solution would be the interlocking of the pieces with a tolerance based on the differences between the bricks. This could allow stability between the parts and a more organic and stable bonding.

Fig 22: Eggshell bricks demonstrator

Fig 23: Individual bricks

FIg 24: Second demonstrator: Eggshell Column

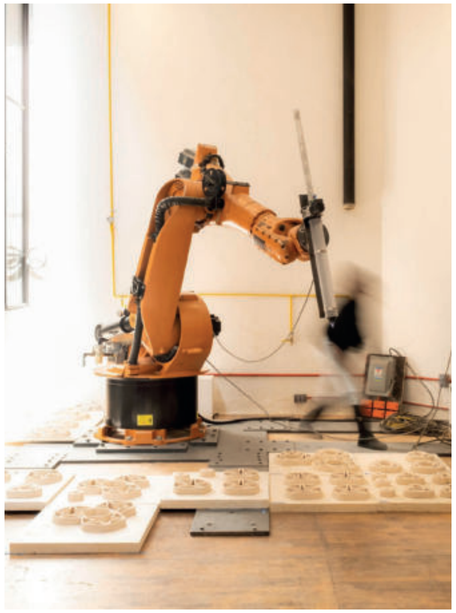

Fig 25: Robotic Setup

Eggshell column

Considering these characteristic irregularities of the material process helped for the second demonstrator Eggshell Column, which was based on a revolving tower with 3 circular sides which transformed into single shapes in the central area of the shape.

In this case, the testing of other geometries was also a particular interest, constant circles had already been tested and could not be supported by the material.

The organizer of the event requested a piece based on 3 towers. Considering that the piece would be formed of discrete elements that needed stability the selected option was a rotating tower that would allow stability between the counterweight of the sides.

In this case the shape is based on 3 points distributed on a circle base, multiplied by 55 layers. The layers get rotated by 1.7° and fitted to a bezier curve to increment the joint area freely. After this general fitting, the size of the circles gets controlled based on a sine function, in order to keep a more sinuous aesthetic that at the same time helps provide more support.

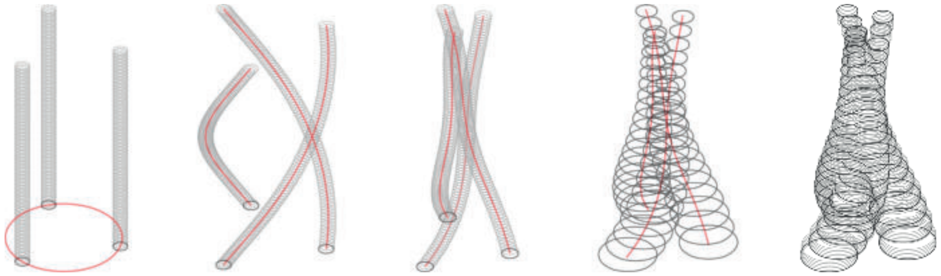

Fig 26: Final brick result

Fig 27: First infill test

Fig 28: Second infill test

Fig 29: Third infill shape tested

The overlapping circles become monolithic pieces, providing more structure and stability to the column. This freedom between the layers helps showcasing the freedom and precision made possible by digital fabrication technologies.

In this case the main challenge came from finding an infill that could support the outer shell of the shape.

Initially a mirror arc infill was tested, of which geometry resulted in excessive material accumulation, leading to visually untidy appearance and prolonged drying times, as the punctual support needs to be included more regularly in order to be effective.

In order to reduce the infill, the next test was based on 4 distributed circles intersecting between each other as well as the outer structure. Nevertheless, this proved to be sensitive to the material and scale variations and less suitable for structural integrity.

The third option was an offset of a cross which would allow a straight support for the circumference. This allowed keeping the punctual supports with more thickness, fewer connections and more right angles. This keeps the contact to the minimum, provides less material, more stability and less drying time.

The four connections worked for the smaller pieces, but not for the big ones, considering that the distance between them increased. The limits for the infill that could allow self support were: maximum 80° for concave angles, and maximum 30 cm for straight walls. These limits were applied generating closer walls for smaller pieces and star-like walls for bigger pieces.

The final element showcased a self supported stable and stiff vertical element, based once more on layer based semi-discrete elements. Showing more possibilities and flexibility of the material, and the possibility of the parametrization of the elements based on their physical limits.

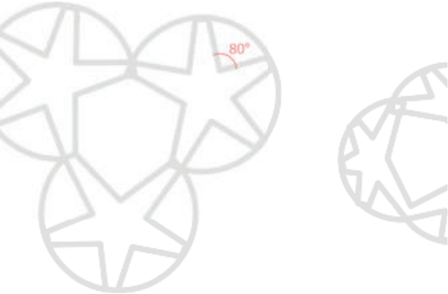

Fig 29: Geometrical restrictions of the infill

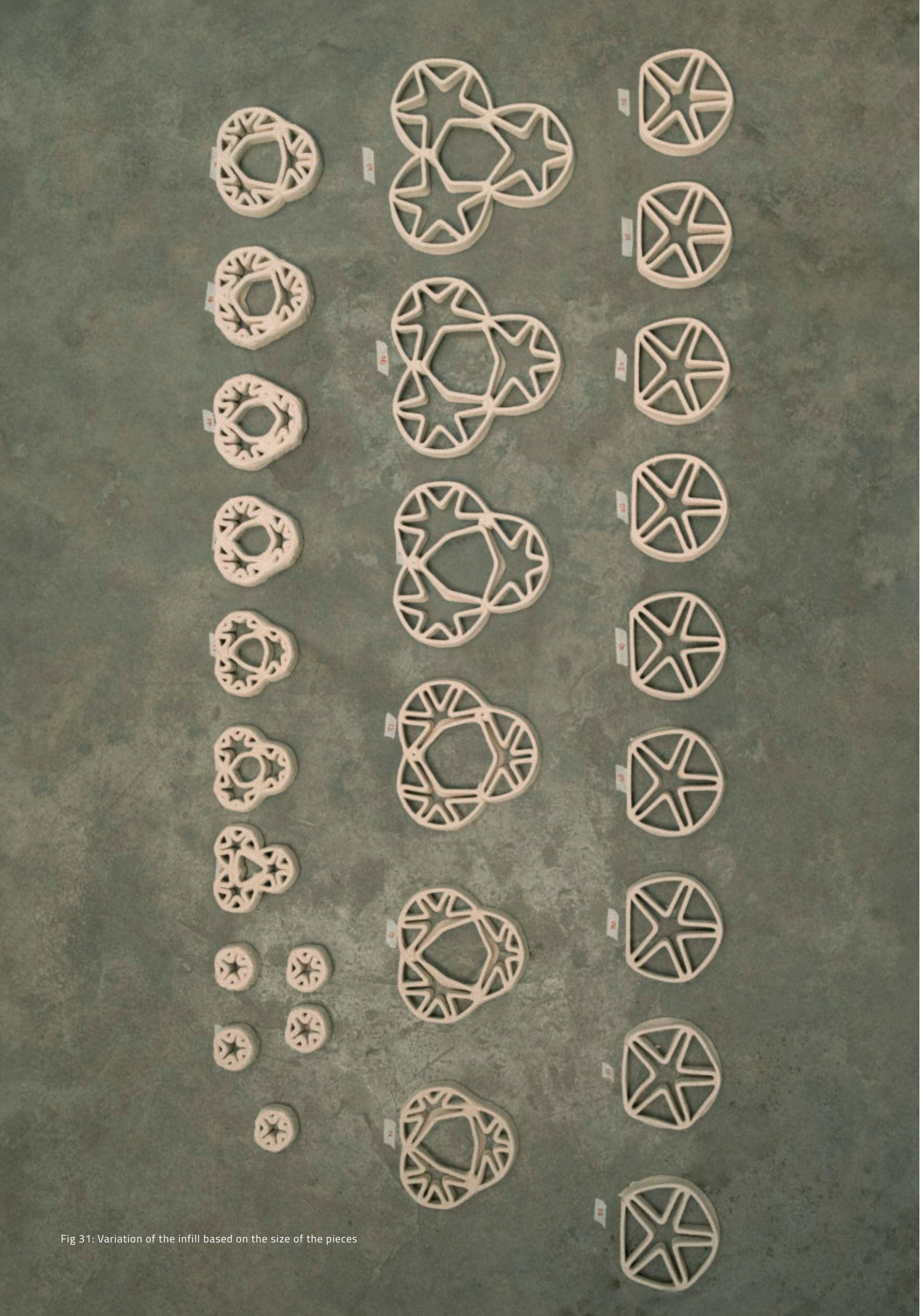

Fig 31: Variation of the infill based on the size of the pieces

CONCLUSION

Based on its characteristics the material shows great potential for different applications. It is lighter than clay and concrete, strong, cost-efficient and promotes a circular economy.

However, further development is required to fully exploit the material's capabilities. Specifically, improvements are needed in the cleaning of eggshells and optimization of environmental conditions to prevent mold growth. Ongoing mechanical testing and analysis are being conducted to refine the material and optimize its use in construction applications.

Moreover, there are additional avenues to explore in terms of fabrication methods to enhance production rates. Techniques such as mold-based extrusion, constant material extrusion through pumping, level molding, compaction, and advancements towards larger elements present potential areas of exploration. The success of this project can be attributed to the synergistic combination of computational design, digital manufacturing technologies, and material innovation. It has provided an opportunity to transform waste material and foster awareness regarding sustainable manufacturing practices. The project has prompted critical reflections on existing manufacturing methods and has catalyzed the creation of circular life cycles, contributing to a more sustainable future.

In conclusion, the ongoing advancements and interdisciplinary collaboration in this field hold promise for unlocking the full potential of the material, revolutionizing manufacturing processes, and embracing circularity in material utilization and waste management. Further research and innovation efforts are warranted to realize the envisioned transformation and create a more sustainable and resource-efficient society.

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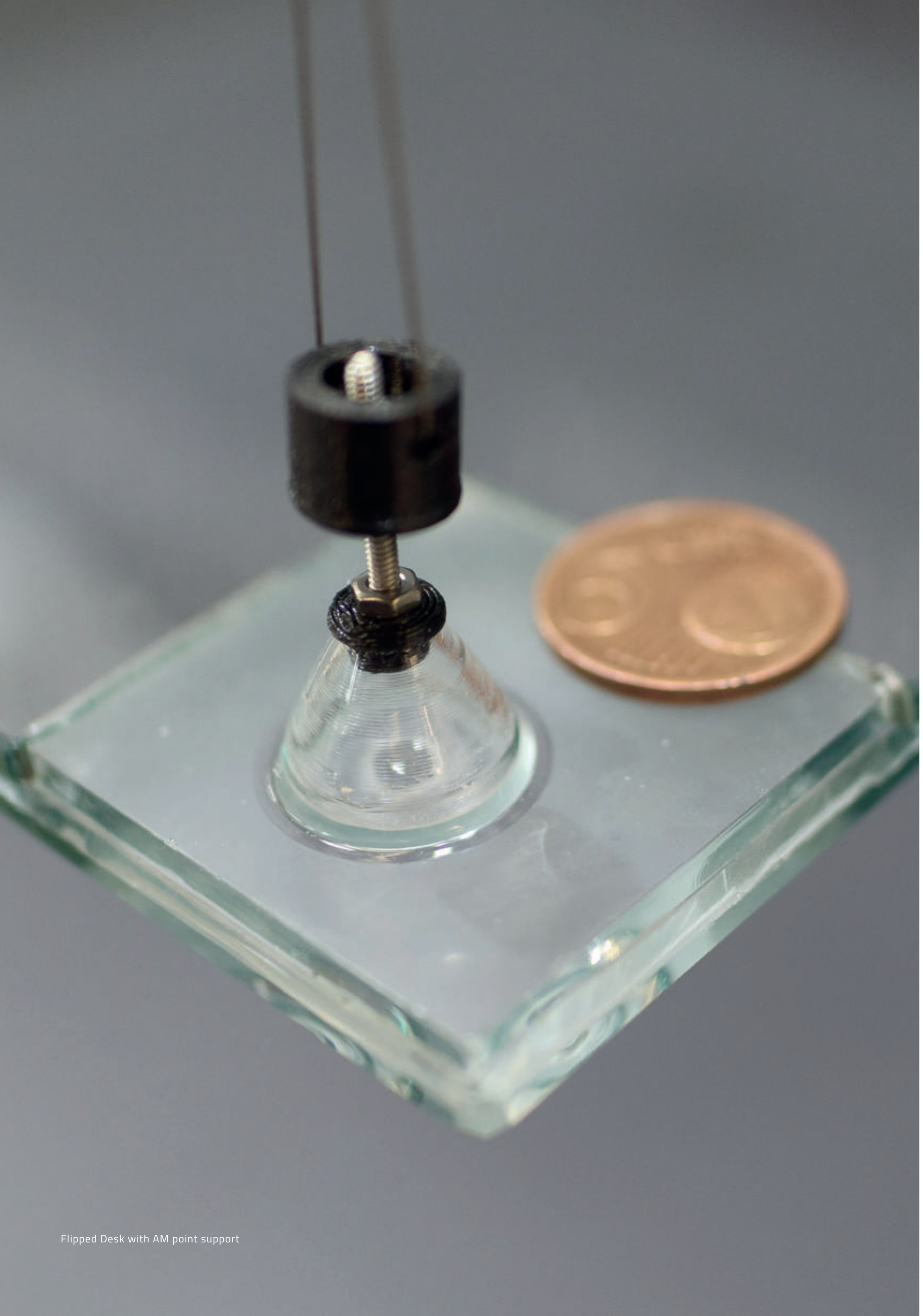

Flipped Desk with AM point support

THINNER GLASS WITH HIGHER STIFFNESS

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Abstract

Glass finds extensive applications in construction and architecture, primarily due to its transparency. Its utility has expanded beyond traditional windows, with recent years witnessing the production of larger glass dimensions and the ability to create both ultra-thin and very thick glass. Consequently, glass is now a prevalent choice for facades and even load-bearing elements. Innovations like additive manufacturing allow for custom transparent glass connections and cross-sectional reinforcements, reducing unwanted deformations and conserving resources. Our current research in 3D glass printing focuses on process development and the mechanical and optical properties of the resulting products.

Introduction

Glass is a favored construction and architectural material mainly due to its transparency. Recent developments have led to glass being available in larger dimensions. In addition, it is possible to produce both very thin (up to 30 μm) and very thick glass structures (Figure 1 A). Its applications in the build environment are varied and reach beyond traditional window installations to facade or structural elements (Figure 1 B and C).

New technologies like additive manufacturing or glass component fusion allow for individual design of transparent glass joints such as point supports (refer to Figure 2 A) or stair brackets. They can create three-dimensional structures on flat glass without the use of molds and reinforcements in cross-section, due to the application of ribs to flat glass (refer to Figure 2 B and Figure 3).

Thin glass with higher stiffness

The application of ribs to flat glass minimizes unwanted deflections or freezes intended deformations through local reinforcement, increasing flexural rigidity and thus reducing the amount of glass used, thus conserving material resources.

For example, a uniaxial glass slab with a supporting length of 1500 mm, a width of 1000 mm and a load of 0.001 N/mm² (typical wind load) would require a glass thickness of 9,1 mm to meet the serviceability limit state (ULS) according to the German glass design code DIN 18008-2 [1]. However, a similar moment of inertia, and therefore similar deflection, can be achieved with a 6 mm thick glass sheet that also has three printed ribs 14 mm high by 10 mm wide. This results in a weight saving of approx. 30%, which, in addition to material savings, also has a positive effect

Fig. 1A: Glass brick

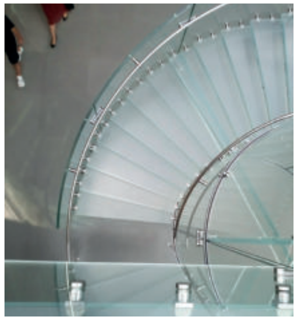

Fig. 1B: Inside the Apple Store of Shanghai

Fig. 1C: Apple Store in Shanghai

on transportation and installation. Another example of material savings through AM ribs can be found in [2]. In addition to the printed ribs, local deformation of the glass is also possible to increase the moment of inertia of the glass panels and is being investigated in the GCC.

Currently, our research in 3D printing of glass is mainly concerned with the processes and the characterization of the mechanical and optical properties of the resulting products. A homogeneous glass joint means that the interface between the joining partners is undetectable (optically), free of cracks, crystallization, bubbles and residual stresses. In addition, there is no difference in mechanical properties, such as strength, in the joint area.

In [3], shear tests were performed on fused silica glass specimens. The specimens consisted of a base plate (approx. 50 mm x 25 mm x3 mm (l x w x h)) on which a wall of approx. 23 mm x 6 mm x 6 mm was printed using a laser glass deposition (LGD) process. This was done by the Laserzentrum Hannover e.V. (LZH). In this process, glass fibers (400 µm diameter) are melted onto the glass base plate. A CO2 laser is used as a heat source to melt the glass fibers. The fused silica fiber is fed laterally into this process zone at an angle of approx. 50° and a speed of 324 mm/min. The wall is built up layer by layer by translating the linear axis system. To achieve a wall thickness greater than the substrate thickness, multiple tracks are placed side by side with a 20% overlap. The printed samples show high transparency and surface quality, and the individual layers of the print are not visible, indicating complete fusion of the individual layers. The surface of the samples has not been post-treated, but the samples have been post-annealed in an oven process to reduce thermal stress.

The shear test setup is shown in Figure 4 A. The soft lead strip underneath the specimen accommodates the uneven surface of the printed specimen and provides even load distribution. The polytetrafluorethylene (PTFE) acts as a frictionless bearing. 10 specimens were tested. The results of the failure load and the resulting failure stresses are shown in [3]. Interestingly, in none of the 10 tests did the crack migrate through the AM glass wall (case 3 in Figure 4 B). Instead, the crack either migrated through the baseplate (case 1 in Figure 4 B) or it migrated in a crescent shape through the glass plate to the opposite edge of the AM wall (case 2 in Figure 4 B). However, it should be noted that the number of specimens tested was relatively small, so future cracking through the AM wall cannot be excluded.

Fig. 3: Rendering of flatt glass with reinforced cross section due to AM ribs

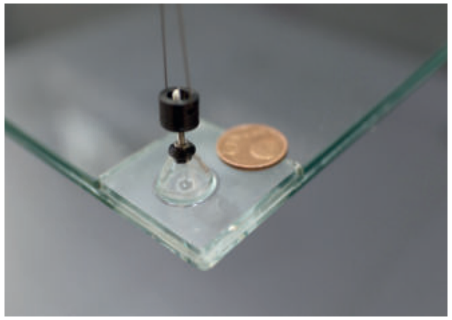

Fig. 2A: Flipped Desk with AM point support

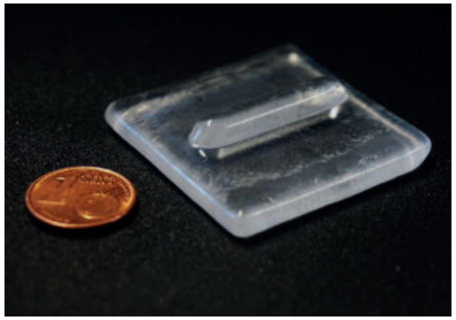

Fig. 2B: AM rib on flat glass

To further understand the influence of different printing process parameters and to obtain larger dimensions at relatively high speeds, a glass 3D printer will be built by the Glass Competence Center and partners. The printing process is based on the FDM (Fused deposition modelling), in which melted glass is deposited on a flat glass base. In the initial version, the printer should have the capability to print a base plate measuring 200 mm x 300 mm, with a print height of around 50 mm and a nozzle output ranging from 2 to 10 mm. The upcoming larger version targets a base plate size of 500 mm x 1000 mm.

Our focus is on soda-lime silicate glass and borosilicate glass, which are the main glass types in the building industry. In future, we also want to investigate the use of glass waste as printing material.

Conclusion

This article showed that glass 3D printing promises many exciting applications in the built environment. In addition to completely transparent connections, the realization of higher stiffness by application of 3D glass structures compared to flexural 2D flat glass applications is of particular interest. This allows both an individual facade design and the reduction of required glass volume and thus the saving of valuable resources. One vision of the ISM+D and MPA-IfW as part of the ZIM innovation network AMglass+ is to realize 3D printed glass on flat glass in the dimensions 3.25 m × 20 m. Thermal aspects and industrial realization play a decisive role in this context. The network AMglass+ with its partners from the fields of facade construction and design, research institutes, glasswork and industry provide the basis for the sustainable development and establishment of additive manufacturing with glass in the building sector.

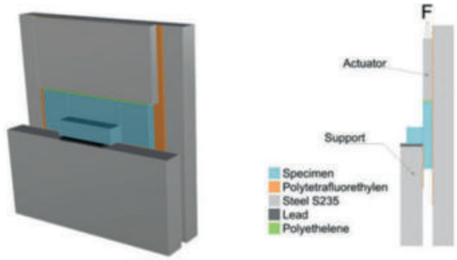

Fig. 4A: Test set up

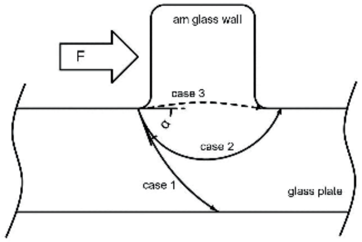

Fig. 4B: Crack propagation cases

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Fig. 1: Innovative renovations of vernacular houses carried out ad hoc by builders in remote locations in rural China

ART OF COMPROMISE

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Abstract

Traditional House of the Future is a prototype combining traditional wood craftsmanship with on-site 3D printing, encapsulating the realities of a rapidly changing lifestyle, at the intersection between traditional and modern, that is neither rural nor urban. Located in the Guizhou province of China, in the village of Nanlong, it questions the built environment and its implications at the scale of time – past, present, and most important – future.

Introduction

In Nanlong village, changes in livelihood have made traditional houses obsolete, in favor of generic concrete ones. The house project is part of a government plan to revitalize the village, by offering a wooden house prototype that can respond to modern needs. Therefore, the project proposes strategies for recycling and revitalizing vernacular houses.

It is the result of two very different bodies of work coming together as a collaboration: investigations in rural China, and robotic fabrication. Previously, John Lin has worked, researched and designed around the issues related to the urbanization of China, with projects such as House for All Season, Jintai Village Reconstruction,The Pinch (with Olivier Ottevaere), and As Found Houses (in collaboration with Sony Devabhaktuni), the later investigating innovative renovations of vernacular houses carried out ad hoc by builders in remote locations in rural China (fig 1). Lidia Ratoi's work researches the potential of using technology as part of a design framework that caters to vulnerable natural entities, being part of projects such as Reformative Coral Habitats, a collaboration between architects and marine biologists at HKU (fig 2), or TerraPerforma, which focused on ancestral climate adaptive design as a potential for robotic fabrication (fig 3). As the project brought together research and teaching, together with year 2 students of Hong Kong University, the team has surveyed a number of houses and interviewed the inhabitants, in order to create a design brief. The research showcased the necessity to evolve and adapt the traditional wooden house, incorporating modern amenities with flexible spatial organizations. In response to this, the question was – how can we re-think an ancestral way of making, in order to give it a place in the contemporary and future design vocabulary? How do we build in a world that is overbuilt?

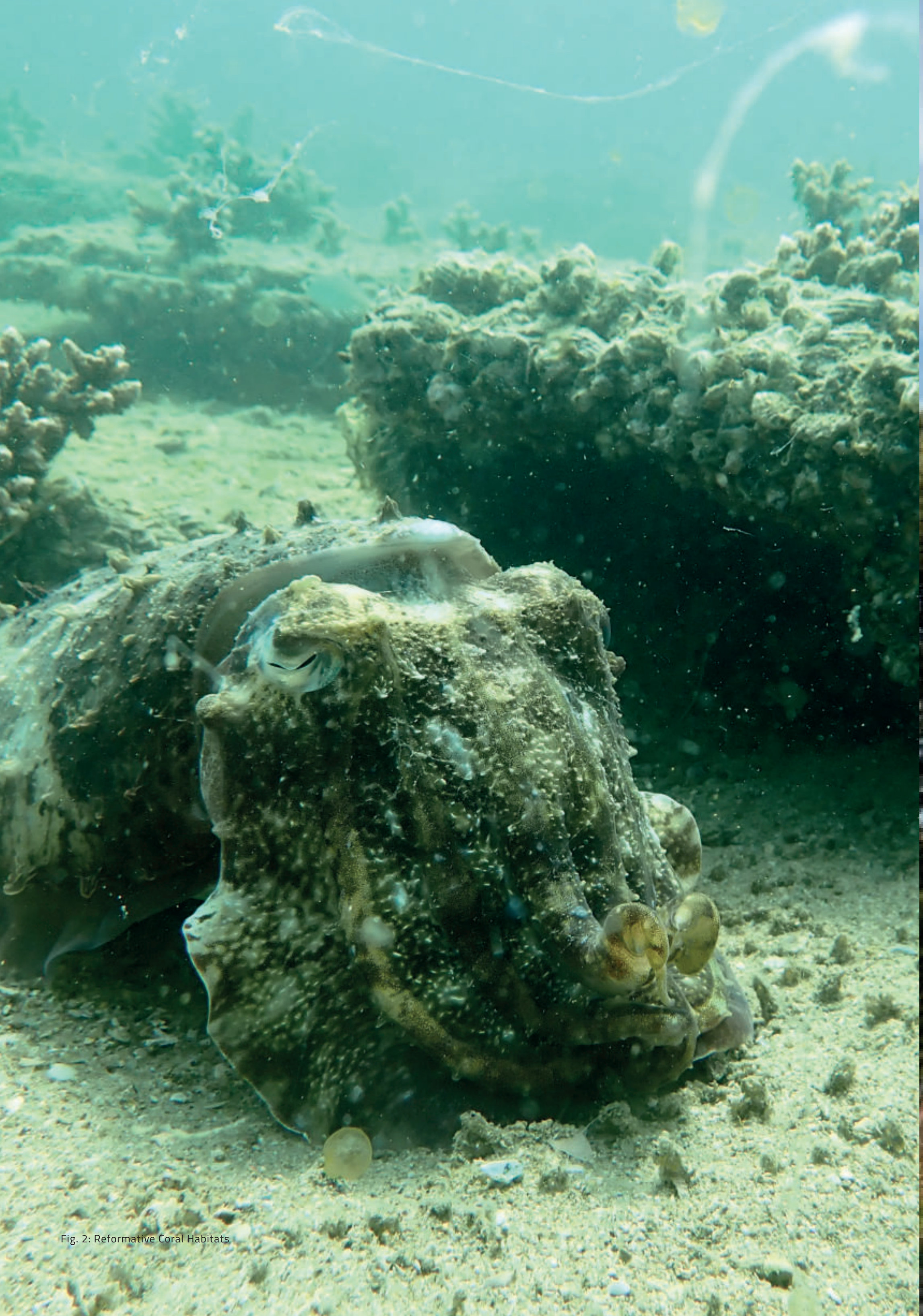

Fig. 2: Reformative Coral Habitats

Fig. 3: TerraPerforma

Fig. 4: Robot displacement

Fig. 5/6: Association with the ancient wooden structure

PROCESS

Working with robots and working with traditional craftsmen are similar methods, as there is no need for drawings – robots operate based on code, and woodworkers learn from mock-up models and adapt on site. Therefore, the combination between the robotic printing and traditional woodworking techniques was natural.

(1) Form-finding techniques

There were a series of iterations on creating the relationship between the existing structure and the new one. The 3D printed wall was considered a continuous wall, as well as a series of partition walls. In the end, the one-wall strategy proved most efficient, both in terms of on-site construction (as it would have been difficult to use a rail network to move the robots (fig 4), due to the natural topography of the site) and as a programmatic scheme. (fig 8)

Fig. 7: 3D-printed concrete associated with ancient wooden structure

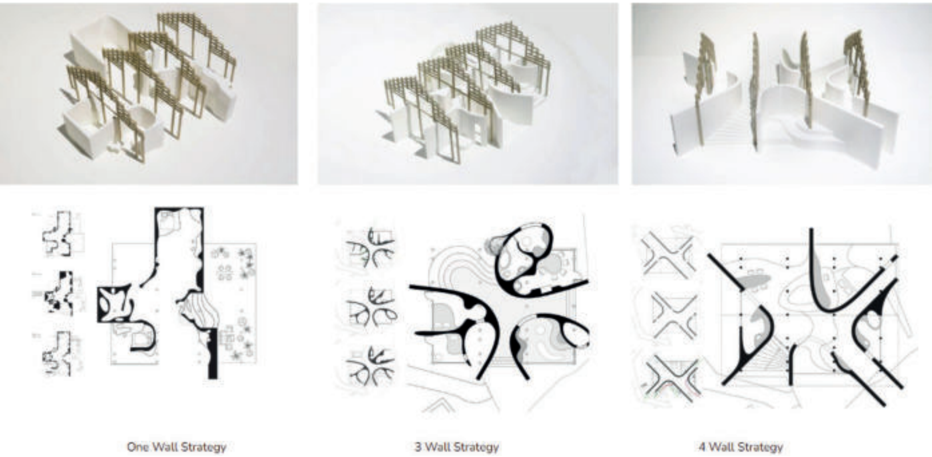

Fig. 8: Transformation strategies for the existing ground floor.

(2) Scanning

Chinese traditional houses are built in such a way that they can be dismantled in a single day. The original house was scanned, as the aim was to use the versatility of 6 axis 3D printing to account for each imperfection, flaw or natural element of the ancient wooden structure. (fig 5, fig 6)

(3) 3D Printing

3D printing allowed for the incorporation of modern amenities, as it could adapt to site, original structure, and to "imperfections" from the original structure. The new walls allow for all the spaces established in the design brief with the villagers - planting, entrance courtyard, skylight, balcony, kitchen, and bathrooms. It also possible that a one level house, with a ground floor traditionally used for animals, to be turned into a two-storey house, as the villagers do not raise domestic animals anymore. (fig 7)

Fig. 9: Reintroduction of wooden structure and roof

Woodworking

After dismantling, the wood was reconditioned. The craftsmen then reintroduced the wooden structure into the house, having to adapt the traditional way of building wooden frames. Usually, wooden frames are constructed horizontally on the ground and then erected. As the new walls were already 3D printed, and each column had to fit it's exact nook into the 3D print, the craftsmen had to constantly re-adapt the way in which they do things and throughout the entire process, there was a constant loop between the teams. (fig 10)

Working with the villagers

The project involved as many local entities as possible, with different participants involved in different stages. As it was a government initiative, the plan for the project is to continue iterating on different houses in the village, the current project being the first prototype. Therefore, the first entity involved was the local governing institution, which helped with on-site logistics, creating the program for the prototype etc. The wood craftsmen were involved from beginning to end, with dismantling, reconditioning, and putting back together the original wooden structure. But there were also untrained villagers who were involved in the process working to reassemble the roof tiling. From the beginning to end, local dwellers were cooking, cleaning, waterproofing for typhoon, and doing all the adjacent jobs, therefore the project really became an opportunity to earn an income locally, which was another issue brought up during the aforementioned interview stage. (fig 9)

Fig. 10: Dismantling, reconditioning, and putting back together the original wooden structure

CONCLUSION

Traditional House of the Future serves as a model for on-site robotic fabrication as means to mediate between key areas of sustainability: technological, social and environmental. Robotic arms are versatile tools and their potential relies not only on their capacity of creating intricate geometries, but in creating geometries tailored to specific conditions, and through the multitude the methods that can be used with only one tool. The project also demonstrates that high-tech and low-tech system can co-exist within the same design and construction narrative, and the potential of merging traditional craftsmanship with innovative technologies, adapting to overbuilt environments, and engaging local communities as active participants in the design process.

Fig 1: Altar consecration, Retabel of Altmühldorf

SCALE EFFECTS: CHALLENGES FOR SUSTAINABLE MANUFACTURING IN ARCHITECTURE

BRUNO KNYCHALLA
ADDITIVE TECTONICS GMBH

Abstract

Additive manufacturing in the architecture and construction industry allows for digitally bespoke construction with minimized material waste while introducing novel material and geometric explorations that could improve the sustainability and functionality of our built environment. While first houses are already produced using concrete extrusion printing, the application of other 3D printing technologies and material systems in the construction practice is usually limited to larger art projects or design ideas.

additive tectonics GmbH aims to change that by developing a broad range of alternative additive manufacturing technologies and materials for construction in the Big Future Factory (Fig.2). In the past, the focus lied on construction materials like stainless steel and aluminum with wire arc additive manufacturing (Fig.4) or Portland Cement with selective cement activation (Fig.5). Also, hybrid technologies were being investigated, as seen in the project of the "Retabel of Altmühldorf". Here, a novel wire-arc-spraying technology was combined with selective laser sintering to investigate the architectural application of sintered polyamide when being reinforced with aluminum. (Fig.1/3)

Fig. 2: Big Future Factory

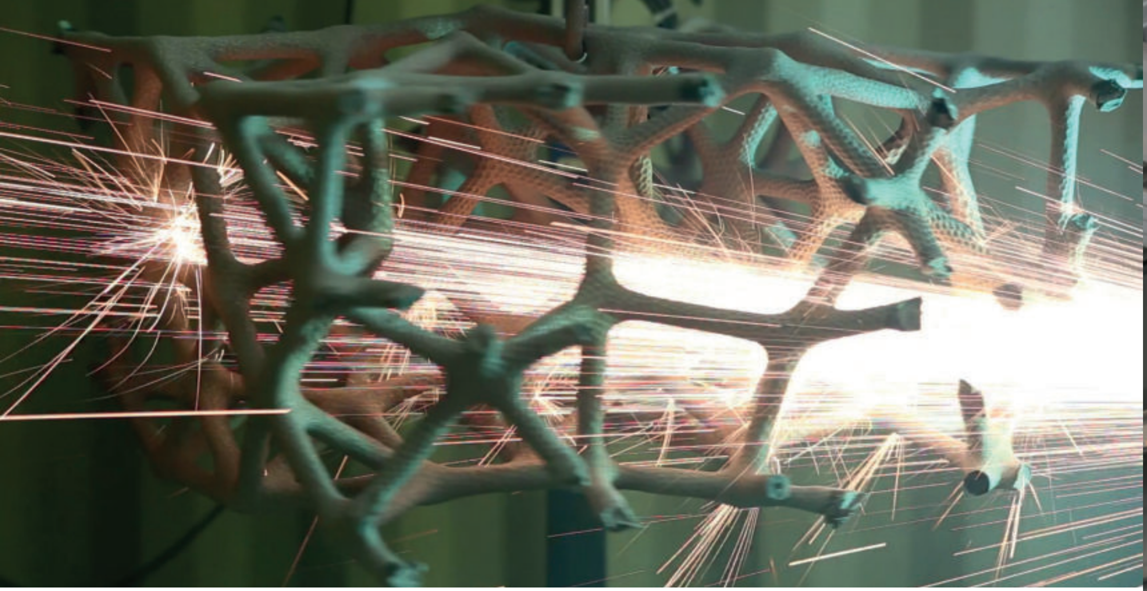

Fig. 3: Sintered Polyamide reinforced with aluminium

Fig. 4: WAAM, Wire-Arc-Additive-Manufacturing

Fig 5: Portland cement with selective cement acitivation

Fig. 6: Fused Deposition Modeling

On Printing with Biomass to Scale

At the beginning of 2021, additive tectonics ventured into additive manufacturing with biomass, using biopolymers based on wood in Fused Deposition Modeling (Fig. 6). These Biodegradable synthetic binders undergo an energy-intensive production process and, for now, exhibit dripping burning problems that prohibit most architectural applications. While the binders that are used at additive tectonics are biocompatible, fixing the flammability issues most likely leads to the loss of biodegradability.

Nevertheless, the most urgent problem that these extrusion-based technologies need to face today is that they are generally only using one nozzle, which makes speed and/or resolution reasonably limited. Furthermore, possible material systems for these technologies rely on early-stage material curing to support multiple layers that are stacked on top. His limits either the scale of application, when slow-curing alternative materials are used, or the range of applicable materials for construction projects.

econitWood

A novel way of using biomass in additive manufacturing is particle-bed additive manufacturing with wood particles. Selective Binder Activation (SBA), is currently being developed for the AEC sector for its capacity to produce complex pre-fabricated elements in precision and volume output that far exceed extrusion technologies, as hundreds of small nozzles are employed during fabrication. In the SBA technique, the particle bed consists of a dry mixture of fine aggregate (<1-2 mm) and binder. The binder inside the particle bed is locally activated by spraying water or water admixture into the packed particles, thus forming a binder paste matrix around the aggregate particles. [1] In the case of econitWood, the particle bed consists of raw beech wood chips that are mixed with a small percentage of cellulose additives and dry magnesium oxide binder. The activator liquid is a brine made of water and magnesium chloride. The layer height was set to 1.5 mm with a spray resolution of 1 nozzle (150 μm nozzle diameter) per mm. The machine dimensions are 4000x2500x900mm (lxwxh), and the printhead, which is installed along the width of the machine, sports 2500 nozzles.

Fig. 7: 50x50cm acoustic panels fabricated in econitWood

What to expect of 3D-printed Wood

Figure 7 shows 50x50cm acoustic panels fabricated in econitWood with a thickness of 2.5 cm in an industrial production setting. The fabrication time needed for an object like this is 40 seconds, assuming that multiple panels are being fabricated by the machine at the same time. Here, the magnesium-oxide-cement used in combination with wood particles is not only a potent binder but also reduces the flammability of the wood aggregates immensely. Furthermore, the fibers inside the lignocellulose matrix increase the flexual strength of the material (4,2 MPa) by 30% compared to other SBA materials with similar density and no fiber content (density of econitWood: 890 kg/m^3). While magnesium cement is a more sustainable alternative to standard Portland Cement [2], it exhibits problems when exposed to water for extended periods of time. For that reason, this material system can, for now, only be applied to interior environments. Another question econitWood has to face lies on its surface. Even though it is possible to fabricate very complex, novel geometries in architectural scale and materiality (Fig. 8), there is, as of yet, no solution on how to create a smooth or even surface finish.

Outlook for econitWood

The use of wood in additive manufacturing has great potential for architectural applications. Firstly, it uses the benefits of form, speed, resolution, and industrial processing of particle bed additive manufacturing. At the same time, the possibility of using raw untreated materials that are potentially fast-growing or come from waste streams of other sectors shows a fabrication technology that can contribute immensely to solving pressing climate challenges. Here, large amounts of CO2 could be sequestered from the atmosphere and locked into architectural elements with a long life span. Through its excellent density and mechanical properties, this material system will see little challenges when facing scale effects that limit most sustainable materials as they are being put to use in large-scale applications in architecture. With more researchers being invested in alternative mineral binder systems, the potential application range for this material system could broaden towards exterior and even load-bearing applications, making wood particle bed additive manufacturing an interesting new approach for building construction.

Fig 8: Material Limitation econitWood

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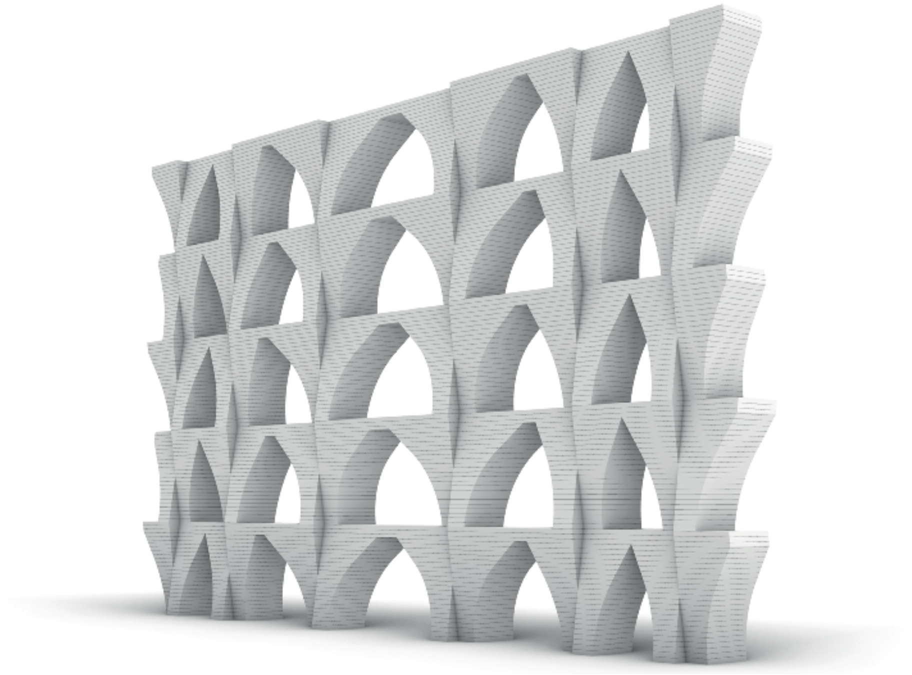
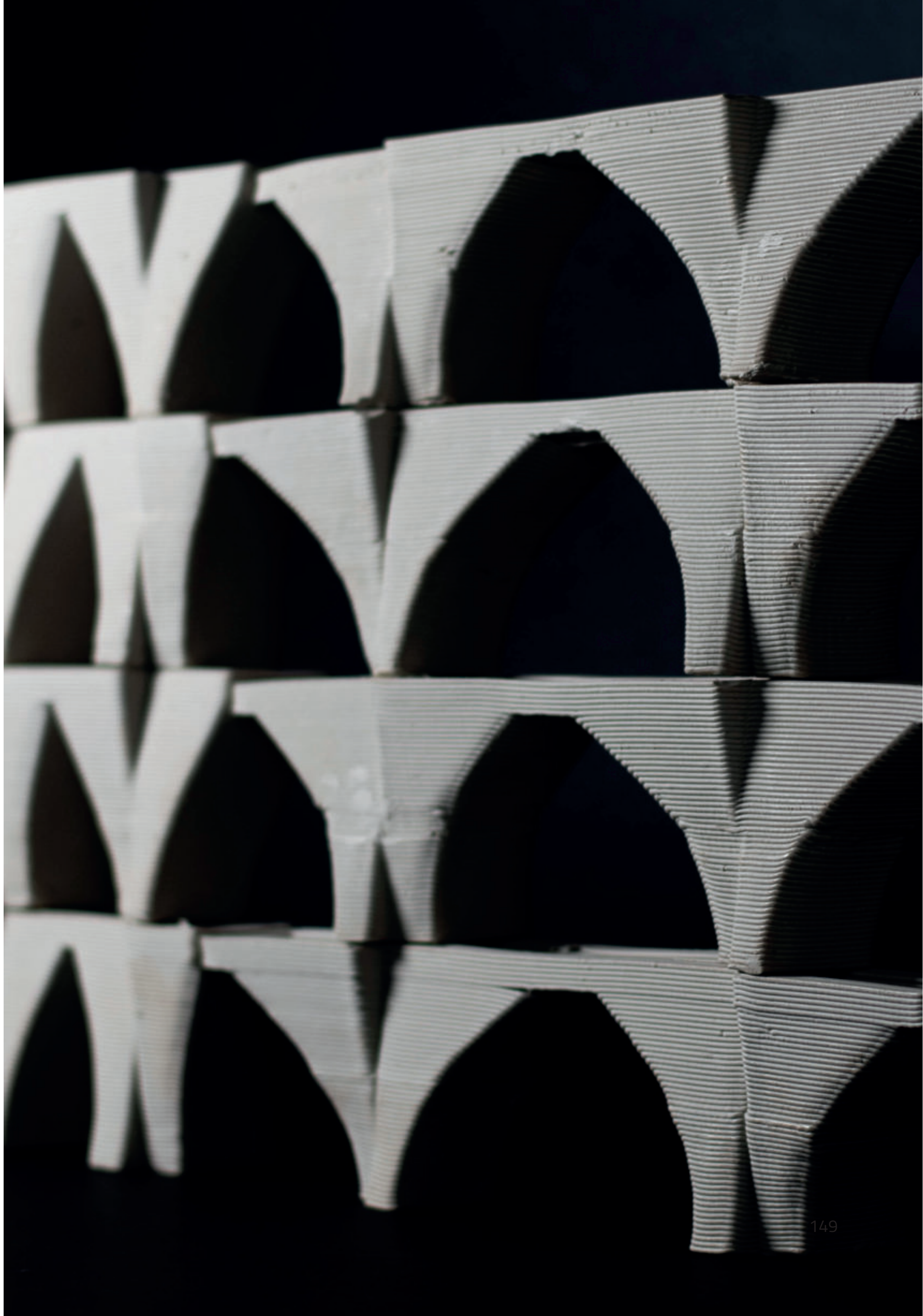
PROJECTS

BRIDGING THE VOID

Technical University of Darmstadt, Institute of Structural Mechanics and Design (ISM+D)
Alexander Wolf, João Carvalho, Tatiana Campos, Bruno Figueiredo, Paulo J. Cruz

This exhibit demonstrates the ability of printed ceramic components to overcome voids by bridging such areas. While the narrower pieces on the sides show what the clay used is capable of spanning on its own, the wider pieces in the centre have been produced using strategies to support overhanging areas. In addition to filling material from printed clay that was broken away after drying, supports from other materials, as well as separating interfaces were used to achieve this geometry. The exhibit is the result of a joint venture between TU Darmstadt's ISM+D and the Advanced Ceramics R&D Lab of the University of Minho in Guimarães. In addition to the strategies used to produce its components, the research has explored several other approaches to overcome the material-related limitations of printed clay. An detailed documentation is available in the proceedings of the eCAADe 2023 conference under the title "Support-strategies for Robocasting Ceramic Building Components".

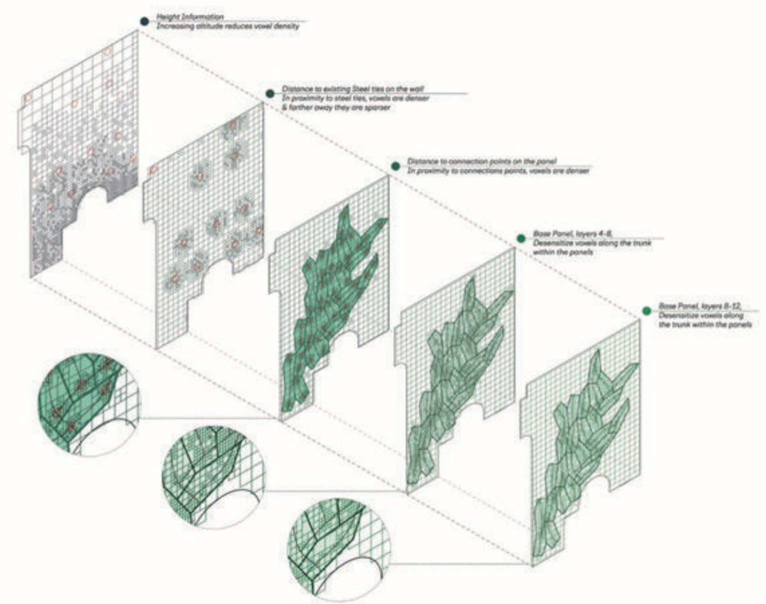




RADICANT

Royal Danish Academy, Centre for Information Technology and Architecture (CITA)
CITA, Mette Ramsgaard Thomsen, Paul Nicholas, Martin Tamke, Carl Eppinger,
Ayoub Lharchi, Hasti Valipour Goudarzi, Gabriella Rossi, Ruxandra Chiujdea, Anders Daugaard,
Arianna Rech

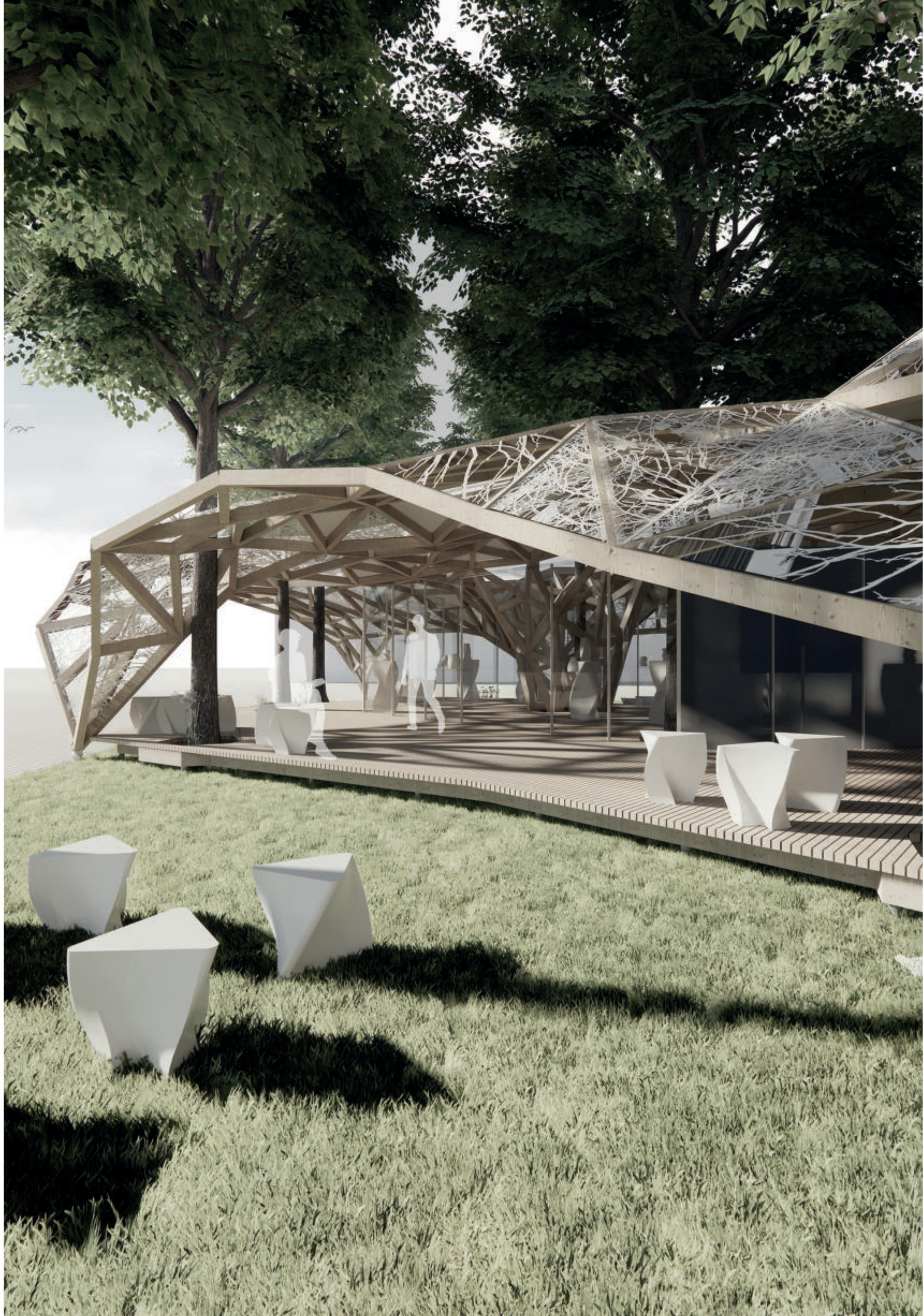
Radicant is a panel-based wall screening system created from a collagen-glue-based biopolymer composite reinforced with various types of cellulose from waste products. It explores the design, fabrication and creation of a bio-based architecture. Each panel is created out of several interwoven layers of material creating a highly differentiated multi-material prints, which respond to local material availability. We use local cellulose-based waste stream materials that are abundant within the Danish industrial ecology. The material is also fully circular as it can be melted down and reused in new slurries or biodegraded without chemical additives. The printing is made possible thanks to in-house developed hot extruder head coupled with a multi-material pump. With a design inspired by the silk tree, the biomaterial tiles are printed more densely where they are fixed at their trunks and become more open towards their leafy edges.



DIGITAL CABIN

Darmstadt University of Applied Sciences, Chair of Architecture
Franziska Schöler, Max Fritsche, Alexander Wolf, Lars-Uwe Bleher, Ulrich Knaack

In the winter semester of 2022/23, students from the Faculty of Architecture at Darmstadt University of Applied Sciences, in cooperation with students from the Institute of Structural Mechanics and Design at TU Darmstadt, investigated the application of 3D printing in the construction industry. The task was to design a pavilion for the exhibition of 3D printed objects, which was also to be built itself using additive manufacturing. The students worked out their designs according to their own specialization. The constructional elaboration, economic efficiency or even ecological backgrounds were important aspects in the development of the projects. The handling of the new technologies required an adaptation of the design paradigms to the new construction method and resulted in exciting free forms. The resulting, design-dependent, nodes and details were worked out in greater depth in order to later generate an additive manufacturing process. The results were 14 individual pavilions, from which a jury selected winners in a competition. The winning design is shown here.



AM CLIMATE-POSITIVE CERAMIC FACADES FOR BIODIVERSITY

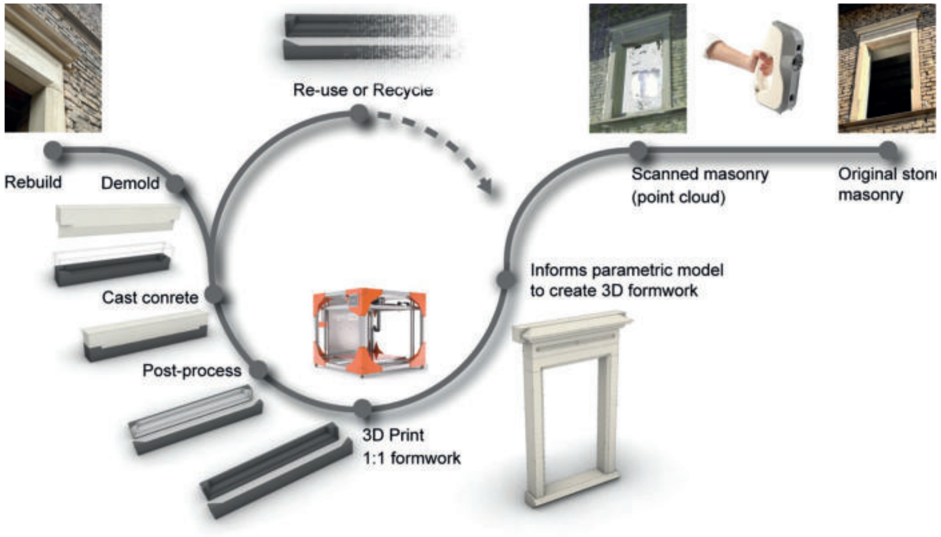
Technical University of Munich, School of Engineering and Design
Julia Larikova, Kathrin Dörfler, Wolfgang Weisser

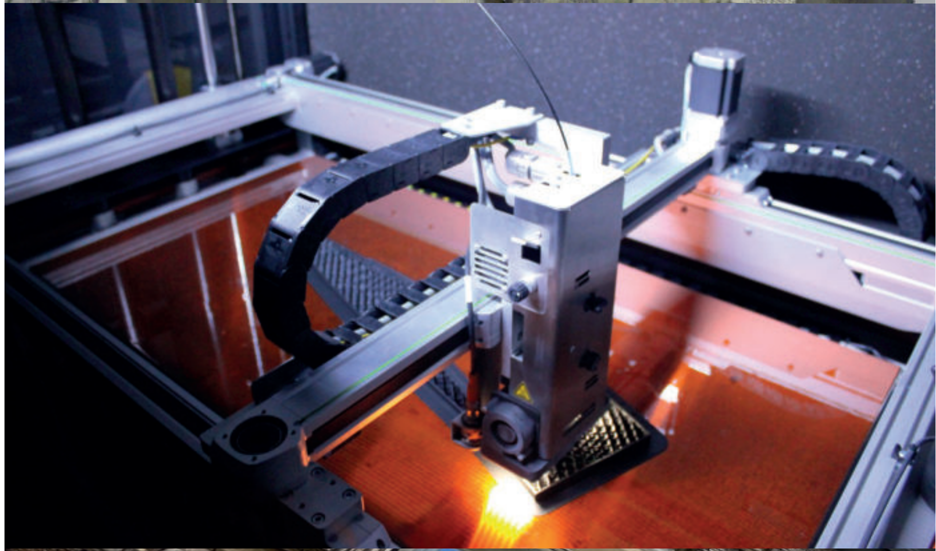
Additive manufacturing allows to realize complex geometries, within that expanding the functionality of building envelopes. Multifunctional envelope that is made of sustainable material, providing sufficient energy-efficiency qualities, contributing to the biodiversity, and influencing positively on the climate is the aim of the project. These 3D printed ceramic façade elements are designed to host small birds, that are living with us in the cities, such as house sparrows, but endangered due to building renovation processes and emerging urbanisation. The front surface of the element creates self-shading effect that contributes to the cooling of the façade surface, within that reducing Urban Heat Island Effect. The elements are fitting into the standard ventilated façade system, which enables their usage for both renovation purposes and new buildings. The usage of the natural ceramic materials contributes both to humans' and animals' well-being – the nature-based material is safe for birds and captures CO2 from the environment. Moreover, those elements are fully recyclable.

LOW CARBON RE-BUILD

New Digital Craft GmbH
Jörg Petri

„Low Carbon Re-Build" from New Digital Craft offers a contemporary and sustainable alternative to classic stone masonry works. New Digital Craft developed a unique production method to replace 1:1 stone masonry works in a short time. The existing stone masonry works are 3D scanned providing exact information to inform a parametric 3D model. From this model a formwork is generated to be directly 3D printed in 1:1 large format scale and then casted with a low carbon concrete. After standard curing time the new parts are ready to be shipped and installed on the building site. Of course, new stone masonry works from scratch without existing examples to be scanned can be produced with the same effectiveness. The circle closes after end-of-life of the 3D printed formwork, when it is recycled to be printed again for the next formwork. The innovative and new manufacturing method enables the installation of insulating cores in the concrete components, which prevent cold bridges and are thermally more sustainable compared to the classic stone masonry solution. New Digital Craft is using alternative concretes (e.g. geopolymers) instead of the classic Portland cement based concrete. That minimizes the ecological footprint by reducing CO2 emissions by 80% and results in a clear advantage compared to a reconstruction in natural stone. The contemporary reconstruction also provides strong arguments on the cost side, because we speak here about a saving of up to 50% compared to the classic stone carvings and masonry works from batch size 2 onwards.





3DCP FREEFORM FILIGREE

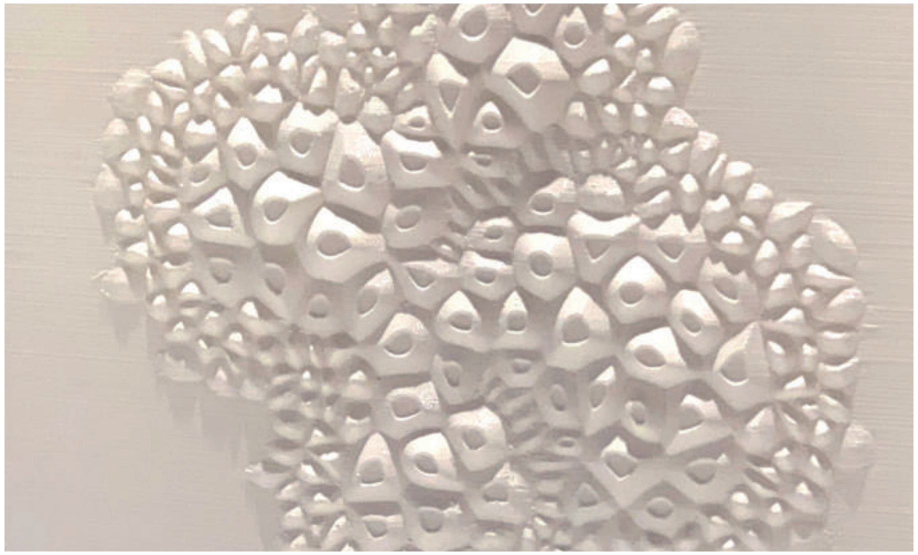
Eindhoven University of Technology, Chair of Architectural Design and Engineering
Cristina Nan, Juliette Bekkering, Volker Ruitinga, Michiel Riedijk, Chaoyu Huang, Alessio Vigorito, Kees Leemeijer, Orestis Pavlidis, Cindy Vissering

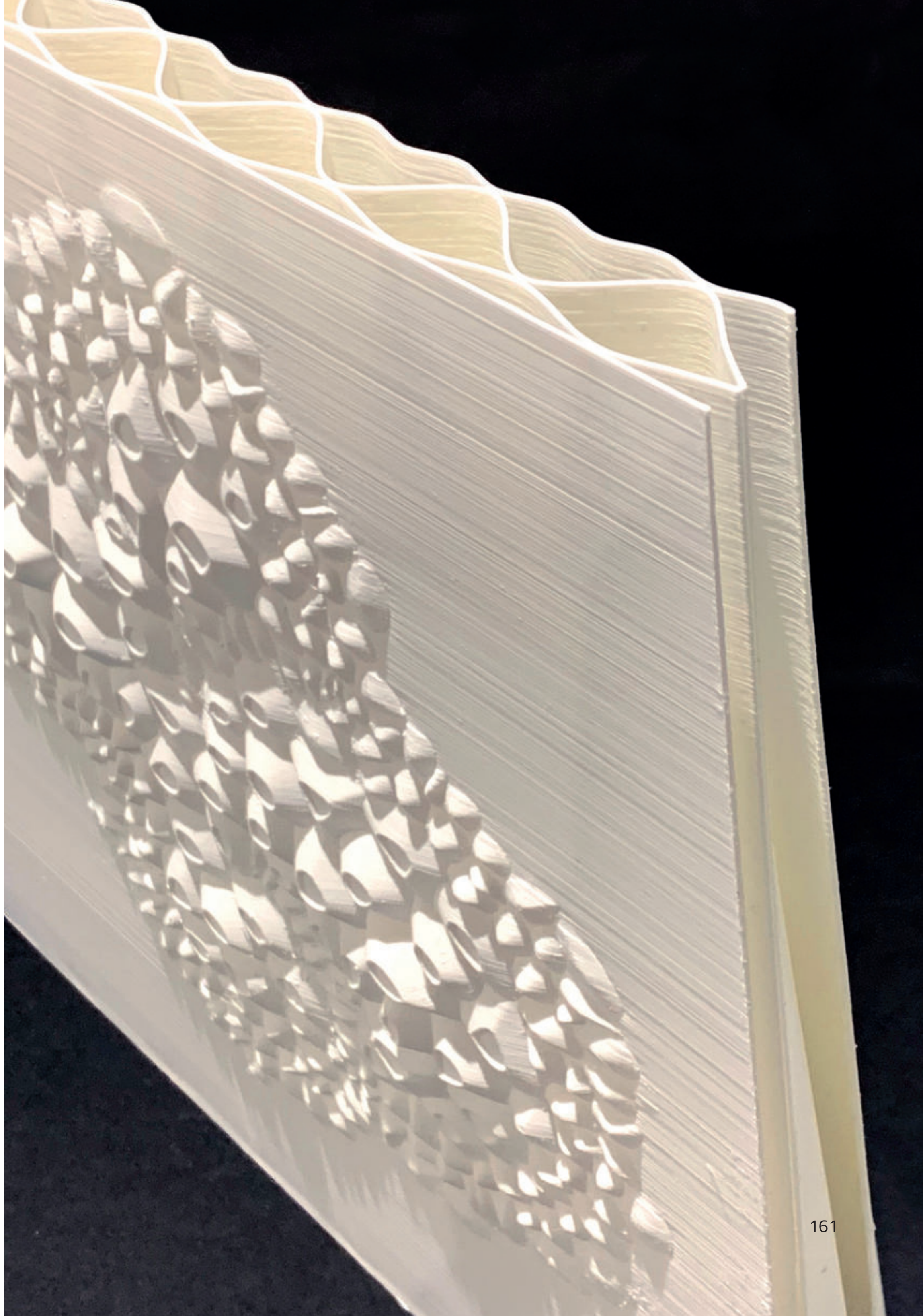
3DCP Freeform Facade Filigrees bypasses the use of wasteful scaffolding and moulds, by exploring 3D concrete printing (3DCP) on reusable sand-based substructures. Non-standard, complex geometries generally require the use of formwork, leading to wasteful, material-intense manufacturing processes. The investigation explores optimised material depositing strategies for 3DCP on robotically shaped sand formwork. The need for timber scaffolding, plastic or foam-based moulding for casting concrete is avoided. The fabricated structures are freeform filigree lenses with varying curve densities, envisioned as screens part of facade systems and spatial dividers. The research addresses the need for circular construction, reduction of raw-material usage for concrete formwork and the development of optimised material depositing strategies to undercut concrete usage. The deployed method falls under the category of sub-additive concrete printing. Firstly, the sand-based formwork for printing is shaped robotically through the use of different customised end-effectors. The robotic sand-forming of the substructure can be repeated multiple times, as almost no material loss is encountered. Subsequently, the robot arm is used for 3DCP along a three-dimensional tool path on the robotically shaped sand formwork. Extrusion flow, printing speed and angle were tested and optimised to guarantee high-precision printing and resolution. Different material depositing strategies for the multi-layered printing were explored aiming to improve the layer definition, structural performance of the freeform filigree lenses and to reduce material use. The presented research is funded by the Dutch Research Council (NWO). The research team is made up of the following partners: TU Eindhoven, Neutelings Riedijk Architects and the 3DCP specialist Vertico.

WONOVA INTERIOR

Etcetera
Rob Henderson, Ariane Stracke-Henderson, Miguel Cerezo-Diaz

In the coming years, we anticipate a profound transformation in production and installation methods in the building industry. Evolving technologies and sustainable practices will drive this shift in construction practice, and shape our built environment. For instance, work and retail spaces are constantly being renovated and rearranged. The demolished materials go in the trash. And, in the last several years, the length of a typical commercial lease has shortened from 5-10 years to 3-5 years. Wonova Interior is conceived to meet this demand site for each new tenant fit out. Wonova Interior's solution combines additive manufacturing technology, elegant design, and on-site shredding and refabrication to build circular and responsive interiors. With the assistance of acoustic scanning and parametric generative form, developers, owners, and tenants of commercial and retail spaces can improve their properties and processes. The sustainability of the refabrication process is augmented by the health and comfort of a design focus on acoustic performance. Wonova Interior reduces its carbon footprint through material and transport efficiencies and mono-materiality. Mono-materiality means Wonova uses as little virgin material as needed and provides maximum recyclability. In an effort to reach net carbon zero, structural efficiency is also optimized. In addition to the sustainability and acoustics topics, Wonova Interior is built on ideas of functionality and textures with built-in furniture and increased tactile comfort. Wonova Interior is currently in the research and development phase, and we are interested to hear from potential partners.

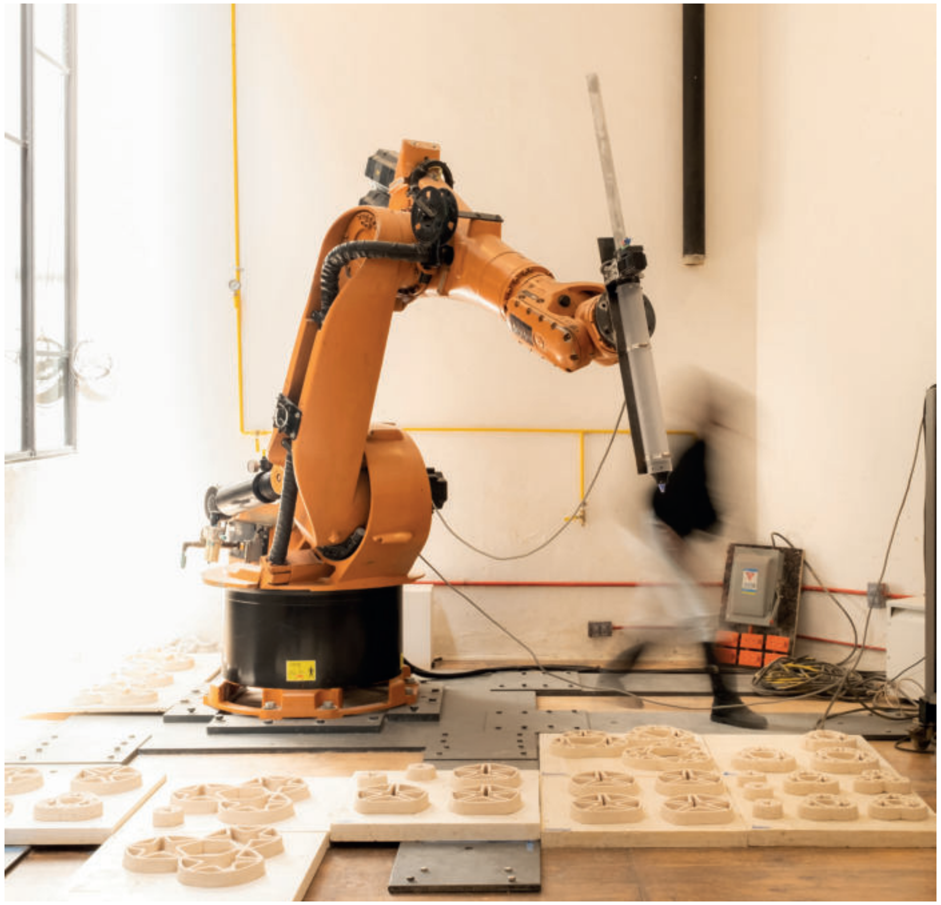


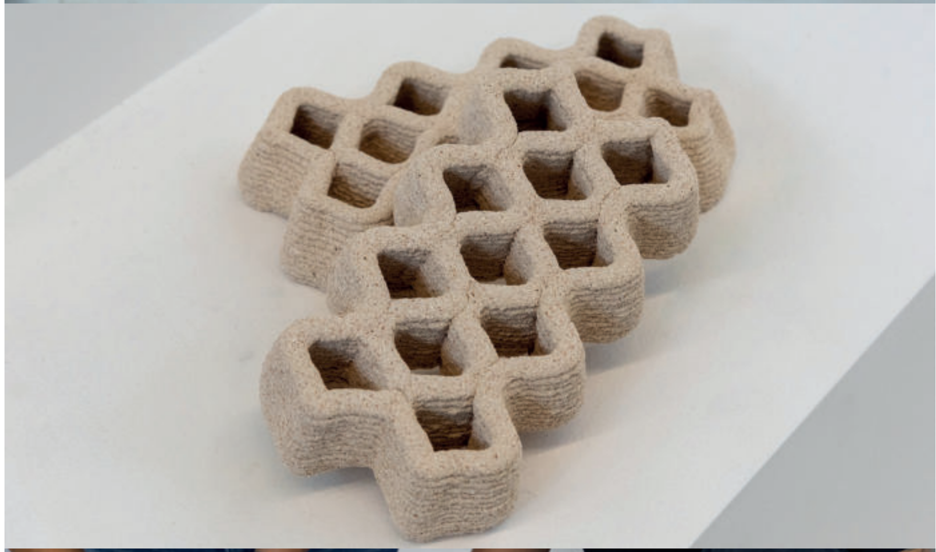


THE EGGSHELL PROJECT

MANUFACTURA
Dinorah Schulte, Edurne Morales, Montserrat Ayala

The Eggshell project is a research project that seeks to take advantage of and transform our organic waste to turn it into a buildable material and open up a new possibility to create our living in an environmentally responsible way. In this project we 3D print a biocomposite made from eggshell and combine it with sustainable aggregates using a KUKA Robotic arm, resulting in a new materiality, which seeks to reduce food / organic waste and generate new opportunities through technology and innovation in Mexico.

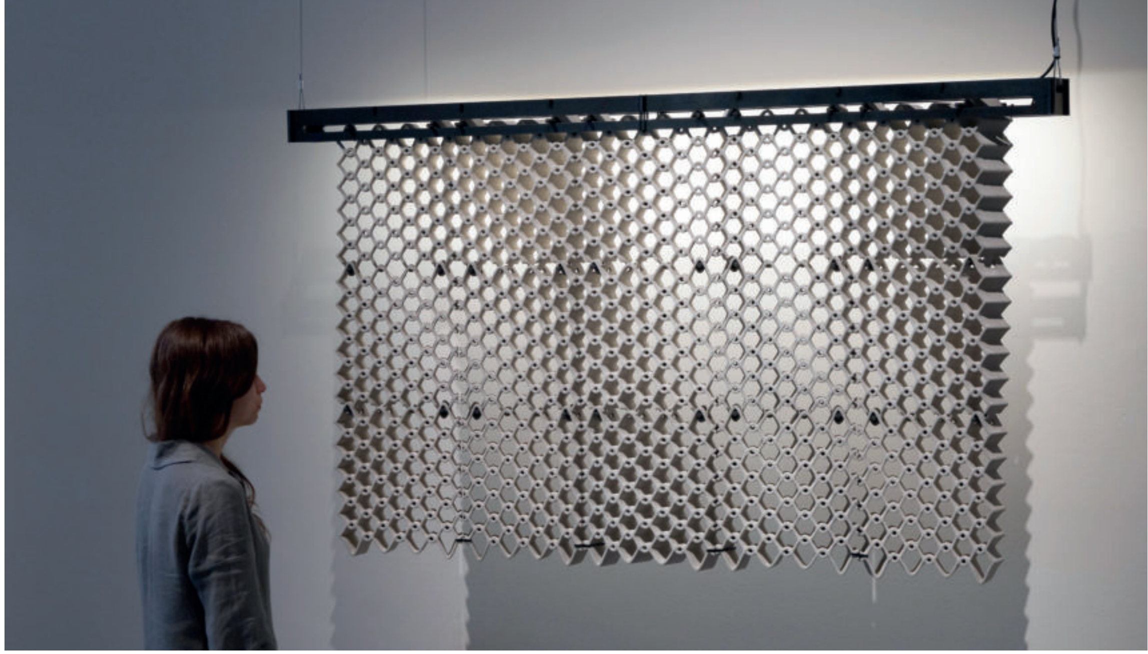


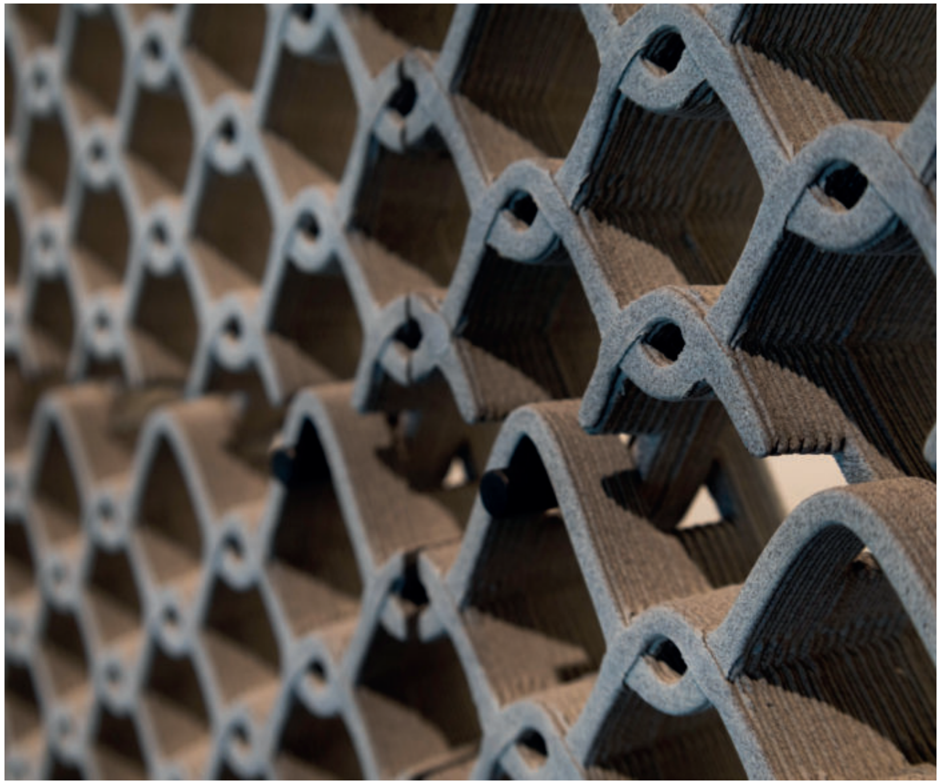


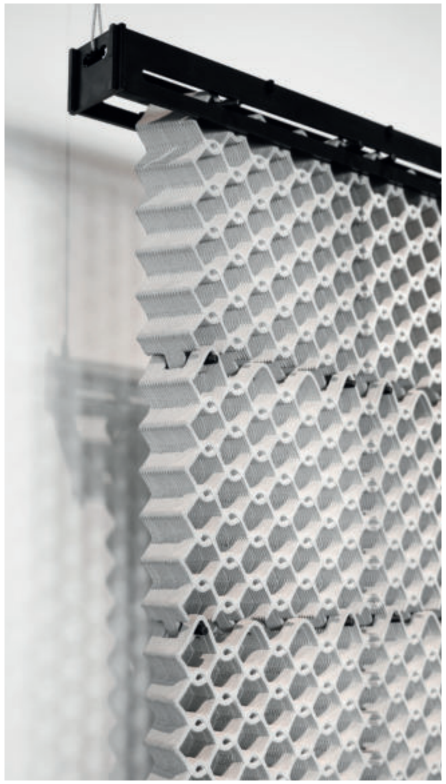
STATIC SHIFT

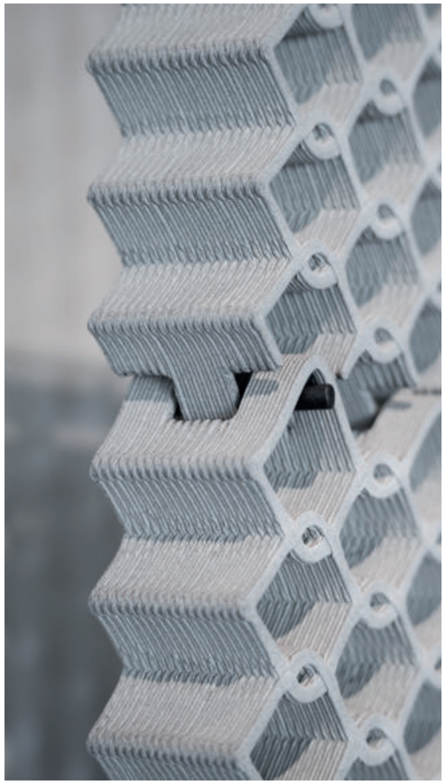
University of Waterloo, School of Architecture
James Clarke-Hicks, Isabel Ochoa, David Correa

Static Shift is best experienced while the viewer is in motion. The wall prototype consists of 15 hanging ceramic tiles that form a planar lattice structure. The tiles are constructed from a self-intersecting 3D-printed lattice consisting of apertures that form porosity gradients relative to the viewing angle. All hanging tiles are mechanically connected with steel pins inserted into the overlapping lattice. Vertical joints overlap to seamlessly transition from tile to tile and enhance visual continuity within the wall prototype. Z-axis variability is utilized in the 3D printing process to maintain the continuity of the overlapping print path. The apertures create a Moiré effect, 'the mechanical interference of light by superimposed networks of lines,' giving viewers the perception that Static Shift is in motion.





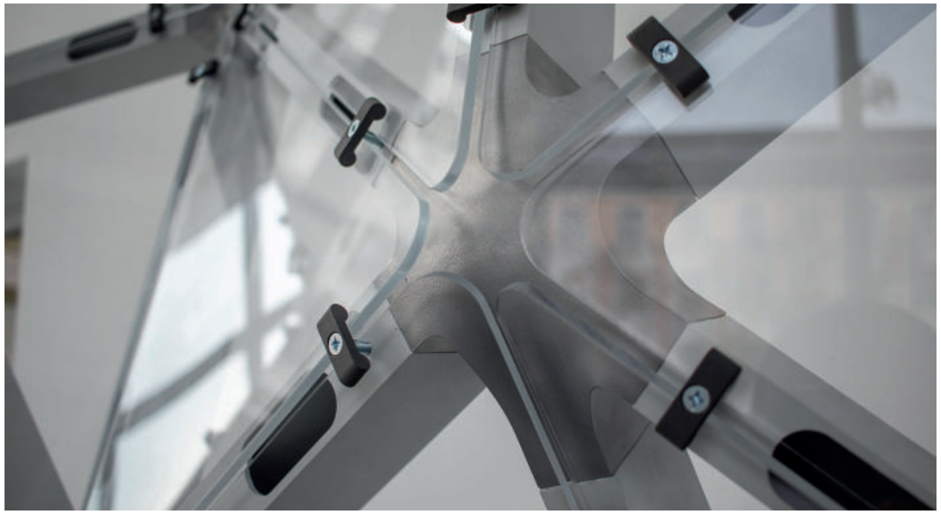




INNOFA2.0 - ONE NODE DEMONSTRATOR

Leipzig University of Applied Sciences, FLEX | Forschung.Lehre.Experiment
Martin Dembski, Alexander Stahr, André Streek, Michael Pfeifer, Martin Erler

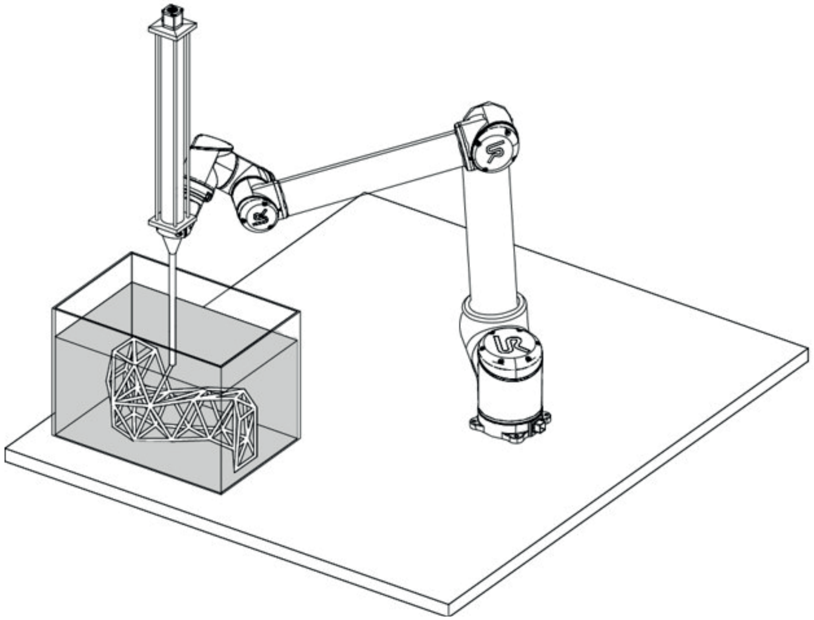
The InNoFa2.0 is a one-node demonstrator, created from the collaboration of the FLEX research group from Leipzig University of Applied Sciences (HTWK) and the Laserinstitut Hochschule Mittweida (LHM). "InNoFa" stands for a facade construction with individual node elements. "2.0" describes the use of the newly developed macro-SLM process, not conventional SLM. Together, LHM and FLEX, developed this new large-volume powder bed-based 3D printing technology, which is no longer based on fine metallic powder, but rather selectively welds metal granules (grainsize: >200 µm) together with high laser power and combines technologies from different additive manufacturing processes (workingtitle: GrobKorn). This significantly increases material turnover during the process, reduces printing time and reduces material costs. The newly developed process is extremely attractive, especially for macroscopic components. The process offers great potential for much larger parts. A demonstrator system with an installation volume of four cubic meters is currently being built. The InNoFa2.0 demonstrator is based on the ParaKnot3D-Concept, a hybrid construction in which straight rods and individual node elements are combined to offer the possibility to form optimized freeform structures. The researchers are currently optimizing the system and developing reliable testing procedures and approvals for components being produced in this way to transfer the new technology from research to industry. Both partners are members of the Saxony⁵ transfer network and expanding this with their know-how in the areas of 3D printing, digital manufacturing, sustainable constructions, parametric design, engineering, laser technology and interdisciplinary cooperation.



INJECTION 3D CONCRETE PRINTING

Technical University of Berlin | Technical University of Braunschweig, Institute of Civil Engineering
Inka Mai, Harald Kloft, Dirk Lowke, Yinan Xiao, Norman Hack

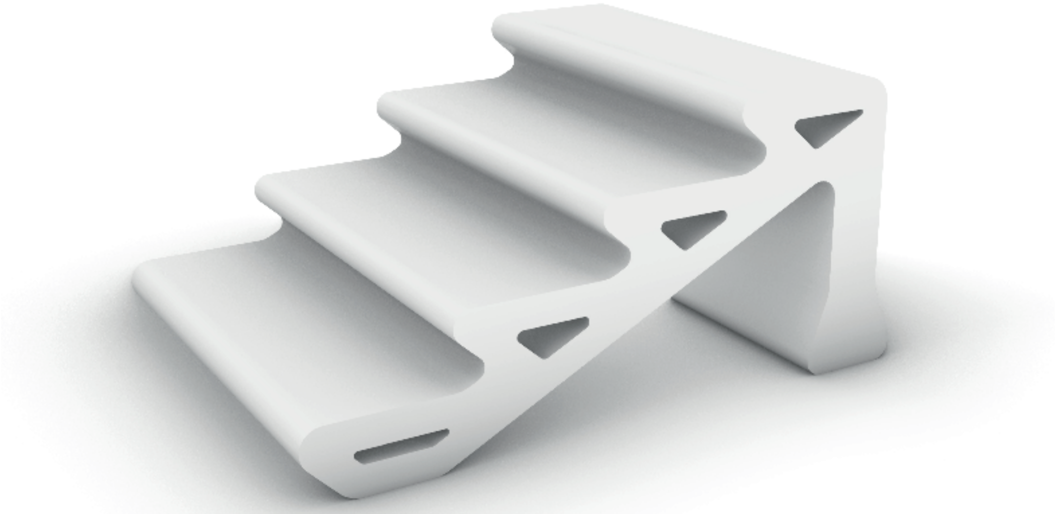
Injection 3D Concrete Printing (I3DCP) is an unique additive manufacturing technique. The basic principle of I3DCP is that a fluid of material A is robotically injected into another fluid (material B). The role of material B is to support material A such that material A maintains a stable position. In general, I3DCP can be categorized into three sub-categories: (a) Concrete in Suspension (CiS): injection of concrete into a non-hardening carrier liquid, (b) Suspension in Concrete (SiC): injection of a non-hardening suspension into a concrete; and (c) Concrete in Concrete (CiC): the injection of a concrete into another concrete with different properties. A key feature of the first two I3DCP sub-categories is the ability to produce intricate lightweight strut-and-tie spaceframes, without the constraints of complex formwork. An example of the CiS-technique, which is currently the most investigated technique, is at display at the formnext/BE-AM exhibition. The third sub-category has the advantage of being able to produce concrete components with specific concrete properties in selective areas. In all techniques, the geometry and stability of the printed strands is influenced by the process and material parameters. To fully understand and exploit this technique further, a more thorough investigation of these parameters are envisaged

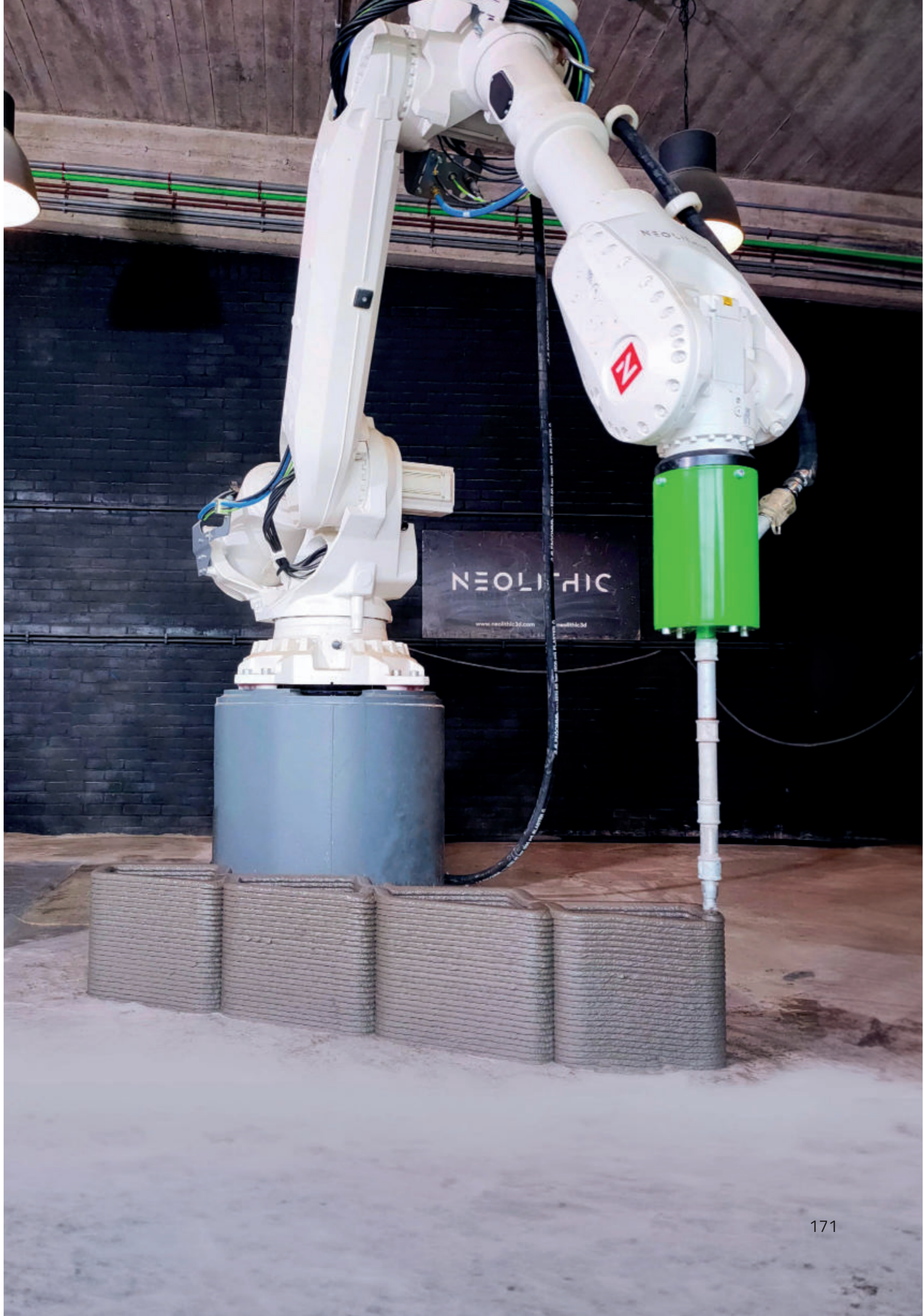


NEOLITHIC'S SLOPED STAIRS: REDEFINING EFFICIENCY AND DESIGN IN CONSTRUCTION

Neolithic BV
Chris Aerts, Tico Beekman

Neolithic is an innovative startup at the forefront of 3D printing and digital warehousing. We specialize in sustainable industrial 3D printing of stone objects using cutting-edge technologies, such as mortars, stone powders, and clay. With our advanced technology and efficient supply chain, Neolithic excels at rapidly conceptualizing, printing, and delivering high-quality products. Our robotic production hubs primarily focus on the creation of modular construction and infrastructure components. At Neolithic, we place a strong emphasis on product development and also provide tailor-made solutions for unique designs in close collaboration with contractors, designers, artists, and municipalities. One of our flagship products is our mass-customizable sloped stairs system. This innovative solution employs modular 3D concrete printed components that can be easily repurposed. Thanks to our material-optimized printing processes, our sloped stairs consume up to 50% less material compared to conventional concrete stairs. Using our digital configurators, you can create a sloped stair design that perfectly suits your requirements. The Neolithic digital processes ensure a seamless transition from design to print data, resulting in speedy delivery within a few weeks. Moreover, our pricing is significantly more affordable than traditional methods. Neolithic stands as a beacon of efficiency and sustainability, setting a new standard in the construction industry.

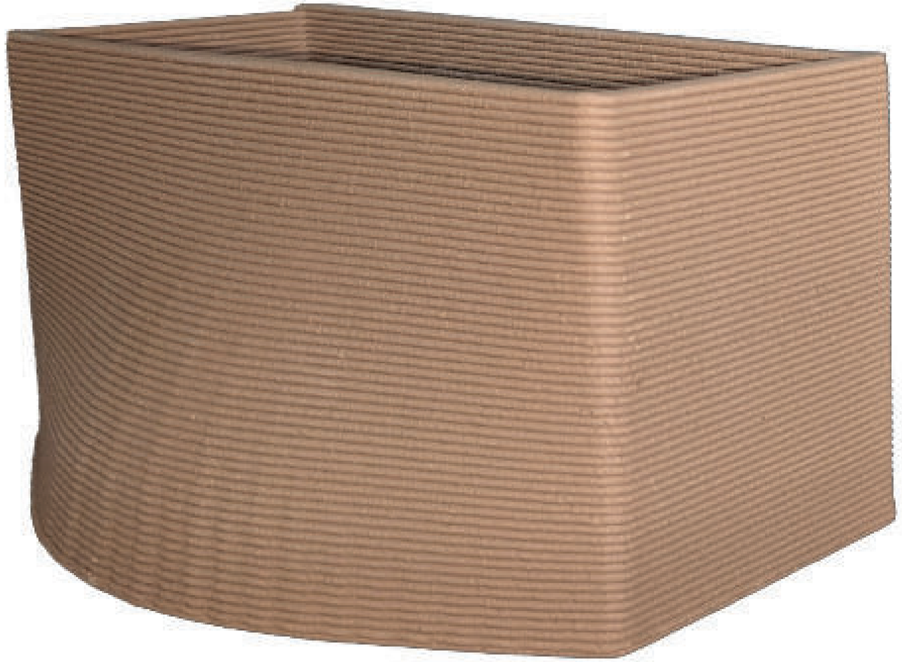




DESIGN AND EVALUATION OF AM CERAMICS IN CONSTRUCTION

Technical University of Darmstadt, Institute of Structural Mechanics and Design
David Fluß

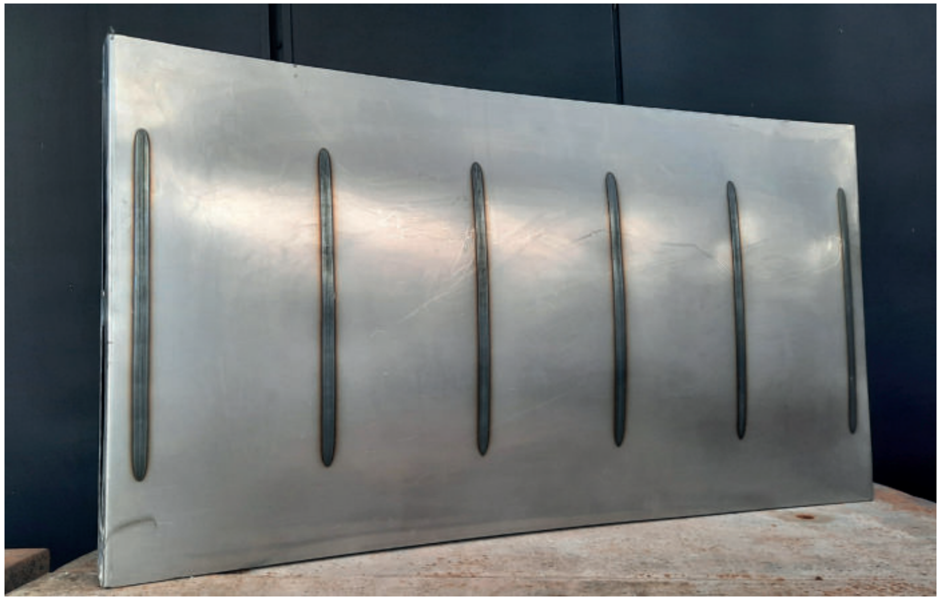
The content of this research work deals with the conceptual design and implementation of a sound-absorbing facade. The building material used for this purpose, ceramic, which initially does not have any salient sound-absorbing properties, is thereby transformed into a form that exhibits acoustic effectiveness by means of additive manufacturing. The individual elements have alternating inward and outward curvatures. On the inside there is a perforated structure.The shape of the elements directs sound into the interior of the component by means of targeted reflections. The internal structure ensures that both a higher degree of damping is produced and that the sound waves are scattered when the sound is reflected back.As part of the research work, it was found that the direction of sound incidence has a major influence on the acoustic effectiveness of the facade. Additive manufacturing makes it possible to respond to this by individualizing the individual components. In this way, the elements can be adapted to different sound situations in order to achieve the best possible result.

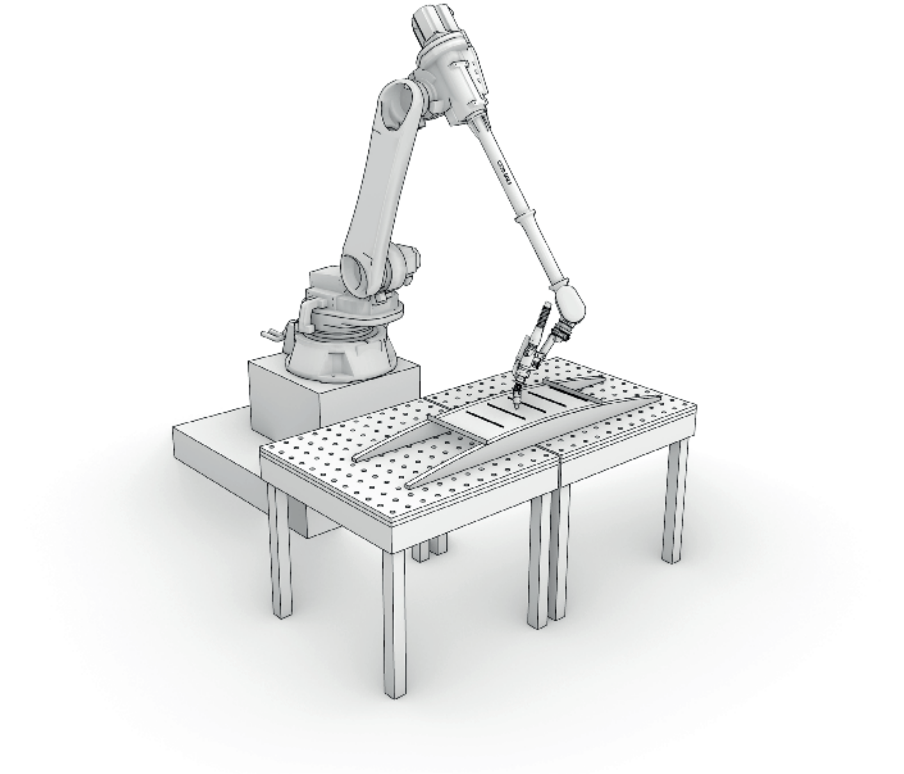


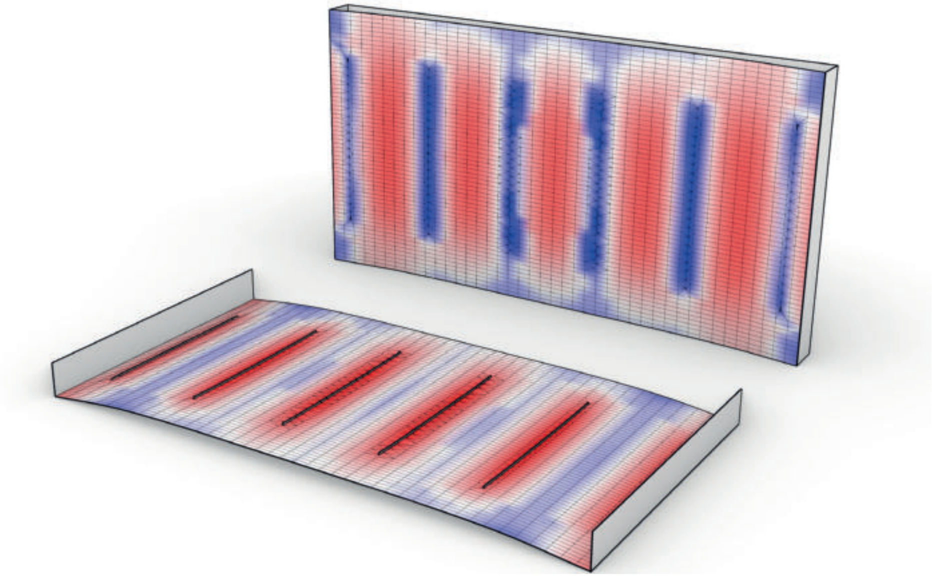
FORMLIGHT

Technical University of Darmstadt, Institute of Structural Mechanics and Design
Juan Ojeda, Philipp Grebner, Ulrich Knaack, Jörg Lange, Philipp Rosendahl, Jochen Hölscher, Martin Manegold

A growing trend in architecture which impacts building technology and the architectural landscape is the use of freeform sheet metal panels in facades. However, these cladding panels are mostly handmade, costly, and require high thicknesses due to structural requirements. To date, architects and engineers are challenged to integrate aesthetics, strength, sustainability, and circularity into building processes. To overcome these challenges, digital fabrication is available. Tools like additive manufacture and robotic fabrication can improve sustainability and reduce human resource. Wire Arc Additive Manufacturing (WAAM) is a metal 3D printing process that is attracting attention in the construction industry, due to its cost-effectiveness and efficiency. WAAM can produce individual components reducing material waste and manufacturing time, providing design flexibility and productivity advantages. The presented panels are the result of a workflow that combines robotic fabrication, depth cameras, computer vision and WAAM, to scan, analyze, shape, and stiffen thin steel sheets for freeform facades. Welded reinforcement simplifies fabrication and reduces manual labour to just pre bending stages. Eventually, this system will be able to operate in the field revolutionizing construction methods, scanning the building structure, forming, and assembling the steel plates with robotic arms.



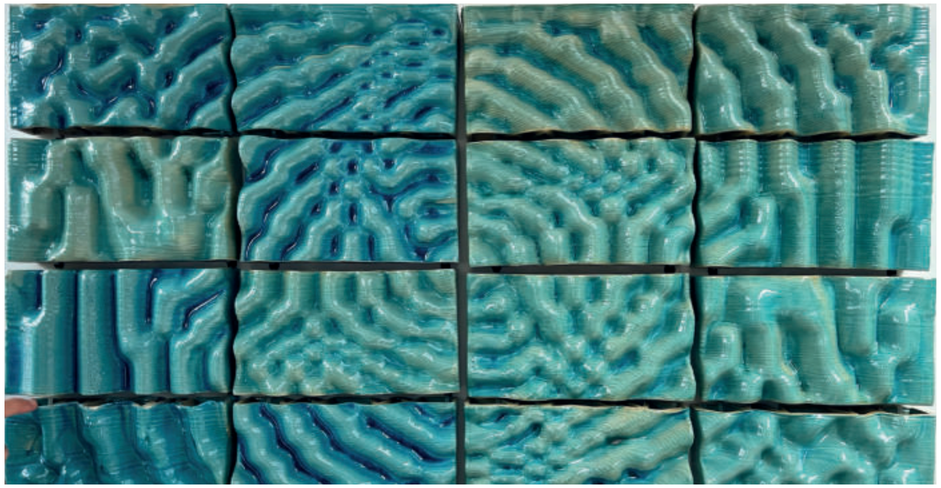


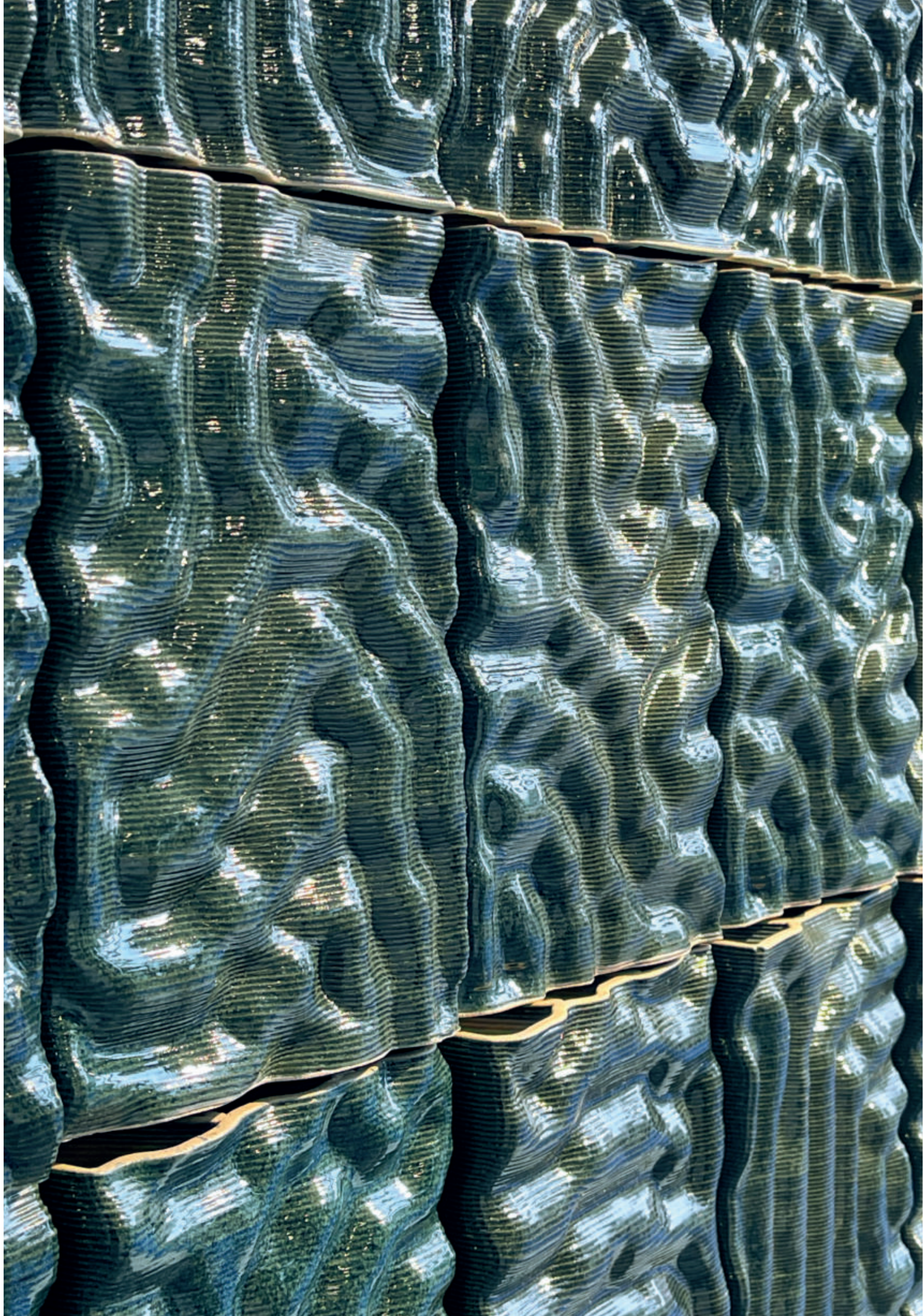


COMPUTATIONAL CLAY PROTOSTRUCTURES

Eindhoven University of Technology, Chair of Architectural Design and Engineering
Cristina Nan, Mattia Zucco (computational specialist), Students: Ruben Deckers, Petar Dobrev Floris Havermans, Harm Herkens, Christian Heusschen, Kevin van Laanen, Don Marsman, Nicky Meenderink, Axel van Nieuwehoven, Jasper Veens

There is no more primordial material than earth - clay or mud. It surrounds us everywhere. It is ubiquitous and there is not shortage of it. Earth, mud and other earth-based material systems have been employed for millennia in construction and architecture. Through the use of algorithm aided design, Computational Clay Protostructures aims to unlock the aesthetic and architectonic potential for clay-based construction. Computational Clay Protostructures explores new material and tectonic expressions through the use of ceramic additive manufacturing in architecture. The project showcases the rethinking of design and fabrication processes surrounding clay and its implementation as an ornamental component. Aspects of craftsmanship relating to working with clay, such as controlling and calibrating its complex material properties as well as behaviour in accordance to complex curvature, were combined with computational design logic and robotic fabrication. Informing new material expressions of clay through 3D printing opens up the disciplinary conversation on the role of the ornament(al) after the Digital Turn as well as the notion of digital craft and transfer strategies of sticky information, as defined by Eric von Hippel. Four 3D printed facade cladding systems explore the use of additive manufacturing with clay and its resulting ornamental quality. The deployed parametric design strategies are informed by the Turing pattern occurring in nature, textile folding behaviour and the computational translation of knitting patterns. Within the larger framework of computational design, robotic fabrication and the concept of digital craftsmanship, the project aims to advance the capabilities of clay as an architectural expressive material by combining complex geometries, computational textures and colour.





ADDITIVE-HYBRIDS

Technical University of Darmstadt, Digital Design Unit (DDU)
Samim Mehdizadeh, Nastassia Sysoyeva, Molham Jorbah, Leon Witschorke, Philippe Wüst, Oliver Tessmann

The „Additive-hybrids" is a demonstrator investigating the potential of additive manufacturing in conjunction with different digital fabrication techniques and multi-materials. The realm of 3D printing with construction materials on a building element scale offers the opportunity for hybrid materiality. The wide range of research on large-scale additive manufacturing addresses open questions such as multi-materiality. In this context, we propose a material system that combines two material organizations simultaneously: 3D printing and casting. This hybrid system employs bio-based plastic material, PET, which offers high recycling potential. The cast material in this demonstrator is a water-based acrylic polymer. The algorithmic design framework minimizes material consumption by deploying each material specifically to reduce material combination. These digital-to-physical materialization frameworks provide geometrical articulation capabilities and, most importantly, can adapt to any force distribution scenario. The building demonstrator was sponsored by the Additive Manufacturing Center TU-Darmstadt and realized through a collaborative effort between the „Digital Design Unit" (DDU), Department of Architecture, and the „Institute of Printing Science and Technology" (idd), Department of Mechanical Engineering at TU Darmstadt.

GENERATIVE DESIGN TABLE BY BONE 4

BigRep GmbH
Silas Dortmann, Emanuel Nowak, Kanbara Tomonori

A organic designed 3d printed table made of PLA. Crafted using Autodesk Fusion 360 by Kanbara Tomonori, modified for optimal load distribution by minimal material usage by Emanuel Nowak. This table, showcasing a remarkable blend of stability and lightweight design, was 3D printed using the advanced capabilities of the BigRep BONE4 printer. This state-of technology allowed the realizatino of the design, underscoring the capabilities and potential of large-scale FFF 3D printing. BigRep's German engineered 3D printers enable engineers, designers, and manufacturers from start ups to fortune 100 companies to go from prototyping to production faster, getting their products to market first. Founded in 2014, BigRep is headquartered in Berlin with offices and technical centers in Boston, Singapore, and Shanghai and strives to transform user productivity and creativity with easy to use additive manufacturing solutions.

INFO

BE-AM 2023 PROJECT PARTNERS

Collaborators

TECHNISCHE
UNIVERSITÄT
DARMSTADT

DDU

Digital Design Unit — Digitales Gestalten

ISM+D

Institute of Structural Mechanics and Design
Institut für Statik und Konstruktion

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for innovation

Generative
Design
Lab

ADDITIVE
MANUFACTURING
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