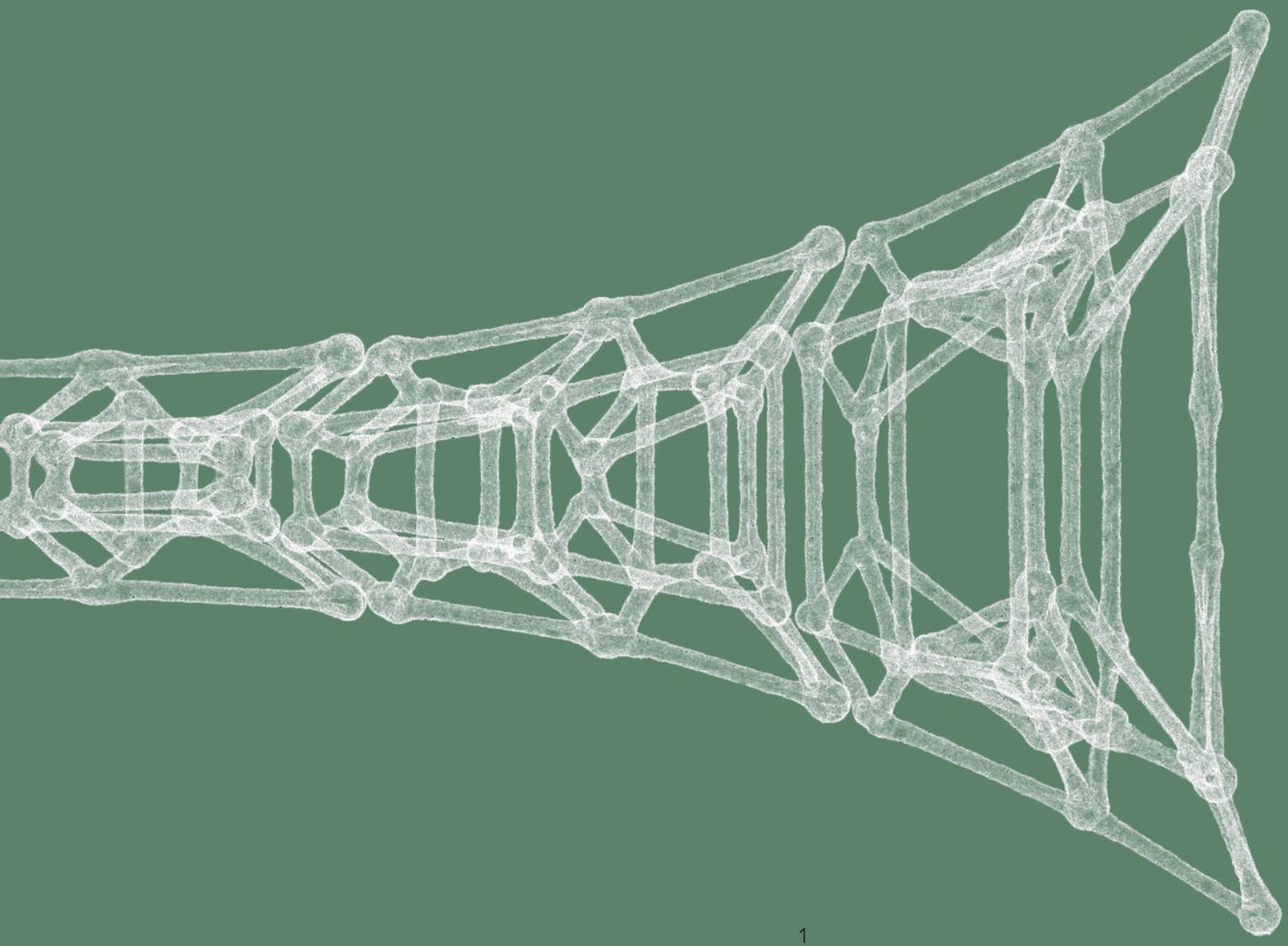
AMC COLLABORATIVE DEMONSTRATORS



AMC COLLABORATIVE DEMONSTRATORS

VALIDATION OF INTEGRATED RESEARCH METHODOLOGIES THROUGH
COLLABORATIVE AMC PROTOTYPING

AMC COLLABORATIVE DEMONSTRATORS

Validation of Integrated Research Methodologies
through Collaborative AMC Prototyping

In association with
Additive Manufacturing in Construction
AMC TRR 277

Publishers:	Dörfler K., Hack N., Henke K., Kloft H.,
Published at:	Technische Universität Braunschweig
Place of Publication:	Braunschweig

Managing Editor:	Janna Vollrath
Associate Editors:	Moritz Scheible, Julia Fleckenstein, Anne Niemann
Layout:	Janna Vollrath, Lea Löwe, Moritz Scheible
Typeface:	Dinamo, ABC Favorit
Printing and Binding:	Offsetdruckerei Karl Grammlich GmbH

ISBN:	978-3-910750-05-0
DOI:	10.24355/dbbs.084-202310041154-0

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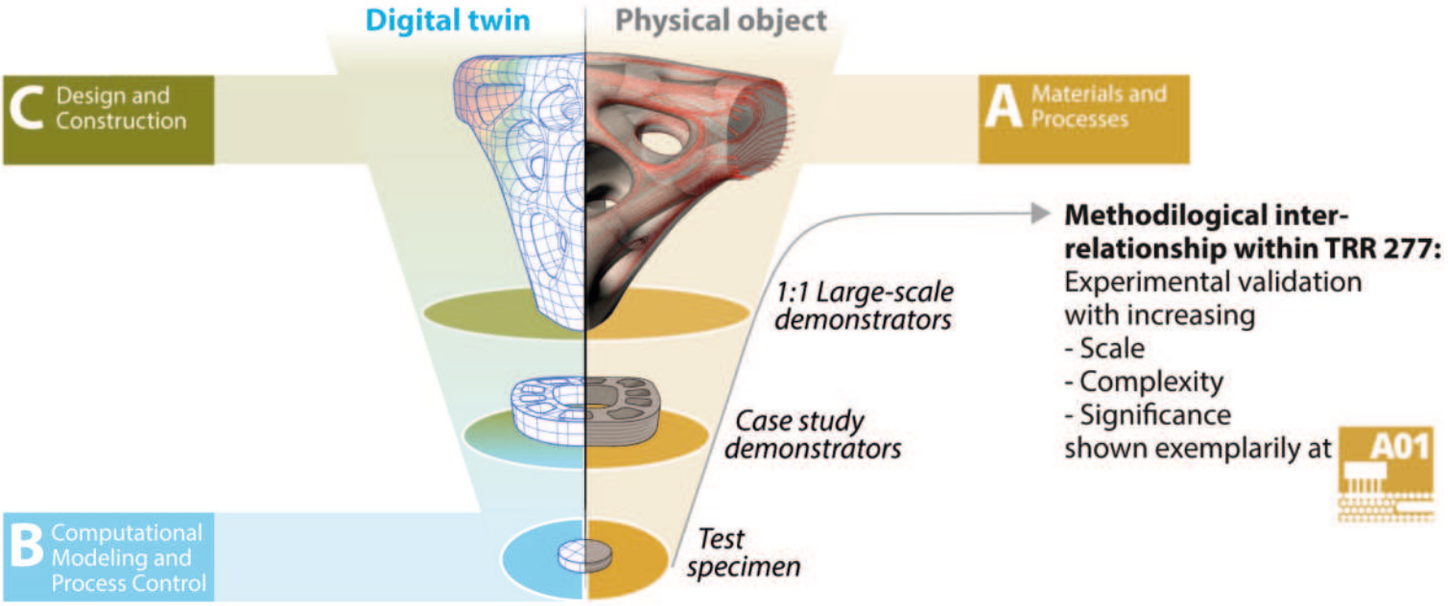

Digital twin
Physical object
C Design and Construction
A Materials and Processes
B Computational Modeling and Process Control
1:1 Large-scale demonstrators
Case study demonstrators
Test specimen
Methodilogical inter-relationship within TRR 277:
Experimental validation with increasing
- Scale
- Complexity
- Significance
shown exemplarily at
A01

BACKGROUND & MOTIVATION

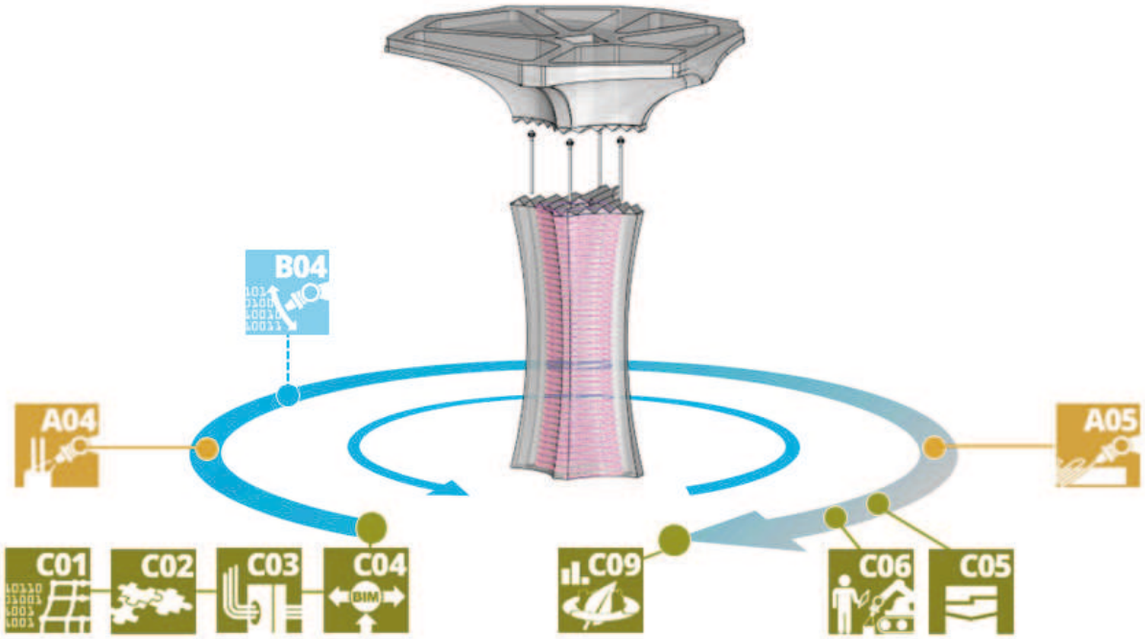
The „AMC Collaborative Demonstrators“ . large-scale additively manufactured sections of building and infrastructure designs at 1:1 scale - serve the purpose of investigating and experimentally validating the methodological connection and interaction between the three main focus areas A (Materials and Processes), B (Computer-aided Modelling and Process Control), and C (Design and Construction) within the Collaborative Research Centre TRR 277 Additive Manufacturing in Construction (AMC).

The AMC was established by the Technische Universität Braunschweig and the Technical University of Munich in 2020, investigating large-scale Additive Manufacturing (AM) as a new key technology for tomorrow‘s construction. The research is based on the hypothesis that AMC can combine the advantages of artisanal construction and craft, namely individualised and non-standardised manufacturing, with the advantages of industrial mass production, namely precision and cost-efficiency. With the concept of mass customisation, new degrees of freedom in design and higher material efficiency in construction can be achieved, mainly because material can be applied only where it is structurally and functionally needed. Within the scope of the AMC, a wide range of mineral-based materials, mineral composites, metals, earth-based materials, fibre-reinforced polymers, and wood are being explored for various additive manufacturing processes. What unifies this diversity of materials methodologically is a profound focus on material-process interaction. In the integrated approach to digitally supported construction, the material and the manufacturing process are consciously considered as a cohesive entity, deeply interrelated and complementary to each other. Furthermore, the research conducted by the AMC is essentially interdisciplinary and goes beyond purely technological investigations. It not only examines material-process interactions but also encompasses simulation and modelling, structural design, and the integration of additive manufacturing in the wider construction ecosystem. The methodological interconnection of the three main focus areas A, B, and C, is based on experimental validation through the production of test specimens, demonstrators of case studies, and large-scale demonstrators. This approach is used for the validation of project-specific research questions. (Figure 1).

Additionally, the design and fabrication of large-scale Collaborative Demonstrators serve as a platform for interdisciplinary teams of AMC researchers across the fields of civil engineering, architecture, materials science, and mechanical engineering to experimentally test and validate the integration of materials and processes (focus area A), computer-aided modelling and process control (focus area B), and design and construction (focus area C) featuring sections of building and infrastructure designs at 1:1 scale (Figure 2).

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, geometric freedoms, etc., 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.

Figure 1 / Left side / The methodological connection between the three focus areas A, B, and C, within the TRR 277 AMC is being investigated through the validation of their interaction via test specimen, prototypes, and large-scale demonstrators.


B04
A04
A05
C01
C02
C03
C04
BIM
C09
C06
C05

CONCEPT & IMPLEMENTATION

The conception and implementation of the Collaborative Demonstrators in the AMC involved the following steps and stages: 1) Investigation of the application potential of AMC research in architectural design projects for building and infrastructure constructions; 2) Synthesis of research results and design ideas for novel integrated construction processes; 3) Scaling up test specimens to case study prototypes; and 4) Fabrication of the demonstrators at a 1:1 scale.

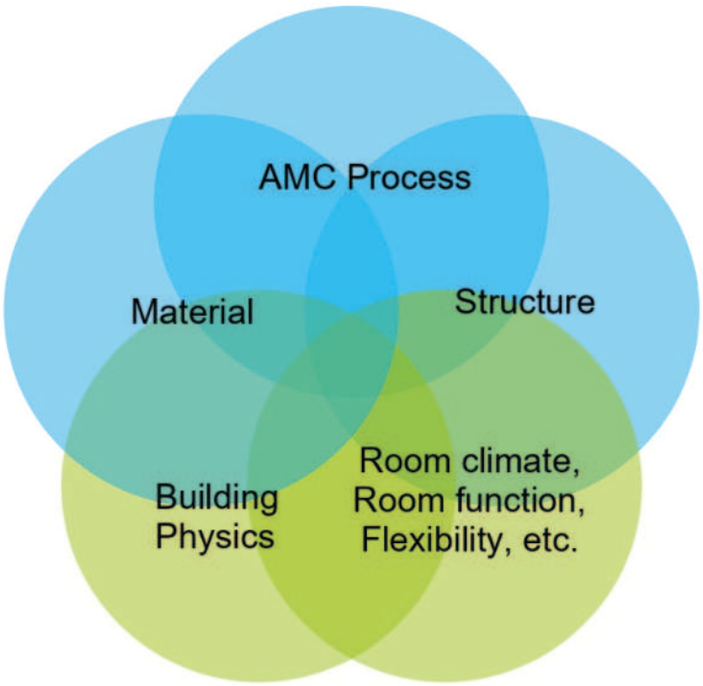
1) Investigation of the application potential of AMC research in architectural design projects for building and infrastructure constructions:

Since the integration and application of new AMC technologies in the construction sector require a rethinking of the sequential process of design, engineering, execution planning, and construction, a holistic approach is needed that combines expertise from different disciplines in early design stages to make informed decisions. For this reason, interdisciplinary teams with researchers were established within the AMC to explore and test this integrated approach in research-based design studios and seminars with varying levels of complexity in the context of infrastructure and building constructions. Instead of starting from a material- and manufacturing-agnostic architectural design that is further detailed, engineered, and made „buildable“, the methodological focus of the integrated approach consciously takes new additive manufacturing processes as a fundamental starting point for architectural design, integrating them into early conceptual stages of the design process (Figure 2). By understanding AM technologies and processes as an integrative design driver, this approach encourages architects and researchers to fundamentally explore and creatively investigate the possibilities of AMC and the application potential of AMC research for a future digital building culture, aiming to make it more sustainable, productive, and resource efficient. The conception and implementation of the Collaborative Demonstrators comprised two main streams of research: infrastructural designs and building designs.

In the infrastructural design stream, the focus is on the integration of form and force. This involves exploring how additive manufacturing technologies can be applied to create infrastructure components that are not only structurally flawless but also exhibit optimised geometries for efficient load distribution. Researchers investigate the interplay between the design of the component, the forces it will be subjected to, and the manufacturing process. By integrating these aspects, they aim to develop innovative solutions for infrastructure projects, such as bridges or structural elements for large-scale constructions.

In the building design stream, the emphasis goes beyond form and force and includes the integration of functions as well. Researchers are delving into the realm of additive manufacturing to explore how it can facilitate the creation of building components that not only fulfill structural demands but also incorporate other building functionalities. These features can range from energy-efficient elements, such as optimised thermal insulation, to intelligent systems that enhance occupant comfort and sustainability. The integration of form, force, and functions in building design allows for the development of customised and adaptive building solutions. To experimentally test the application and use of new AMC technologies in the architectural context of multi-storey building construction, a new cross-university educational format was conceived and implemented in the shape of an architecture design studio named AMtoARC.

Figure 2 / Left side / Exemplary networking scheme within the three focus a reas A, B and C on behalf of the Shelltonics Collaborative Demonstrator.


AMC Process
Material
Structure
Building
Physics
Room climate,
Room function,
Flexibility, etc.

The format was carried out across universities for the first time in the 2022 summer semester as a collaboration between Prof. Dr. Kathrin Dörfler (TT Professorship of Digital Fabrication) and Prof. Florian Nagler (Chair of Design and Construction) of the Technical University of Munich, as well as Prof. Dr. Norman Hack (Professorship of Digital Construction), Prof. Dr. Harald Kloft (Institute of Structural Design), and Prof. Helga Blocksdorf (Institute of Construction), of Technische Universität Braunschweig. The students developed designs for an inner-city residential building, focusing on the development of an intelligent construction configuration and a resilient apartment typology. The challenge for the students was to develop designs that harmonise the architectural programme including the factors of flexibility, spatial openness, and climatic quality, while respecting and incorporating the requirements and constraints of the selected AM technology. These considerations encompassed durability, fair use of materials, resource efficiency, and a streamlined fabrication process.

Overall, the research in both streams aim to push the boundaries of additive manufacturing in the construction industry by integrating design, engineering, and functional aspects. By exploring application scenarios with varying levels of complexity, researchers can validate the effectiveness and potential of the developed concepts and contribute to the advancement of additive manufacturing in the field of construction.

2) Synthesis of research results and design ideas for novel integrated construction processes:

To synthesize research methods with design ideas for novel integrated construction processes, initial informed design concepts are further developed and optimised for the production of 1:1 scale demonstrators by researchers in the AMC. During this process, the researchers consider the existing capabilities and limitations of the respective manufacturing techniques. In interdisciplinary exchanges and multiple feedback loops, the material and process interactions for component geometries are modelled, simulated, and enhance in terms of their functionalisation. Starting from fundamental material and process properties and based on the core idea of customisation, the general goal is to utilise the possibility to optimise geometries so that material is used only where it is functionally necessary, such as for load bearing, insulation, or enclosure purposes, and further, to individually grade material properties and geometry based on local requirements. The focus thereby is not only on the final geometry but also on the underlying manufacturing process, which is modelled, simulated, evaluated, and optimized in interaction with it.

3) Scaling up test specimens to case study prototypes:

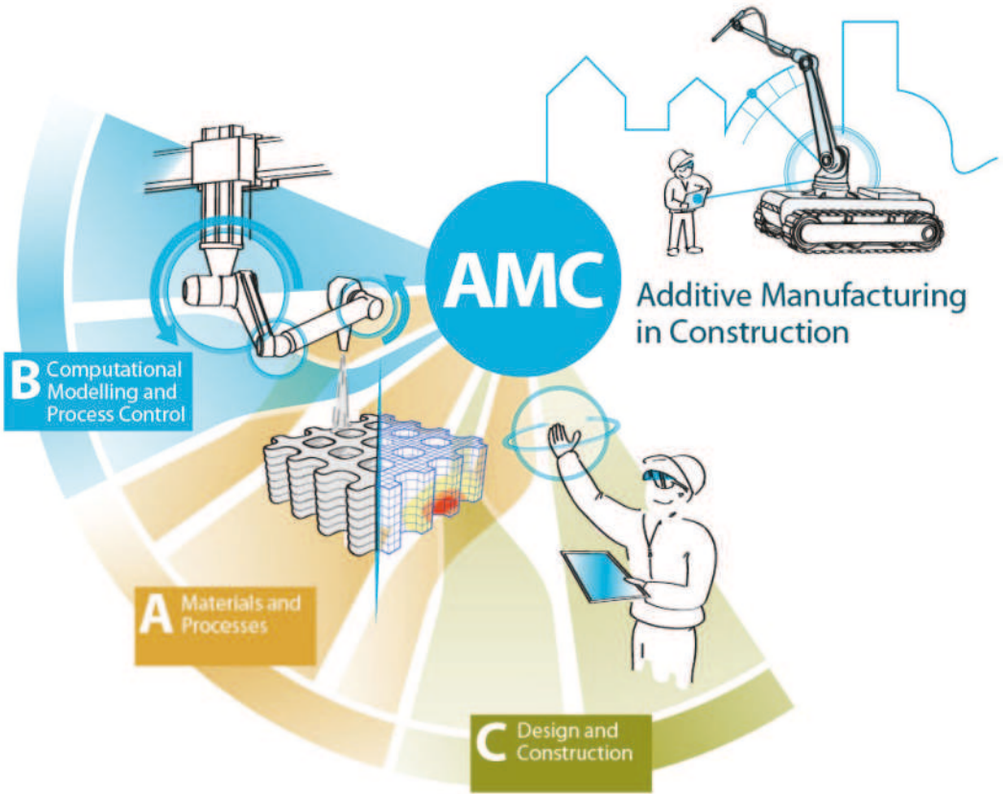
To iteratively validate and improve assumptions of modeling and simulations, test specimens and prototypes are manufactured as part of the development of the Collaborative Demonstrators. These are examined in terms of their manufacturing parameters and resulting material properties (such as flexural and compressive strength, thermal conductivity). Further tests may include the production of connection and joining geometries to assess their shear strength. The outcomes of these tests are incorporated back into the modelling process, facilitating subsequent rounds of digital analysis and iterations for the optimisation of processes and geometries.

4) Fabrication of the demonstrators at a 1:1 scale:

Optimised and refined designs for demonstrators are directly produced by AMC researchers, both in the laboratories of TUM and TUBS with the specially developed research infrastructure, as well as selectively with industry partners. The continuously developed research infrastructures of AMC at both universities are a unique feature that enables the experimental investigation of complex relationships from the microstructural level to the 1:1 component scale.

Kathrin Dörfler, Norman Hack & Klaudius Henke

Figure 3 / Left side / Synthesis of process, material, and functional requirements in early design stages regarding structural requirements in the context of infrastructure, and expanded to include factors such as building physics, room climate, and spatial functions in the context of building designs.


AMC
Additive Manufacturing in Construction
B Computational Modelling and Process Control
A Materials and Processes
C Design and Construction

ADDITIVE MANUFACTURING IN CONSTRUCTION AMC TRR 277

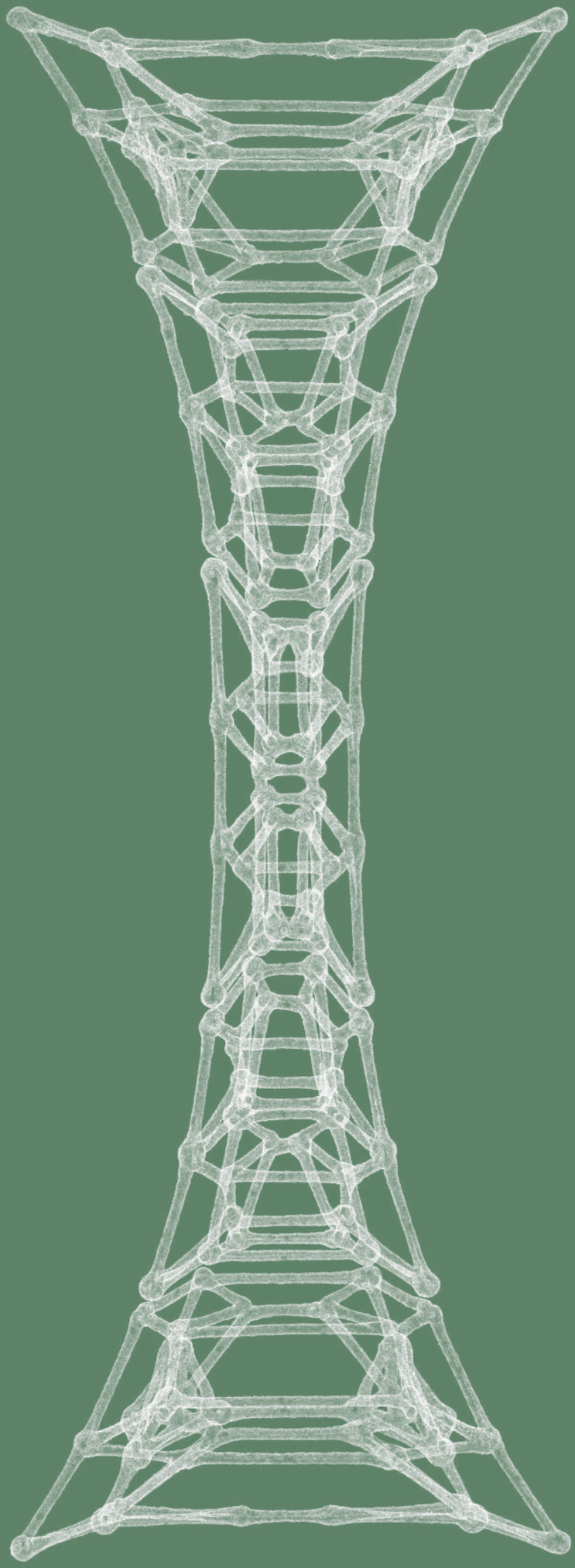
The Challenge of Large Scale - The SFB/Transregio TRR 277 aims to examine Additive Manufacturing (AM) as a novel digital manufacturing technology for the construction industry in an interdisciplinary, cross-location research project. In Additive Manufacturing, the production of building components is achieved solely by a digitally controlled material application, typically done layer-by-layer, without the necessity of mould making or forming processes. This approach represents a paradigm shift to the manual construction processes, which are characterised by traditional, predominantly craft-based techniques. As a result, productivity in the construction industry has stagnated for decades. In addition, these manual techniques foster a rather simple component design and thus inefficient use of materials. Against the background of the enormous demand for resources in the construction industry, such construction methods significantly contributes to global CO2 emissions.

The objective of the TRR 277 is to explore the fundamentals for implementing Additive Manufacturing in Construction (AMC). Automated additive material application enables the construction of buildings with a high degree of design freedom and a resource-efficient use of materials. In order to fully exploit this potential, structural design, material behaviour and manufacturing processes must be fundamentally rethought and, above all, must interact. While additive manufacturing technology is already being used for serial production in other industries, there are still fundamental challenges to be solved when transferring it to the construction industry: First, the transfer of AM technologies to the large scale of construction; second, the necessary material and process diversity, which is determined by the complex functional requirements of a building; and third, the required high degree of individualisation and flexibility in construction. These challenges give rise to complex research questions on materials, process engineering, control, modelling, design and construction, which are investigated by interdisciplinary teams of scientists from the fields of civil and mechanical engineering. The work programme of TRR 277 is guided by two fundamentally new research approaches: 1. Combinations of materials and processes. As a central topic of the research programme, material and process coordination are considered as inseparable units in additive manufacturing. In focus area A, innovative material and process combinations for Additive Manufacturing will be researched and brought to a new logic of form. All A-projects follow a novel integrative approach, investigating structural design, material behaviour and manufacturing processes as inseparable components within an interdisciplinary framework. For this it is essential to open up the material- and process combinations from the outset and not to restrict them to individual materials and/or processes. The focus area B aims to ensure robustness and full automation of additive manufacturing processes by providing feedback and numerical simulation capabilities to the A projects. This aims to achieve a smooth digital transformation within the construction sector. End-to-end digitization is of crucial importance for the successful introduction of additive manufacturing in the construction industry. Focus area C “Design and Construction” is therefore researching the digital interfaces to the upstream planning processes as well as the downstream processes of construction right from the outset. The interaction between digital models and physical objects forms the methodological link of TRR 277 and is the basis for the networking between focus areas A, B and C. The networking across the focus areas is realised by the continuous production of large scale demonstrators and their digital twins.

The TU Braunschweig and the TU München 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 holds the potential for substantial national and international visibility and, together with other research initiatives, it aspires to play a significant role in advancing the digital transformation of the construction industry.

https://amc-trr277.de/trr-277-mission/about-amc/

Figure 4 / Left side / Process scheme of AMC TRR 277
research topics and application scenarios



DEMONSTRATORS FOR INFRASTRUCTURAL CONTEXT

PARTICLE-BED 3D PRINTING BY SELECTIVE CEMENT PASTE INTRUSION

Particle-Bed 3D Printing by Selective Cement Paste Intrusion (SPI) – Particle Surface Functionalisation, Particle Synthesis and Integration of WAAM Reinforcement. Selective paste intrusion (SPI) is a particle-bed-based additive manufacturing technology in which aggregates are spread in thin layers and bonded by cement paste. To qualify SPI for structural concrete elements, the inclusion of reinforcement is mandatory. The innovation introduced here is that reinforcement will be implemented simultaneously in the SPI process using Wire and Arc Additive Manufacturing (WAAM). Different active and passive cooling strategies, e.g. particle surface functionalization and the synthesis of new particles, will be developed to deal with the high temperatures during WAAM.

Project Leaders

Prof. Dr.-Ing. Christoph Gehlen
Prof. Dr.-Ing. Arno Kwade
Prof. Dr.-Ing. Michael F. Zäh

Contributors

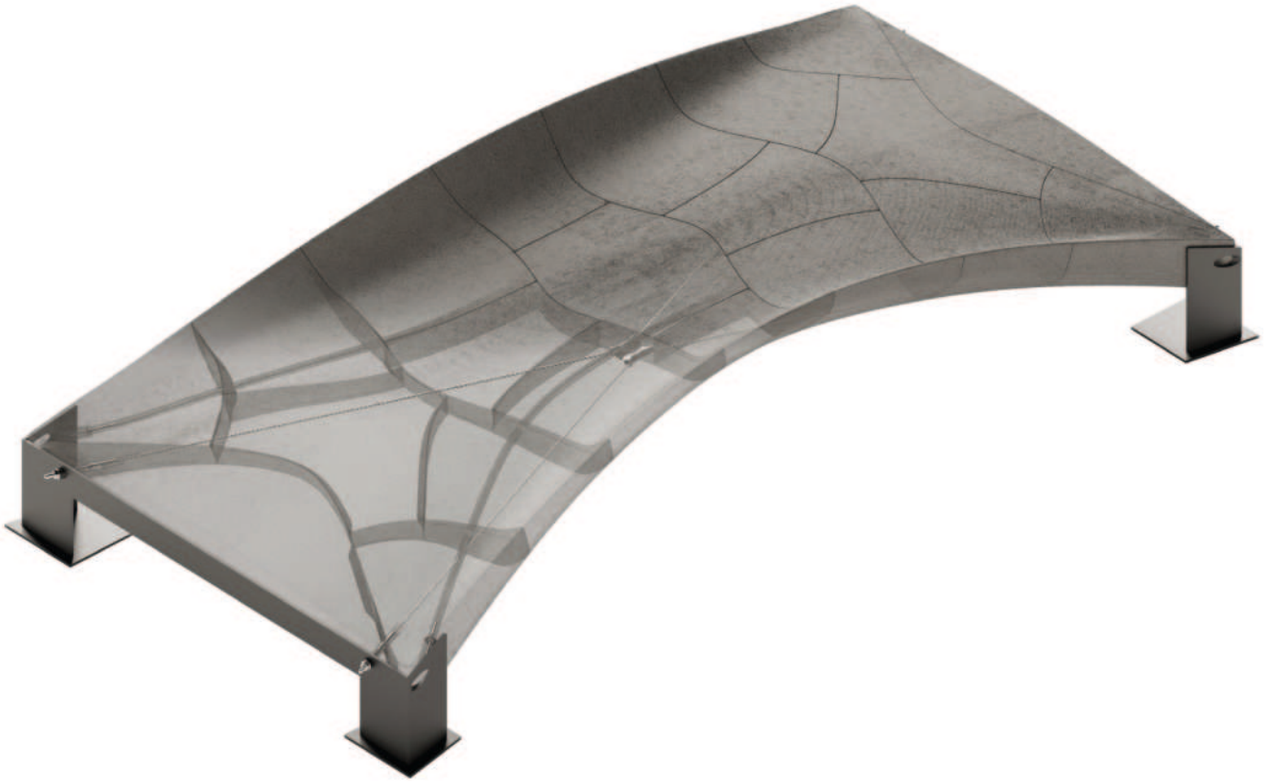
M. Sc. Leigh Duncan Hamilton
Dr.-Ing. Thomas Kränkel
M. Sc. Felix Riegger
M. Sc. Alexander Straβer

AMC TRR 277 Project

A02

Associated Design Projects

Bridge the Gap
Playing with blocks



BRIDGE THE GAP

Collaborators

Research, Planning- and Realisation
Sebastian Dietrich (design lead, structural design)
Philip Schneider (design lead, fabrication, project coordination)
Dr. Reza Najian Asl (optimisation)
Alexander Straβer (material testing)
Felix Riegger (WAAM)

Structural Design
Sebastian Dietrich
Philip Schneider
Dr. Reza Najian Asl
Prof. Dr. Pierluigi D'Acunto

Scientific Supervision
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Prof. Dr.-Ing. Kai-Uwe Bletzinger
Prof. Dr. Kathrin Dörfler
Dr.-Ing. Thomas Kränkel
Prof. Dr.-Ing. Harald Kloft
Prof. Dr.-Ing. Christoph Gehlen
Prof. Dr.-Ing. Michael Zäh

Industry Partners
Metallconcept Group / Scawo3d
Kurt Wohlgemuth

Figure 1 / Left side / Visualization of bridge incl. segmentation, supports and tension cables

INTRODUCTION

The design concept of the 3D-printed concrete pedestrian bridge ‚Bridge the Gap' was originally developed by a group of architecture students (Y. Cai, A. Rasmussen, P. Schneider) as part of a design studio project at the Technical University of Munich, under the supervision of Prof. Dr. P. D'Acunto (Professorship of Structural Design) and Prof. Dr. K. Dörfler (Professorship of Digital Fabrication). Based on this initial concept, a full-scale prototype of a 5-meter-span bridge was structurally designed, engineered, and manufactured as a joint research collaboration between current and prospective PIs of the AMC TRR277.

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

To comply with the constraints imposed by a historical building context – i.e., the inability of the existing structures to accommodate any horizontal support reactions – the concrete structure was supplemented with a system of unbonded post-tensioning cables beneath the 3D-printed concrete segments of the bridge.

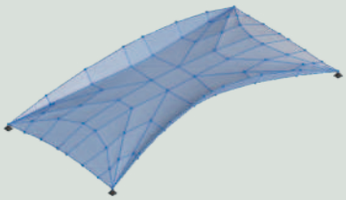
The clear differentiation between compressive and tensile elements in the construction highlights another significant advantage in terms of the recyclability and reusability of the printed components. Unlike conventional reinforced concrete structures that require a time-consuming procedure of crushing and sorting for recycling, the SPI-printed parts can incorporate specially designed channels and voids, thanks to the inherent flexibility in form. These features allow for the inclusion of constructive details like post-tensioning elements while avoiding a permanent bond between the steel and concrete components.

Figure 2 / Left side / Final design of bridge incl. segmentation, supports and tension cables

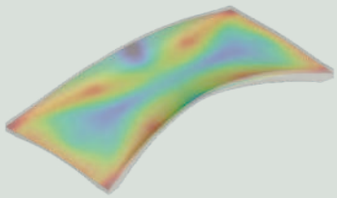
Global Geometry

Discrete approach:
Global form finding

Discrete to continuum



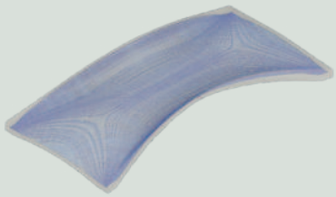
Continuum-based approach:
Thickness optimisation



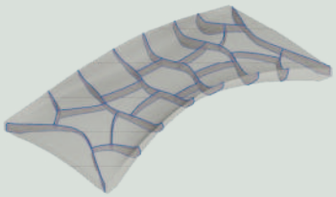
Input: Topology and metric properties → Out-/input: Wireframe model → Out-/input: Shell model → Output: Shell model incl. thickness information

Segmentation

Principal stress lines



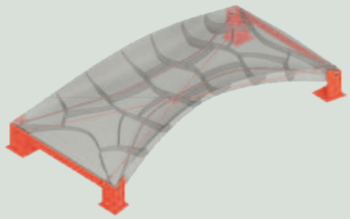
Segmentation



Input: FE shell model → Out-/input FE shell model incl. principal stress lines → Output: Segmented FE shell model

Detailing

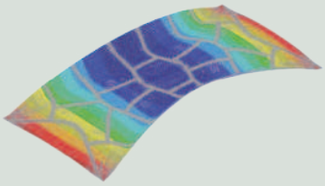
Support and post-tensioning details



Out-/input: FE shell model incl. details

Final Structural Design

Structural analysis incl. segmentation, post-tensioning, and material properties



Final geometry

METHOD

Preliminary studies and material properties

A set of preliminary qualitative tests were performed to investigate different SPI-printed compounds' consistencies of intrusion. The quality of intrusion of a specimen with cement paste is a critical factor influencing the resulting material properties – with an insufficient intrusion resulting in a lacking bond between single layers and an overly intruded specimen resulting in a loss of shape accuracy. Printed test specimens in lightweight expanded clay were shown to have the most consistent intrusion compared to other aggregates, such as basalt, quartz sand, or crushed recycled concrete.

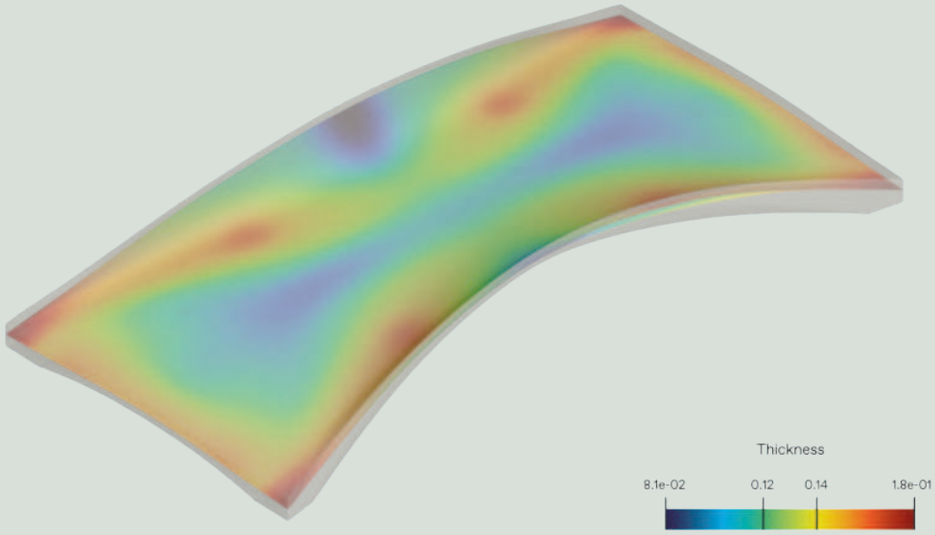
To validate the material properties, a series of tests was conducted at the Centre for Building Materials at TUM. The SPI-printed specimens' material compound consists of lightweight expanded clay aggregates (0-2mm), conventional cement, and superplasticizers. Prisms and cylinders were tested for their compressive and flexural strength as well as their Young's modulus, according to the relevant standards. The following results were yielded and used for structural optimisation:

- Flexural/compressive strength (prisms, DIN EN 196): 3,9/26,8 MPa
- Compressive strength (cylinders, DIN EN 12390-3): 37,1 MPa
- Young's modulus (cylinders, DIN EN 12390-13): 13,4 GPa

Structural design workflow

The structural design workflow (Figure 3) encompasses four key stages to ensure a robust and efficient design process:
- design of the global geometry of the bridge
- segmentation of the global geometry into structurally sound and manufacturable building segments
- detailing of supports and tension cables
- final structural design of the bridge including a comprehensive structural analysis considering the entire features of the de sign– i.e. dry and fastener-free connection between the segments, post-tensioning cables, ties.

Figure 3 / Left side / Structural design workflow


Thickness
8.1e-02
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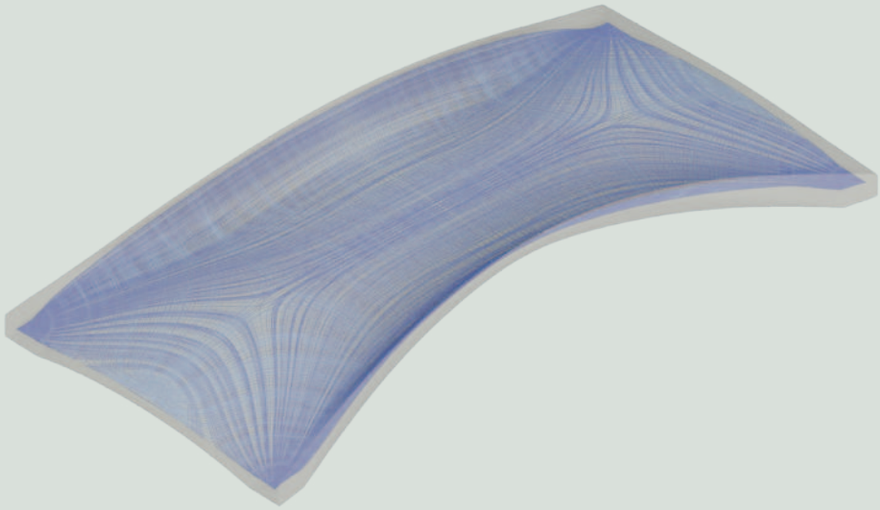
1.8e-01



METHOD

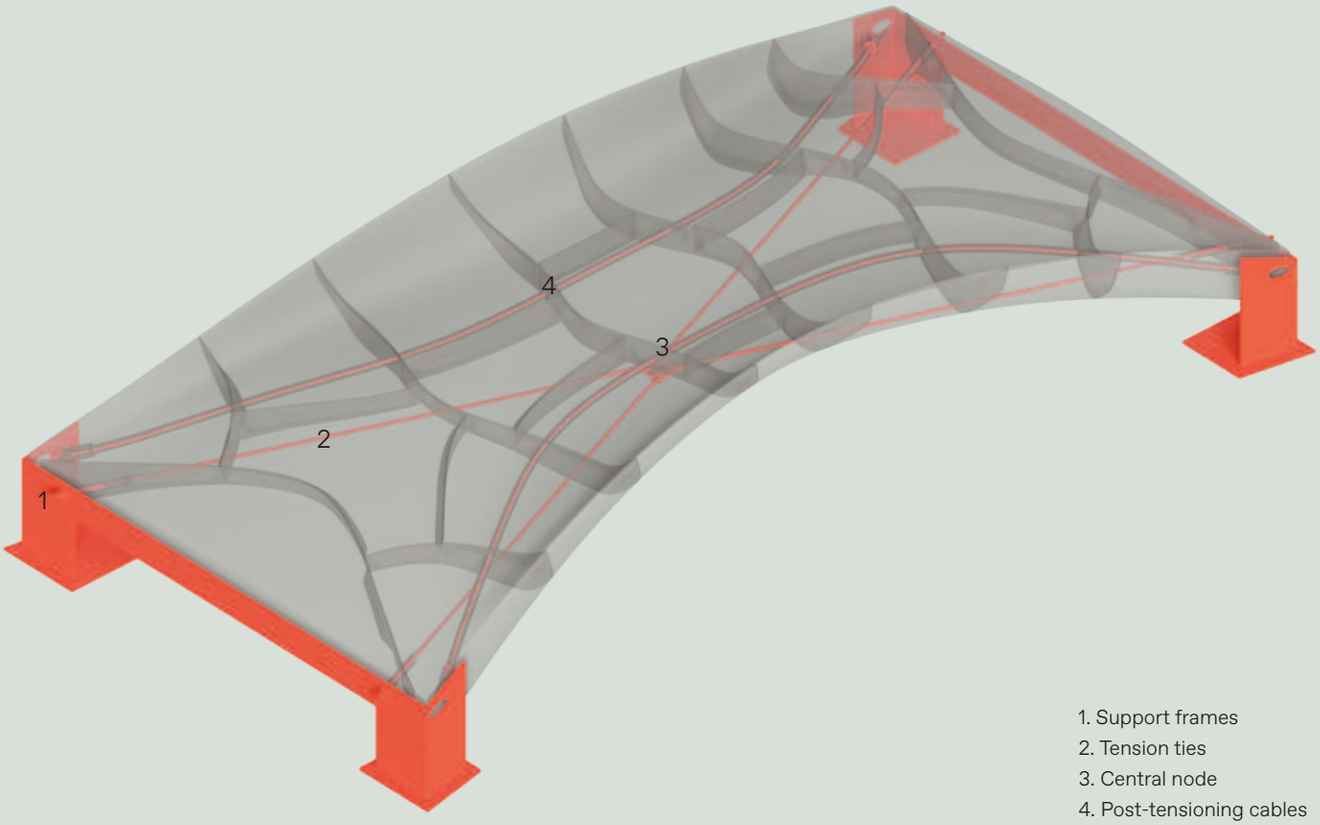
Global geometry

The global geometry design of the bridge follows an innovative multi-fidelity approach, which involves a two-way interaction between low-fidelity and high-fidelity models. The low-fidelity models employ discrete strut-and-tie networks, representing the primary force pathways in the structure, while the high-fidelity models utilize continuous solid geometries. Low-fidelity models are quickly generated using a Discrete Optimization Approach (DOA) employing Vector-based Graphic Statics (VGS) [3] and Combinatorial Equilibrium Modelling (CEM) [1] during the initial design phase to test and optimize various static equilibrium solutions. On the other hand, high-fidelity models are generated by a Continuum-based Optimization Approach (COA) using namely FEM simulation, gradient-based optimization, filtering, and projection techniques [4] for further refinement of the structural geometries. This multi-scale design approach enables the hierarchical handling of multiple scales, ranging from the global geometry of the entire structure to the local geometry of individual structural components and joints.

In the low-fidelity approach, CEM [1] is used to design the topology of the structure and generate the structural geometry. CEM, an equilibrium-based form-finding method, combines graph theory and VGS [3]. It is specifically designed to generate spatial pin-jointed frameworks capable of withstanding both tensile and compressive axial forces based on a user-defined topology diagram and its associated metric parameters. In the standard formulation of CEM [2], the equilibrium-based structure‘s form is generated sequentially, node-by-node, starting from the nodes corresponding to the starting vertices and progressing towards the nodes associated with the support vertices. If specific geometric constraints are applied to the structural form, such as fixed nodes, an optimization procedure is employed [5]. For computational efficiency, by leveraging the geometric symmetries, the model is simplified to analyse only one-quarter of the structure. This involves dividing the model along its mirror plane in the XZ and YZ directions. The CEM model is defined with origin nodes positioned along the cutting plane, including forces in the X and Y directions. These forces represent the internal load transfer between quarters. The primary load paths are defined by trail edges, originating from an origin node and extending to the support. To allow for interaction between trails, deviation edges connect them laterally. During the form-finding process, the model considers the self-weight of the structure and is optimized for compression-only behavior. After form-finding one-quarter of the structure, the complete model is reconstructed by mirroring it along the XZ and YZ planes and joining the quarters together.

Transitioning from a discrete wireframe model to a continuum-based approach, the model is transformed into a mesh shell. To achieve a smoother mesh surface, a Catmull-Clark subdivision is applied for post-processing [6]. The resulting post-processed mesh serves as the input for thickness optimisation. The objective of the thickness optimisation is to create a geometrically efficient structure by maximizing stiffness. This is achieved through simulation-based optimisation, utilising the Finite Element Method (FEM). Multiple load scenarios, including distributed and point loads, as well as symmetric and asymmetric loading, are considered in the optimisation process. Starting with a uniform thickness distribution of 0.13m, the optimisation process allows for thickness variation within the range of 0.08m to 0.18m, utilising projection techniques (i.e. Heaviside projection [8]). Additionally, PDE-based filtering is applied to parametrise the FEM design space, ensuring smooth thickness distribution across the bridge‘s surface [4]. This approach guarantees regularity and feasibility throughout the gradient-based optimisation process, utilsing the richest possible design space. To maintain symmetry even under unsymmetrical loading conditions, plane symmetry constraints are efficiently integrated into the filtering-based thickness parametrisation. This ensures that the optimisation process maintains the desired symmetry property. Figure 4 illustrates both the initial model used for optimisation and the optimised model, showcasing the resulting optimal thickness distribution.

Figure 4 / Left side / Optimal thickness (top), principal stress lines (bottom)



1. Support frames
2. Tension ties
3. Central node
4. Post-tensioning cables

METHOD

Segmentation

After generating an optimal structural geometry on the global scale, the geometry is segmented into pieces of an adequate size, which can be manufactured by the SPI 3D printing technique and easily handled during the actual assembly process. The segmentation pattern of the structure is determined by a series of cutting planes strategically arranged to facilitate the transfer of predominantly normal forces between the joints of the individual segments. To analyze the principal stress lines under specific load conditions such as self-weight and asymmetric point loads, the stress distribution is first examined. To determine the size of the segments, the principal stress lines that best conform to a weight constraint of maximum 140kg per piece are selected. The segmentation planes are then positioned along these chosen lines. Following this, the global geometry of the structure is divided along these planes, resulting in segmented components. To ensure that the individual segments remain securely connected and do not slide apart due to unforeseen shear forces in both vertical and lateral directions, interlocking joints are designed between the segments. These geometrical interlocking joints are devised to provide stability and prevent dislocation of the segments.

Detailing

The detailing involves the design of the supports and tension cables. The concrete bridge rests on two steel frames, which provide vertical and lateral support at each corner of the structure. In the longitudinal direction, the frames are supported by two tension ties, arranged diagonally and linking two supports together. Furthermore, two post-tensioned cables running inside the concrete structure connect all segments. The cables stiffen the structure against unforeseen load scenarios, such as local or asymmetric loading (Figure 5).

A special feature of the tension bands is the node where the two cables meet. To connect the cables, a custom steel node is designed and fabricated using the Wire Arc Additive Manufacturing (WAAM) process. WAAM is a formative build-up welding process [7] that uses an inert gas welding process. Aiming at a structurally efficient design, the initially designed shape of the steel node was optimized using implicit Vertex Morphing [4], considering the maximum overhang manufacturing constraint of WAAM. To this end, a new response function was developed to control the boundary slope. The boundary slope plays a crucial role in determining the structural performance and the amount of support structure required during fabrication by WAAM additive processes. By restricting the maximum boundary slope with respect to the print direction, the need for support structures can be reduced or eliminated. Performing the final optimisation, the mass was minimized while ensuring the structural performance, with 10%, 15%, 20%, and 27% improvements. The final node is manufactured based on the third version, with 20% mass reduction.

Final structural design

After the final geometry of the bridge is defined (Figure 1), a comprehensive structural analysis is performed. This analysis includes all peculiarities of the structure, including segmentation, details, and actual material properties. The aim of this analysis is to verify the structural integrity of the design and to ensure that it meets the desired structural performance.
Overall, by implementing this holistic design approach, material savings were achieved through the design of structurally efficient forms that could be produced using additive manufacturing. This achievement can be regarded as an essential preliminary step and proof of concept for the future research planned during the second funding period of AMC TRR277.

Figure 5 / Left side / Segmented bridge including supports and tension cables

Figure 6 / Kurt Wohlgemuth, inventor of the SPI printhead, excavating the bridge's segments.

FABRICATION

The fabrication of ‚Bridge the Gap‘ utilises the Selective Paste Intrusion (SPI) technique. SPI originated from a feasibility study led by Dr. D. Weger at TUM [2], as part of his doctoral thesis. Currently, ongoing research on SPI is being conducted at the Centre for Building Materials/Chair of Materials Science and Testing, as well as the Professorship for Digital Fabrication at TUM. In parallel, industrial-scale implementation of SPI is being carried out by Metallconcept Group and Progress Group in South Tyrol, Italy.

Printing

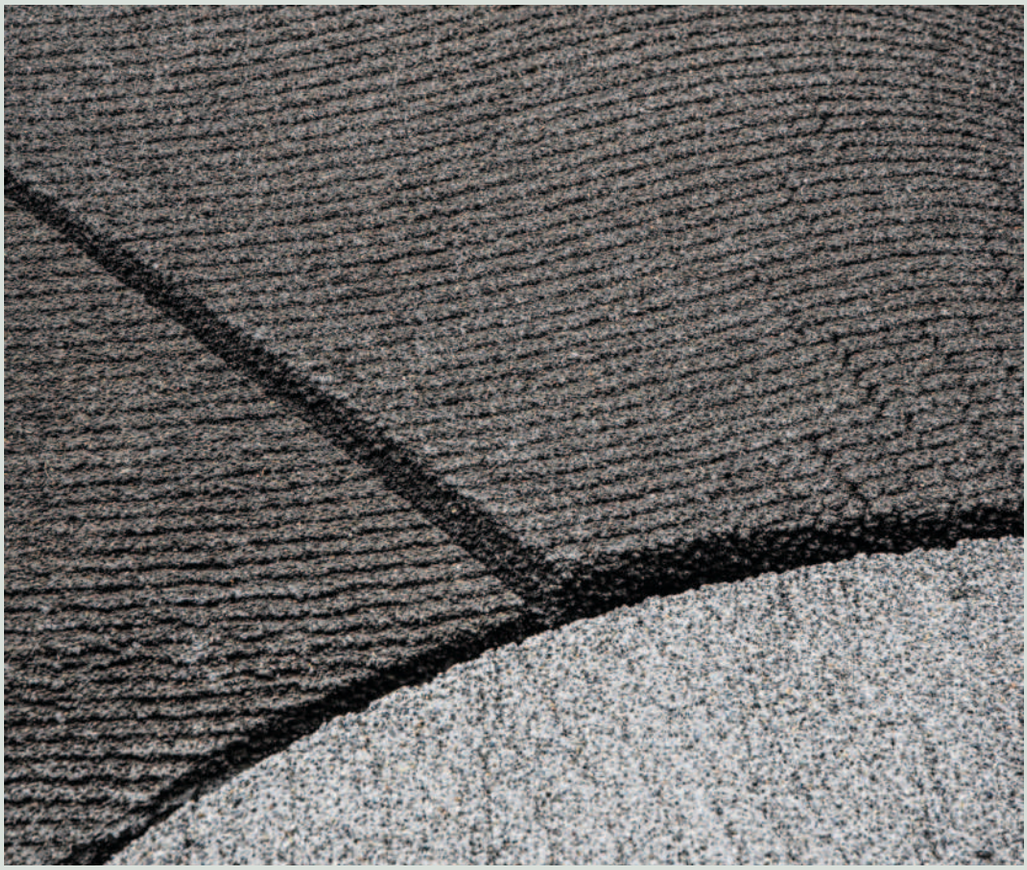
The SPI printer at Metallconcept Group is a large-scale printer with a building volume of 4 × 2.5 × 1.5 meters. This allows for all 21 segments of the bridge to be printed in a single print job, which can be completed within a day. Prior to printing, the individual segments are organised and sliced using Autodesk Netfabb software. To optimize the printing process, the segmented parts are arranged within a boundary volume of 11m^3, with a print height of 1.1m and 360 layers of 3mm each. Considering tolerances, the total net volume of the parts amounts to 1.7m^3. This volume determines the precise amount of cement paste required for preparation and during the printing process. During the packing of the print bed, it is crucial to consider the maximum amount of cement paste that can be produced within a given time to avoid any interruptions during printing. The maximum producible volume of cement paste is determined by the time required for conveying the dry cement and additives, as well as the mixing time needed to achieve the ideal viscosity. By carefully managing the volume of cement paste and production time, a continuous and uninterrupted printing process can be ensured.

In the case of ‘Bridge the Gap’, the mortar that is produced by the SPI process consisted of lightweight expanded clay aggregates (with grain sizes of 0-2mm), cement (CEM II), water, and superplasticizers. During printing, 15 batches of cement paste (80 litres each) are prepared in a mixer that was specifically developed by Metallconcept for the purpose of SPI printing. Before each batch of cement paste is conveyed to the printer, its quality is checked to ensure an ideal intrusion of the aggregate with the aim of achieving isotropic material properties that are not obstructed by the layered nature of the printing process. At a printing speed of 180mm/hr in height (equivalent to 60 printed layers), the print took a total of nine hours, including all work that is necessary for preparing the printer before and cleaning it after printing.

Excavation

Unpacking of the bridge’s segments begins after leaving the print bed untouched for approximately 18 hours, with the loose aggregate surrounding the bound volumes functioning as a temporary formwork. Prior prints of large-scale elements show that, after 48 hours, the printed concrete developed enough strength to be handled outside the previously surrounding loose aggregate. With a crane mounted above the SPI printer, the single pieces (with a maximum weight of 140kg) are removed one after the other from the print bed while the loose aggregate are extracted partly with a large-scale vacuum cleaner and partly by opening flaps at the bottom of the print bed. The whole process of excavating the bridge’s segments takes eight hours.

Figure 7 / Left side / Final Demonstrator



TECHNICAL DATA

Construction system
Segmented concrete vault with integrated post-tensioning

Process
Particle-bed 3D Printing

Integrated functions
Post-tensioning

Material
Mortar including lightweight expanded clay aggregate

Density
1300 kg/m³

Length x Height x Width
5,00 m 0,80 m x 2,50 m

Volume
1,70 m³

Weight
2.2 tonnes (21 segments with weights between 50-140 kg)

Manufacturing time
Printing: 6:06 hours
Excavation: 1 day
Curing: 28 days
Assembly: 3 days

Figure 8 / Left side / Detail of the final Demonstrator

References
[1] Ohlbrock PO, D'Acunto P. "A Computer-Aided Approach to Equilibrium Design Based on Graphic Statics and Combinatorial Variations", Computer-Aided Design, 121; 2020.
[2] Weger D. "Additive Fertigung von Betonstrukturen mit der Selective Paste Intrusion – SPI", PhD dissertation, Technical University of Munich; 2020.
[3] D'Acunto P, Jasienski JP, Ohlbrock PO, Fivet C, Zastavni D, Schwartz J. "Vector-Based 3D Graphic Statics", Int J Solids Struct, 167:58-70; 2019.
[4] Najian Asl R, Bletzinger K. „The implicit bulk-surface filtering method for node-based shape optimization and a comparison of explicit and implicit filtering techniques." Structural and Multidisciplinary Optimization 66, no. 5:111; 2023
[5] Ohlbrock PO, D'Acunto P, Jasienski JP, Fivet C. "Constraint-Driven Design with Combinatorial Equilibrium Modelling," Proceedings of the IASS Annual Symposium; 2017.
[6] Catmull E, Clark J. „Recursively generated B-spline surfaces on arbitrary topological meshes" (PDF). Computer-Aided Design. 10 (6):350; 1978.
[7] Schuler V, Twrdek J. „Praxiswissen Schweißtechnik. Werkstoffe, Prozesse, Fertigung, sixth ed.", Springer Vieweg, Wiesbaden, Germany: 506; 2019.


STÄUBLI

INTEGRATED ADDITIVE MANUFACTURING PROCESSES FOR REINFORCED SHOTCRETE 3D PRINTING

Integrated Additive Manufacturing Processes for Reinforced Shotcrete 3D Printing (SC3DP) Elements with Precise Surface Quality. Within this project, basic research on various SC3DP strategies, materials, tools and methods will be conducted with regard to enhanced material and process control, reinforcement integration, surface quality and automation. To that end, different reinforcement materials in combination with suitable reinforcement manufacturing and integration concepts will be investigated based on force-flow optimised reinforcement alignment. Besides, design strategies as well as material and process control will be investigated in detail. Furthermore, tools and strategies for precise control of the surface quality and geometric resolution of SC3DP elements are subject of research. Finally, strategies, materials and tools elaborated within the project will be synergistically combined and validated at large scale.

Project Leaders

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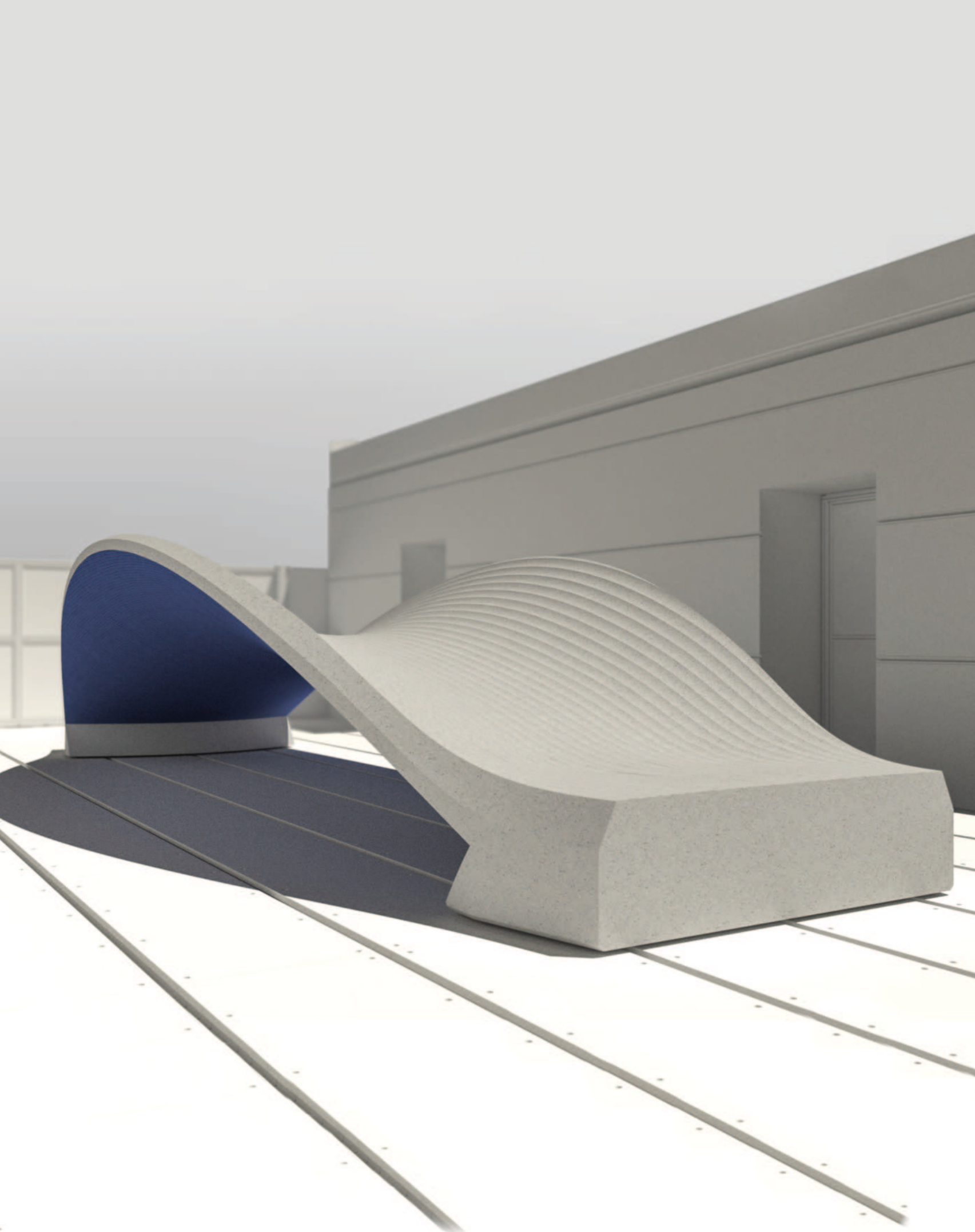
AMC TRR 277 Project

A04

Associated Design Projects

Robotic KnitCrete
Shelltonics



ROBOTIC KNITCRETE

Collaborators

Research, Planning- and Realisation
Philipp Rennen (project lead, fabrication-informed design strategies for SC3DP, Holcim)
Stefan Gantner (project lead, integration of individualized prefabricated fibre reinforcement in Additive Manufacturing with Concrete)
Gido Dielemans (principles of mobile robotics for AMC)
Robin Dörrie (integrated Additive Manufacturing processes for reinforced SC3DP Elements with Precise Surface Quality)
Lazlo Bleker (design optimisation)
Majid Hojjat (design optimisation)
Inka Mai (materials)
Karam Mawas (3D scan)
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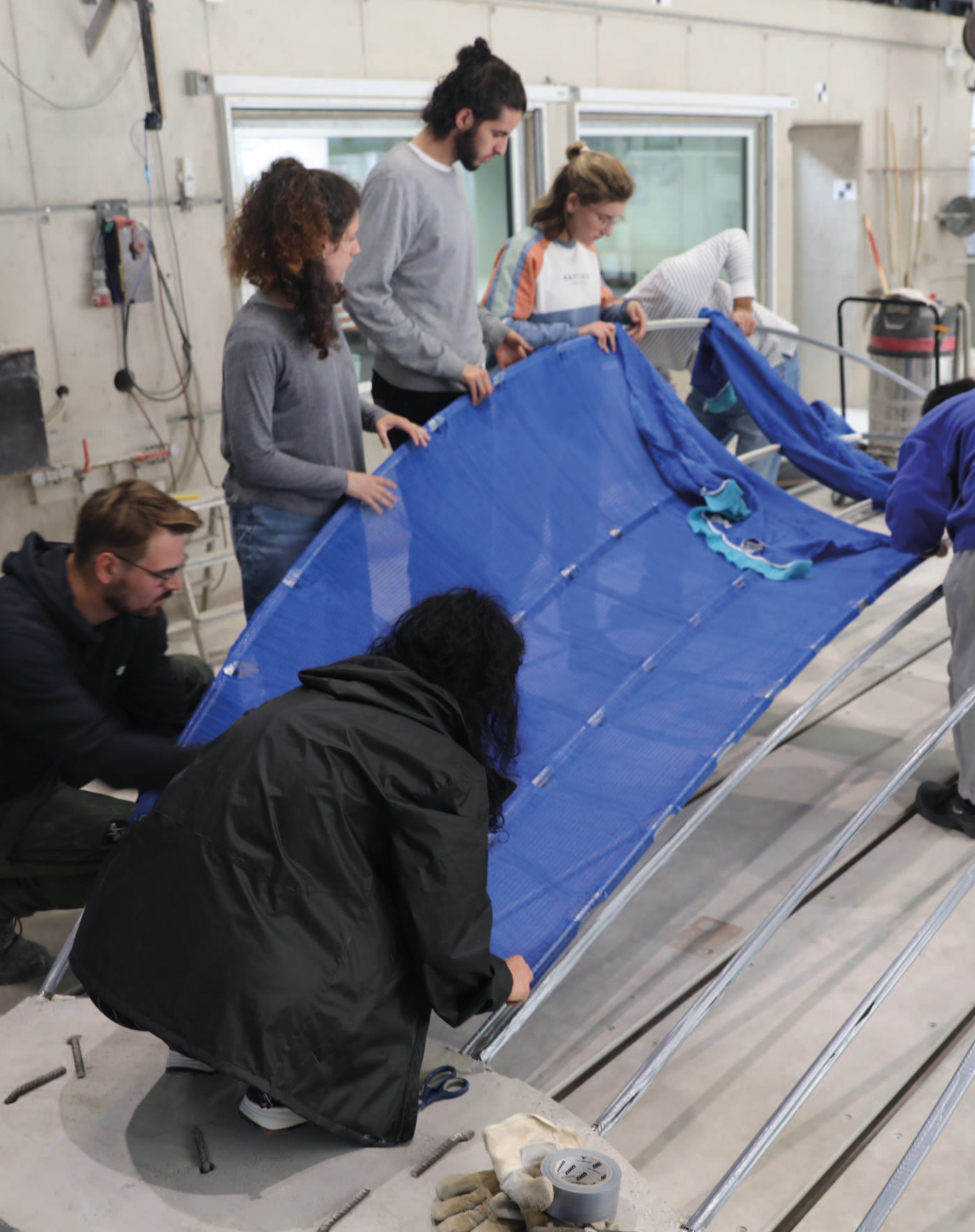
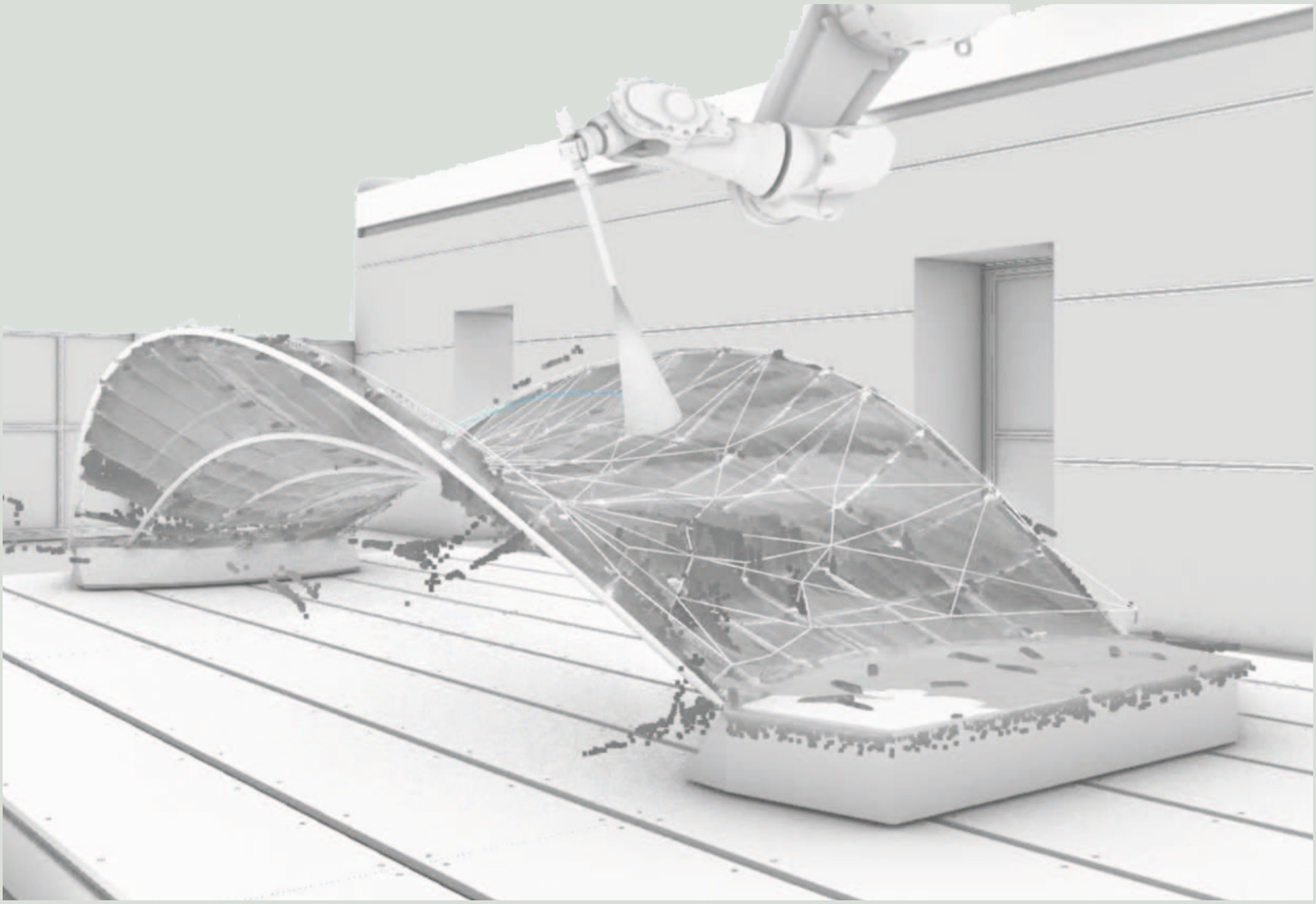
Figure 1 / Left side / Perspective from the planned object



INTRODUCTION

KnitCrete has gained significant recognition as a digital fabrication method for producing lightweight and flexible stay-in-place formworks[1]. This methodology enables the creation of thin concrete shells with complex geometries and unique textile surfaces. So far, the process of applying concrete to these textile formworks has historically been a labor-intensive and imprecise manual task.
To address this challenge and further automate the KnitCrete process, a concept was developed within the framework of a multi-university design course. This concept seamlessly integrates KnitCrete with Robotic Shotcrete and incorporates Dynamic Fiber Winding Reinforcement, feature detection from 3D laser scans, CNC green-state post-processing, and CNC milling. The culmination of this endeavor resulted in the creation of pedestrian bridge as a real-scale demonstrator (Figure 1). It not only brings together KnitCrete and Robotic Shotcrete but also showcases the integration of multiple advanced technologies into a single object.
This innovative approach represents a significant step forward in the automation and precision of the KnitCrete process, opening new possibilities for the fabrication of intricate and structurally sound architectural elements. The following sections provide an overview of the methods used in the design and construction of this groundbreaking pedestrian bridge and demonstrate the seamless integration of various state-of-the-art digital fabrication techniques.

Figure 2 / Left side / Preparation of the printing process with the students from the CDF-Course



METHOD

3D Knitted Stay-in-Place Formwork

The construction process started with the creation of the 3D knitted stay-in-place formwork, a pivotal component for the subsequent phases of the project. The formwork was prefabricated at TU Delft using a CNC weft-knitting machine to produce four double-layered interlock knit textiles with integrated channels for form-giving rods. The dimensions of these textiles were tailored to match the bridge's geometry, constituted by bending-active steel rods whose flexed shape was calculated beforehand. (Figure 2). Transversal cables were installed to put the final shape under tension, so it could withstand the following robotic concreting process.

Robotic Shotcrete and Dynamic Fiber Reinforcement

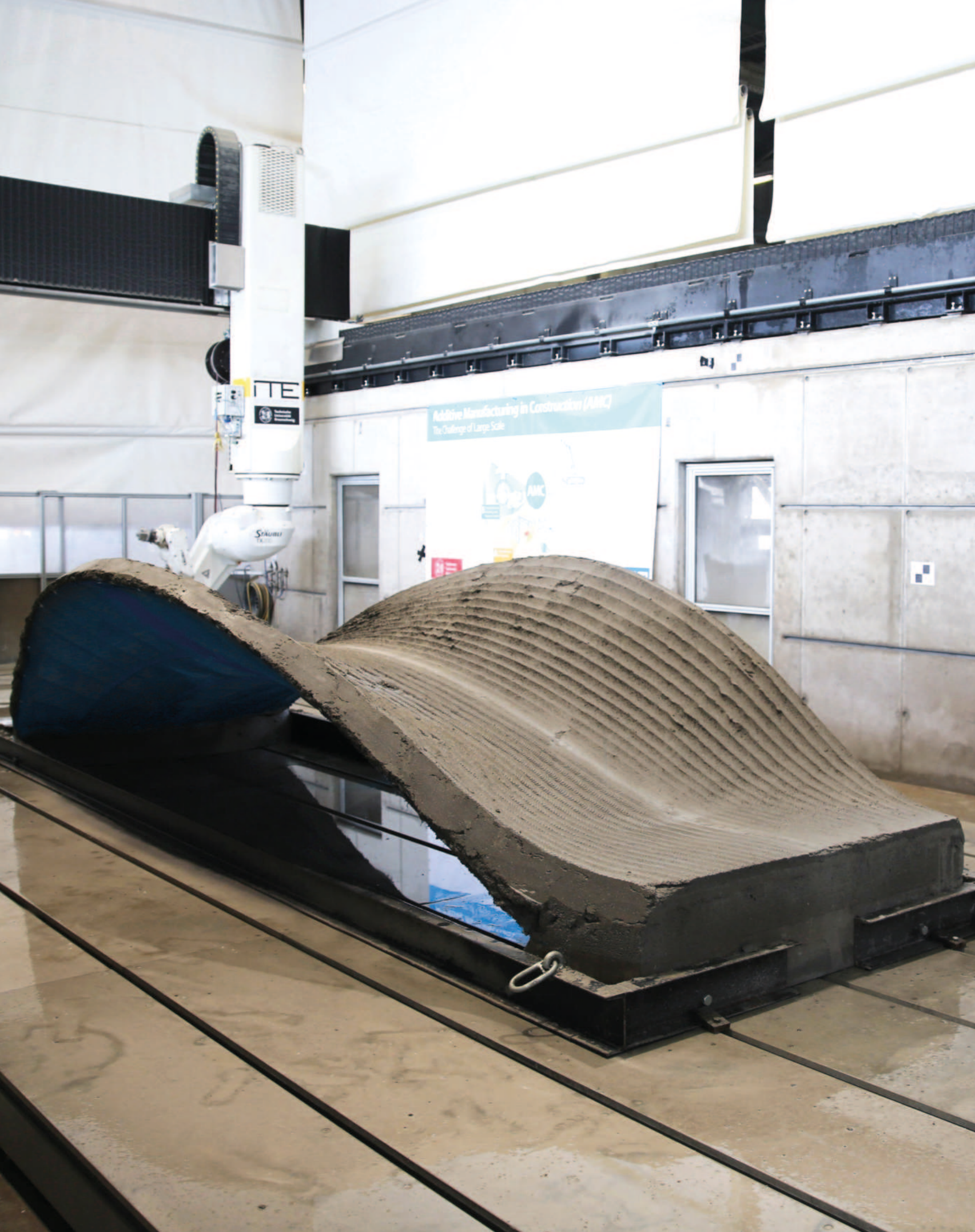
In this phase, automated processes were employed to apply shotcrete and dynamic fiber reinforcement, contributing significantly to the structural formation of the bridge (Figure 3).
A thin layer of cement paste, approximately 3 mm in thickness, was applied in two passes. Its curing achieved a „freezing" of the textile so that sagging was prevented during further concreting. (Figure 4). Following this, continuous glass fiber reinforcement was applied robotically using the so-called Dynamic Winding Machine (DWM). The reinforcement strand, coming from the DWM, was systematically wound along predefined pins, with the winding process adjusting to the pull-out speed. Challenges included interruptions due to yarn breakage and issues arising from the curvature of the pins. Subsequently, the load-bearing layer of fine-grain concrete was added layer by layer through Shotcrete 3D Printing (SC3DP).
Path planning was adapted to accommodate varying layer thicknesses, and parameters were optimized to achieve even material distribution. Challenges included the uneven embedding of pins and fiber strands within the concrete.

CNC Post Processing

The final phase involved CNC post-processing techniques to enhance surface quality and achieve the desired architectural appearance.
Surface irregularities were addressed through collaborative machining, with precise 3D scanning data guiding the process. Concrete layers were added to fill low areas while redistributing the uncured material using the CNC mill. This approach led to the creation of a symmetrical surface, despite initial deviations.
Surface quality was further improved through the application of a spherical surface structuring tool. Parameters were adjusted for architectural design considerations, and the tool simultaneously distributed and smoothed the material. Although deviations were observed, each repetition of the smoothing process enhanced surface quality.
After curing, the last step in the CNC post-processing phase was contour milling. Using a customised side cutting milling drum, the concrete edges of the bridge were shaped to achieve a defined silhouette. The milling process involved dynamic tilting of the mill to remove excess concrete and achieve the desired edge profile. Any deviations were addressed through manual filling and additional milling steps, ultimately resulting in the final desired surface quality.

Figure 3 / Left side / SC3DP on double curved surface

Figure 4 / Freezing process with cement paste at the digitial buildung fabrication lab (DBFL) at the TU Baunschweig


Additive Manufacturing in Construction (AMC)
The Challenge of Large Scale

RESULT

The research aimed to combine 3D knitted formwork with robotic shotcrete spraying, advancing toward the full automation of the KnitCrete manufacturing method. This objective has been successfully realized, opening up new possibilities for additive manufacturing to produce slender, material-efficient shell structures.
Throughout the experimentation process, challenges emerged in the SC3DP of the structural layer, resulting in surface irregularities and deviations from the planned design. This predicament catalyzed the development of an innovative surface leveling technique, proven effective in rectifying inaccuracies and enhancing overall structural quality.
The utilisation of multi-material robotic shotcrete spraying emerged as a valuable asset at various stages of the process. By employing distinct materials for specific purposes, such as applying a lightweight freezing coat and subsequently introducing structural mass with concrete, the fabrication process attained increased versatility, aligning precisely with project requirements.
The inherent advantages of formwork were preserved while significantly reducing formwork mass through the adoption of CNC knitted stay-in-place formwork. This reduction not only yielded cost savings but also minimised construction-related waste generation.
Another notable achievement was the substantial reduction in manual labor traditionally associated with the concreting of knitted formwork. Beyond CNC knitting, the automation was extended to shotcreting and fiber reinforcement integration, leading to a streamlined process with reduced labor intensity.
Overall, the as-built geometry of the bridge closely mirrored its planned geometry, a testament to the hybrid manufacturing approach that seamlessly blends additive and subtractive manufacturing methods (Figure 5). This underscores the exceptional precision and fidelity achieved through this innovative fabrication process.

Figure 5 / Left side / Finished Demonstrator inside the DBFL

References

[1] M. A. 'Popescu, "KnitCrete: Stay-in-place knitted formworks for complex concrete structures (Issue 26063)," ETH Zurich, Zurich, 2019. doi: 10.3929/ethz-b-000408640.

TECHNICAL DATA

Construction system
Shell structure reinforced by robotically wound fiber reinforcement and tension cables

Process
SC3DP on textile formwork

Integrated functions
Anchoring systems

Material
MC Bauchemie - Nafufill KM 250 (maximum grain size 2mm)

Density of the material
Ca. 2,1 kg/m³

Length x Height x Width
5,80 m x 1,20 m x 2,40 m

Volume
2.01 m³ incl. foundations

Weight
4,20 t

Spann
5,00 m

Manufacturing time
Knitting and construction: ~64 hours
Freezing: 20 minutes
Shotcrete: 8 hours
Winding: 10 hours
Surface leveling: 8 hours
Surface finishing: 6 hours
Edge milling: 6 hours

Figure 6 / Top / Detail of the Finished Demonstrator

LASER POWDER-BED FUSION OF STEEL ELEMENTS FOR CONSTRUCTION

Laser Powder-Bed Fusion (LPBF) of Steel Elements for Construction – Basics of Design and Mechanical Resilience. This project aims to explore and evaluate the factors influencing the manufacturing of safe and durable structural steel elements by Powder Bed Fusion of Metals using a Laser Beam (PBF-LB/M). Thereby, the PBF-LB/M process, the post-treatment, and the geometrical aspects in terms of microstructure and mechanical properties will be investigated and correlations determined. In the first funding period, it is focused on analyzing small-scale specimens and complex facade elements with multiaxial stress states. Based on the results, a first methodology for a qualified Additive Manufacturing (AM) design of safe and durable structural steel elements will be derived.

Project Leaders

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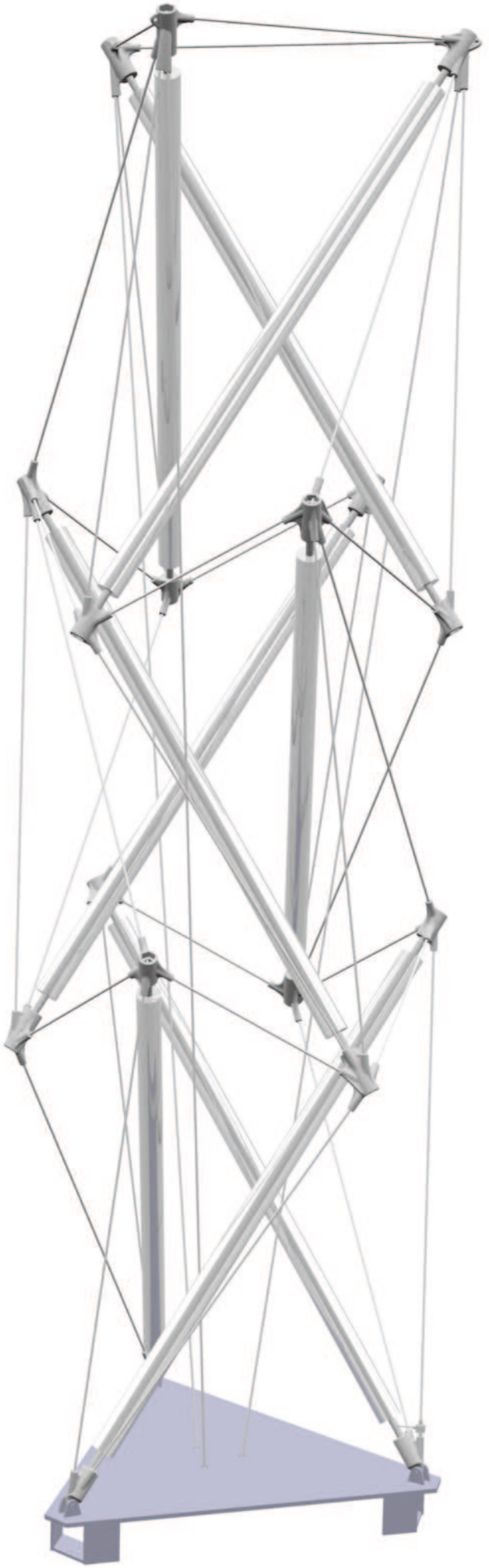
AMC TRR 277 Project

A06

Associated Design Projects

Tensegrity Tower



TENSEGRITY TOWER

Collaborators

Research, Planning- and Realisation
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Reza Najian Asl (shape optimisation)
Armin Geiser (shape optimisation)

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Scientific Supervision
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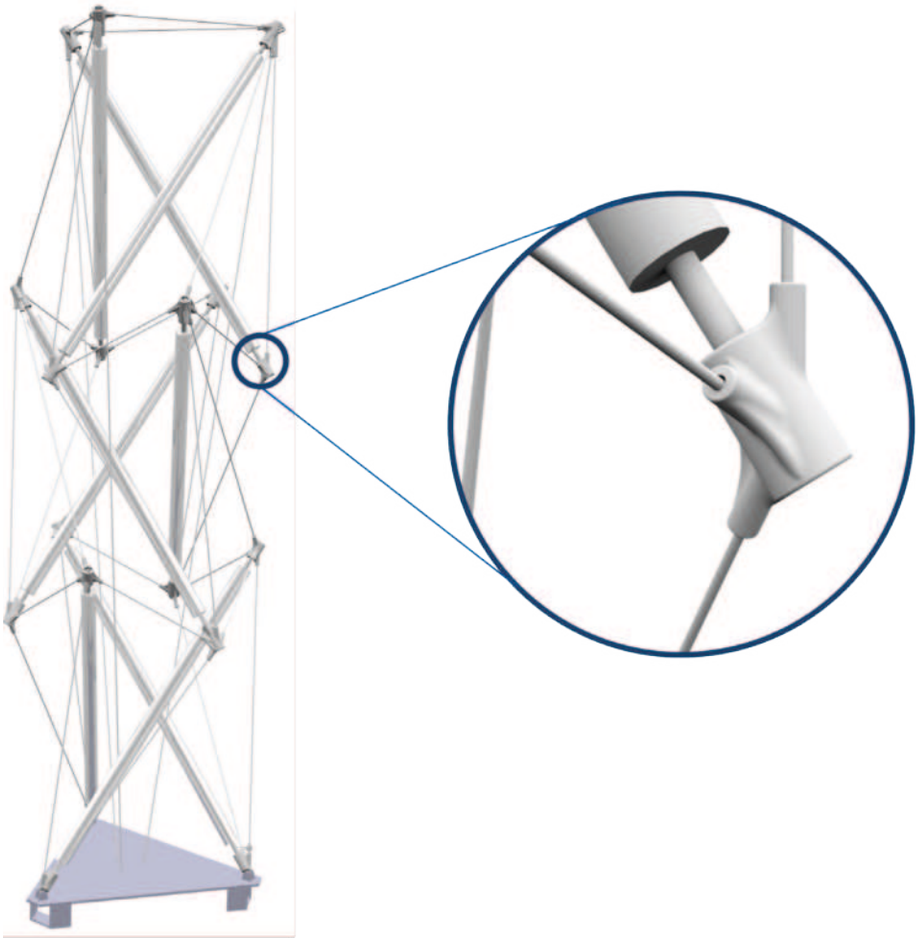
Industry Partners
Hausmann GmbH & Co. Stahlbau KG
Rösler Oberflächentechnik GmbH

Figure 1 / Left side / Perspective from the planned object



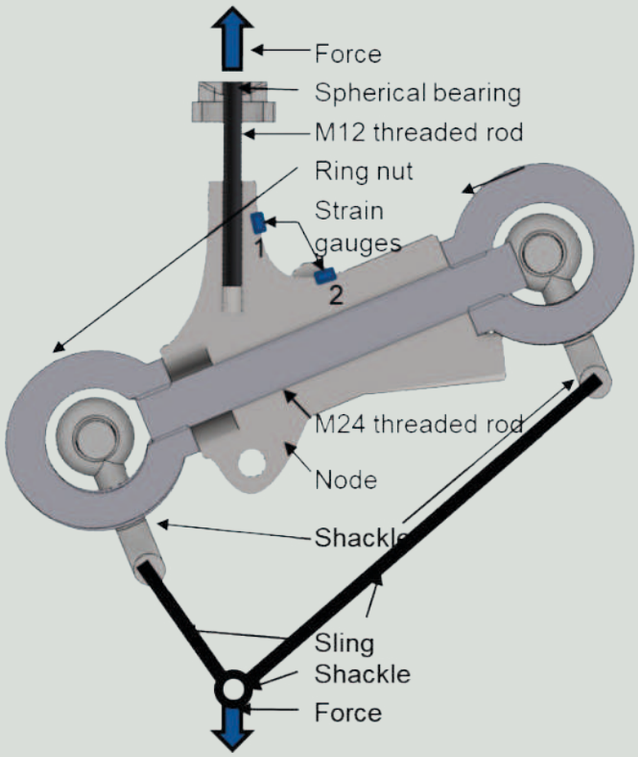
INTRODUCTION

Tensegrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension. This is achieved in such a way that the compressed members (usually bars or struts) do not touch each other, and the pre-stressed tensioned members (usually cables or tendons) delineate the system spatially. The connections between the compression rods and the tension cables require nodes with a complex geometry. These challenging structures are excellently suited for the LPBF process. The initial design of the nodes was done manually, followed by shape-optimisation. The tower consists of 18 nodes with four different geometries. The nodes were subsequently manufactured using the LPBF process. The used material was AlSi10Mg for the demonstrator in the Deutsches Museum and 316L for the scaled-down demonstrator.

The respective nodes of this tower require multiple physical constraints. The cables were connected to each node via threads (M12). To ensure sufficient cross-section for mounting the cables, a minimum wall thickness of 3 mm had to be excluded from the design space. For pre-stressing the threads of the cables, a flat support surface at the end of every sub-node was required to apply screw nuts. The main cylinder‘s height remained unchanged. The diameter of the inner cylinders also remained the same to maintain structural integrity.

Design optimisation has been an indispensable part of the engineering design process across many disciplines. Prominent fields include aerospace and airplane design. Topology optimisation procedures are prominently used to improve the designs and automate the design process in the above disciplines. However, the application of these techniques is limited as they result in complex free-form geometries that can hardly be built by conventional manufacturing processes such as milling or casting. Additive manufacturing techniques such as laser-based powder bed fusion of metals (LPBF) have shown the potential to change this. LPBF allows to economically produce topology-optimised components. In the course of these advancements, the construction sector is also making increasing use of optimisation methods and additive manufacturing techniques such as LPBF. Manufacturing topology-optimised components using LPBF results in considerably more support structure, as the topology optimisation process typically removes material, creating holes and overhangs. In contrast to that, shape optimisation modifies the shape of the component without changing the topological features. Thus, the shape optimisation process will neither create new nor remove existing holes. Shape optimisation, especially in combination with the vertex-morphing technique can further improve the engineering designs. Four different node geometries have been optimised. The economical production of such intricate geometries is only possible with the LPBF process. This potential can thus be fully realised and demonstrated.

Figure 2 / Left side / Tensegrity tower with close-up of tensegrity node; right: shape-optimised nodes


Force
Spherical bearing
M12 threaded rod
Ring nut
Strain
gauges
1
2
M24 threaded rod
Node
Shackle
Sling
Shackle
Force

METHOD

The shape optimisation of the tensegrity node was performed with minimum mass as objective and compliance as a constraint. This means that the shape of the nodes was optimised to reduce the mass by keeping the compliance of the node below the value at the beginning of the optimisation process. The choice of compliance as a constraint was motivated by the fact that it is opposed to the mass objective and is an aggregated quantity on the entire domain. This choice increases the stress in some locations, but care was taken that it stayed below the yield stress of the material.

The LPBF process was applied to manufacture the nodes. 18 nodes consisting of four different geometries were manufactured. After the manufacturing, the nodes were heat treated (T6) to improve the mechanical properties and subsequently cut off the building plate. The surface roughness was reduced by applying vibratory grinding.

Mechanical tests were carried out to test the mechanical behaviour of such complex structures and to validate the structural optimisation methods used. This was necessary because results from standardised tensile specimens may differ from complex geometries. Therefore, standardised tensile tests were carried out additionally. The results showed no different behaviour. In this study, the optimised node was subjected to tensile loading (Figure 3). However, it is not possible to test all the sub-nodes at once, as the tensile testing machine can only apply one level of load at a time. Therefore, a spherical bearing was applied to the top to ensure continuous tensile loading of the sub-node (Figure 3).

The lower part was tightened with load slings on a shackle, resulting in a fully hinged connection that only transmitted axial loads. Two strain gauges were attached to the bend to measure the elastic strains. The resulting stresses were calculated and compared with the results of the numerical simulation.

Figure 3 / Left side / Half-section of the testing setup of the optimised tensegrity node; right: Initial node geometry, red areas are not changed in the optimisation process, grey area marks the design area which is allowed to be modified by the vertex morphing technique.

Figure 4 / Manufacturing In-Process


BRÜCKENBAU

RESULT

A novel application of shape optimisation was recently introduced for additively manufactured parts. This innovative methodology was specifically employed on a remarkable tensegrity tower that featured intricately designed connection nodes. The nodes, initially designed by A06, were further optimised by C02 using shape optimisation techniques. The optimised nodes were then displayed as an exhibit in the prestigious Deutsches Museum.

To achieve the desired optimisation, the connection nodes underwent a process known as vertex morphing, which allowed for intricate shape adjustments. The nodes were subsequently fabricated using the Laser Powder Bed Fusion (LPBF) technology, resulting in a remarkable reduction of at least 25% in mass when compared to the original design.
To assess the mechanical performance of the optimised tensegrity nodes, a series of tests were conducted using a fully articulated setup to subject the nodes to tensile loading. Additionally, finite element simulations were performed on the test setup, incorporating the optimised nodes.

The results obtained from the physical tensile tests were then compared to the findings of the finite element simulations, revealing a satisfactory level of agreement between the two. This demonstrated the reliability and accuracy of the simulation models in predicting the behavior of the optimised nodes under real-world conditions.
Remarkably, despite the notable reduction in mass achieved through shape optimisation, the mechanical properties of the optimized nodes exceeded the safety threshold set for the desired mechanical properties. This indicated that not only did the optimised nodes maintain their structural integrity, but they also showcased improved mechanical performance when compared to the original design.
The successful application of shape optimisation in the fabrication of tensegrity tower nodes highlights the potential of this methodology to revolutionise the design and production of additively manufactured parts. It opens up new avenues for creating lightweight and high-performance structures that meet stringent mechanical requirements, contributing to advancements in various industries such as aerospace, architecture, and engineering.

Figure 5 / Left / Final demonstrator in the Deutsches Museum in Munich

TECHNICAL DATA

Construction system
Tensegrity / frame construction

Process
LPBF (Laser Powder Bed Fusion)

Integrated functions
Light construction

Material
316L / AlSi10mg

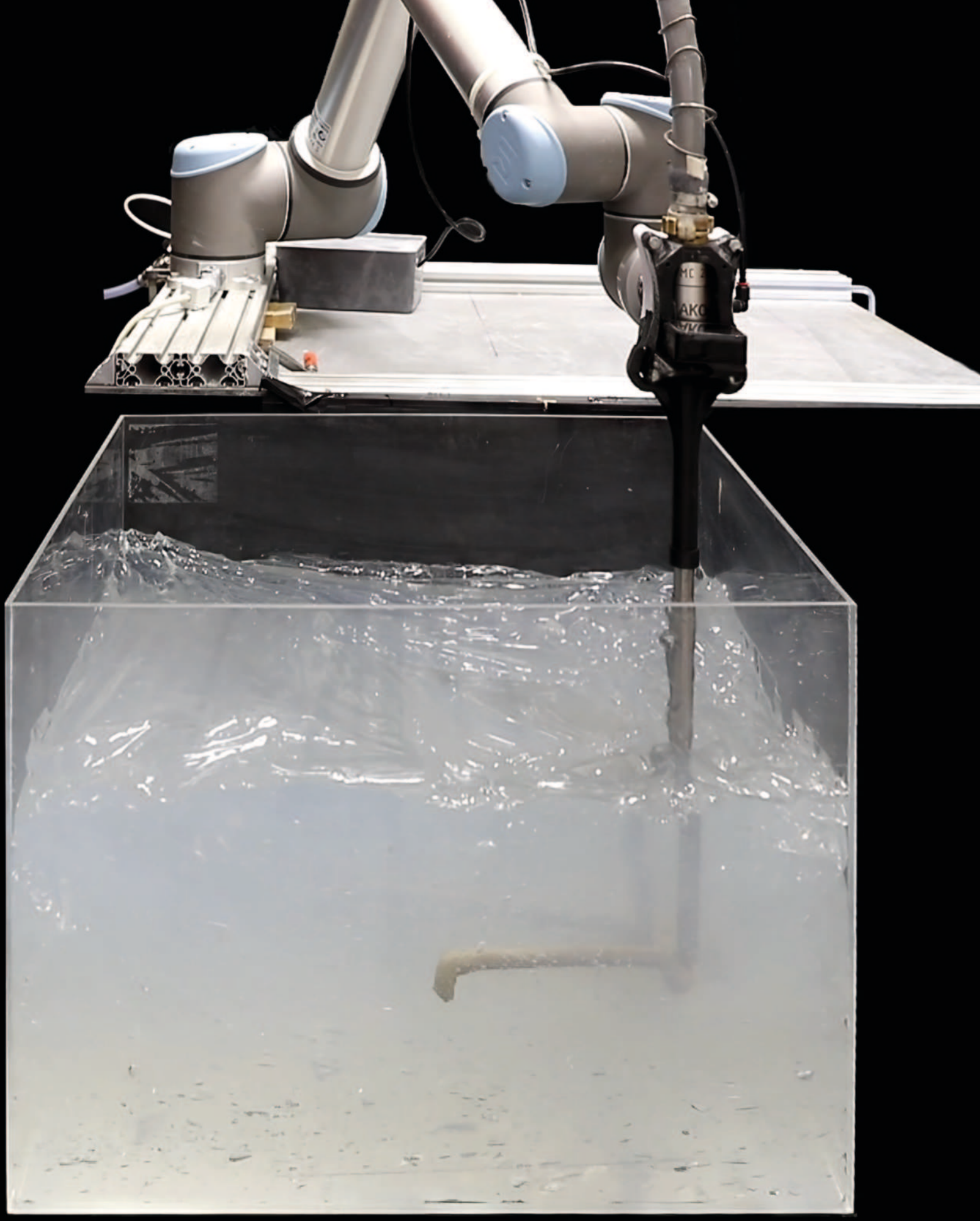
Density
8 g/cm³ / 2,7 g/cm³

Length x Height x Width
0,40 m x 0,40 m x 1,80 m

Weight
30 kg

Manufacturing time
6×3 Days / 2 × 4 Days

Figure 7 / Left side / Node after postprocessing



INJECTION 3D CONCRETE PRINTING

The research project aims to fundamentally understand the two Injection 3D Concrete Printing (I3DCP) techniques Concrete in Suspension (CiS) and Concrete in Concrete (CiC) with regard to the underlying material and process interaction as well as its process applications and control. Physical and digital investigations set the basis for a robust and controlled process and are utilized to achieve the following aims:

- Develop rheologically suitable materials for the I3DCP process
- Establish a method for 3D path planning and structural design
- Integrate reinforcement
- Predict and model print stability
- Geometrically precise multi-strand-printing

Project Leaders

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Prof. Dr. Norman Hack

Contributors

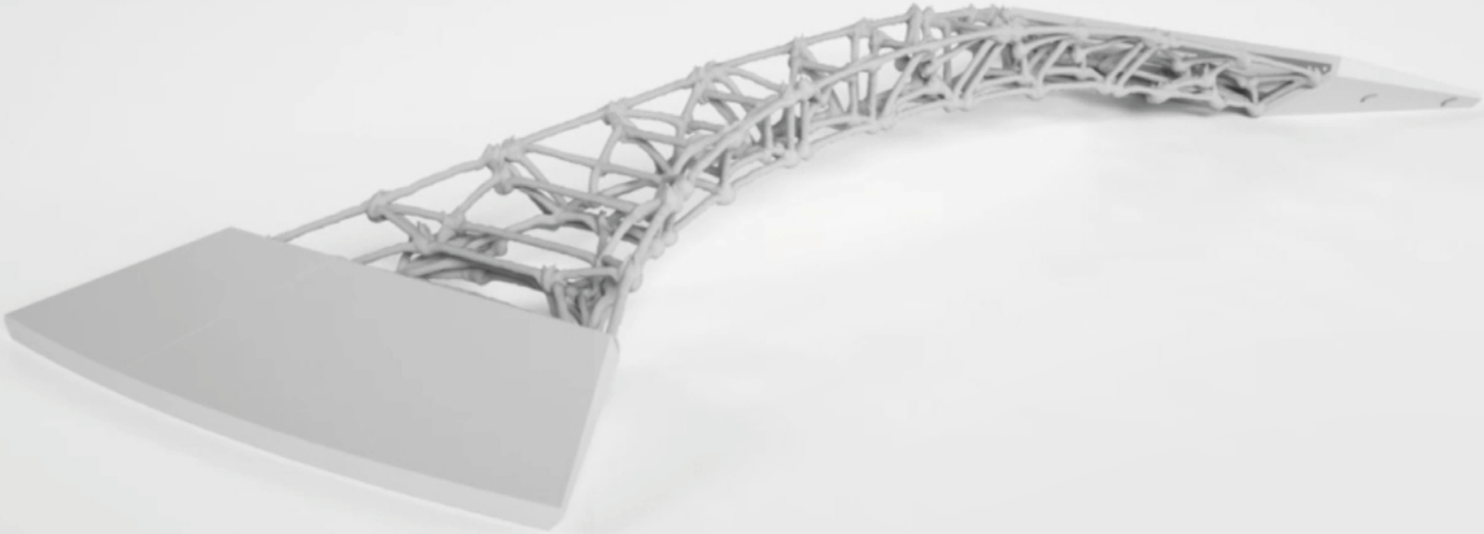
M.Sc. Yinan Xiao

AMC TRR 277 Project

A09

Associated Design Projects

Injection 3D Concrete Printing Bridge



I3DCP BRIDGE

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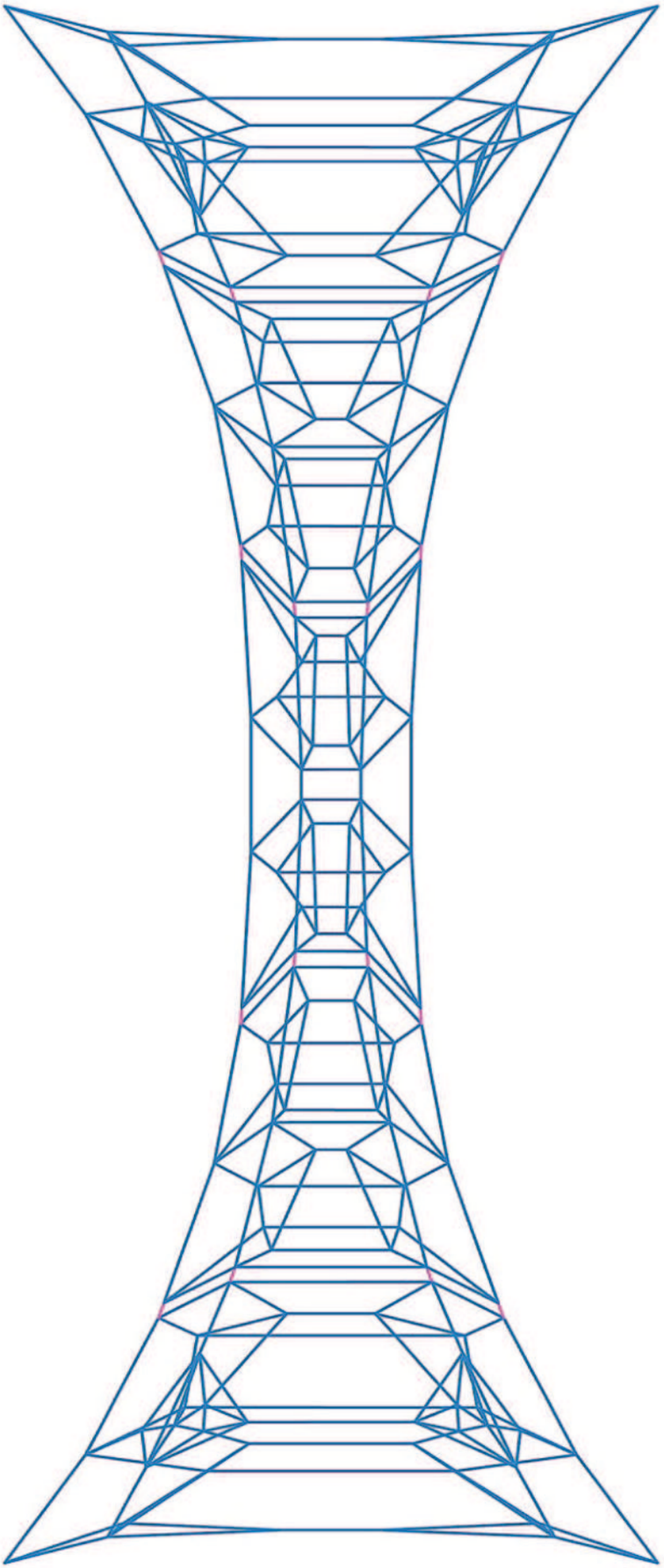
Prof. Dr.-Ing. Inka Mai

Industry Partners
Progress AG

Figure 1 / Left side / Perspective from the planned object

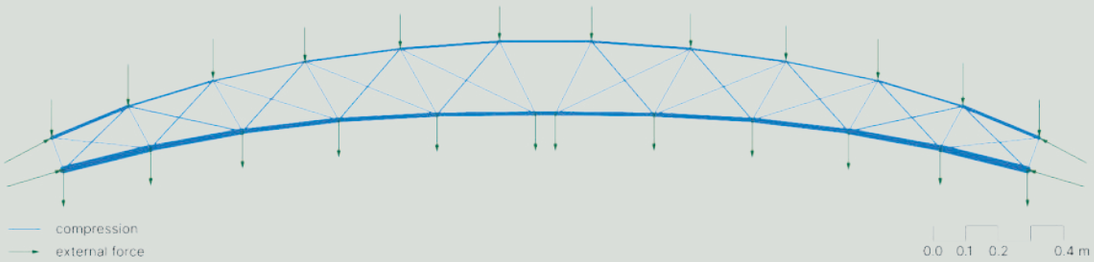


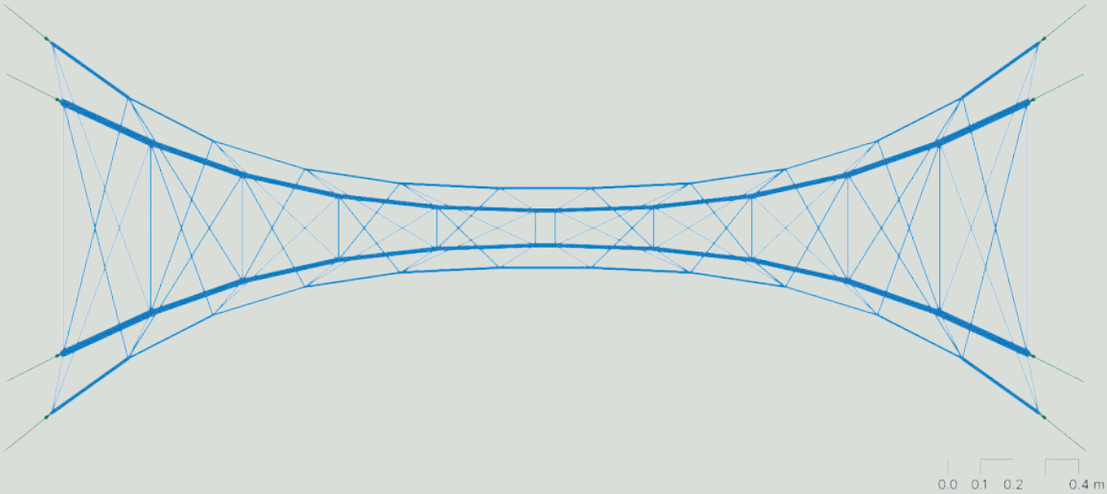
INTRODUCTION

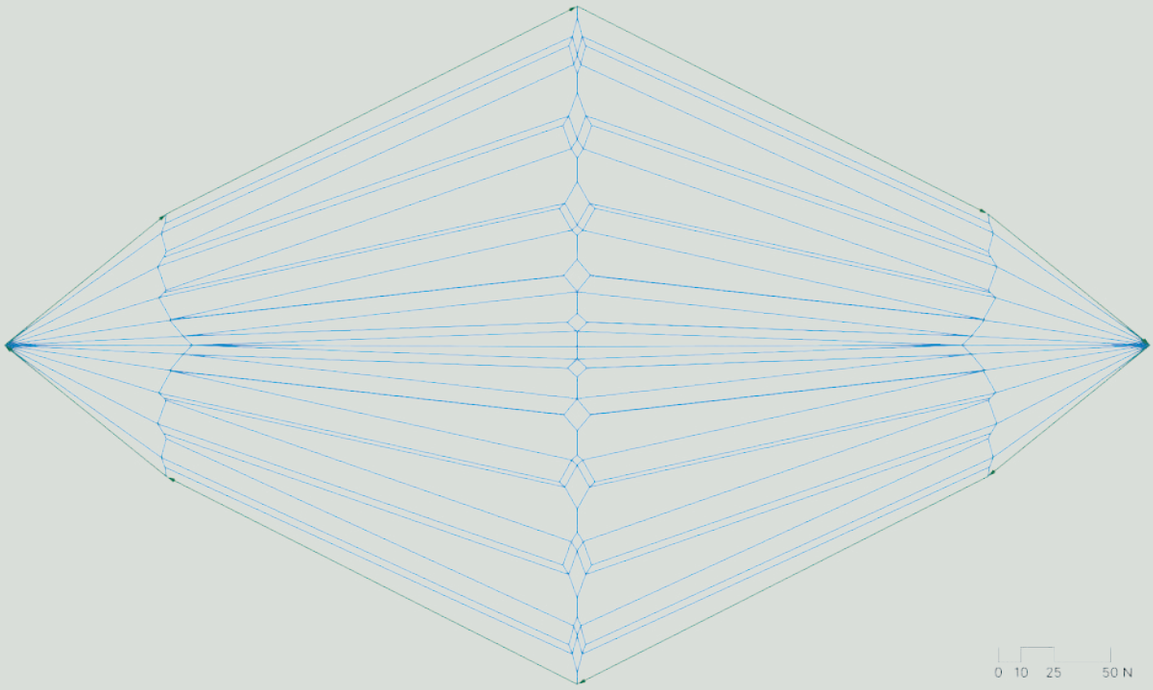
Over the past few decades, the construction industry has undergone significant changes due to the emergence of automation and digitalization. One of the most promising technologies in this regard is 3D concrete printing, which offers numerous advantages over traditional construction methods, such as reducing materials, waste, and energy, achieving higher degrees of geometric complexity of structural members, and increasing automation. However, current additive manufacturing techniques primarily focus on layer-by-layer based 3D printing techniques that are commonly applied in horizontal layers. While layer-by-layer processes feature a set of distinct advantages, there are inherent limitations to them, i. e. a limited ability in geometric complexity such as overhangs, which need additional structural support.

The novel approach of Injection 3D Concrete Printing (I3DCP) has been recently introduced to overcome the above limitations. 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, we can create intricate and filigree lightweight structures, which are today completely unknown with concrete as a construction material. Furthermore, the use of I3DCP allows the print path to be aligned with complex spatial 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). VGS is a geometry-based approach to the analysis and design of structures in static equilibrium that is particularly effective for designing spatially complex, lightweight, and material-efficient structures. VGS uses the form diagram to model the geometry of a structure with its applied loads and the force diagram to represent the equilibrium of the forces applied to the nodes of the structure. By combining VGS and I3DCP, the geometry of the lattice structure can be 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.

Figure 2 / Left side / top view of the final structure


compression
external force
0.0 0.1 0.2 0.4 m


0.0 0.1 0.2 0.4 m


0 10 25 50 N

STRUCTURAL DESIGN

The structural design of the global geometry of the bridge was motivated by the potential to integrate structure- and fabrication-informed strategies at the early phase of design to significantly improve the efficiency of the whole process from design to fabrication. The computational framework is built upon graphic statics, a geometry-based approach for analysing and designing structures in static equilibrium. Graphic statics relies on the form diagram to model the geometry of a structure with its applied loads and the force diagram to represent the equilibrium of the forces applied to the nodes of the structure. In particular, the proposed computational framework takes advantage of Vector-based Graphic Statics (VGS), a 3D graphic statics approach in which form and force diagrams are made of vectors. In the proposed approach, the geometry of the original lattice structure is optimised to fulfill static requirements and match the goals for fabrication.

Form-finding of the global geometry

The global geometry of the bridge was determined using the Combinatorial Equilibrium Modelling (CEM) form-finding method based on given topology diagram and metric parameters. The shape of the bridge was then optimised considering the supports‘ positions. To this end, the Vector-based Graphic Statics (VGS) tool was used to generate and transform the form and force diagrams. The bridge was designed as a pure compression structure with a span of 3.0 meters without considering the support bases. In this design phase, an estimated modulus of elasticity of the concrete with a value of 3.0 × 10^4 N/mm² was considered. This estimate will be refined in the future through extensive material testing to obtain a more accurate value. In addition, a load of 2.4 kN distributed evenly across the top of the bridge was considered. The diameter of the compression struts in the bridge was set at 20 mm, in compliance with the internal diameter of the compression nozzle. This choice ensured compatibility with the manufacturing process.

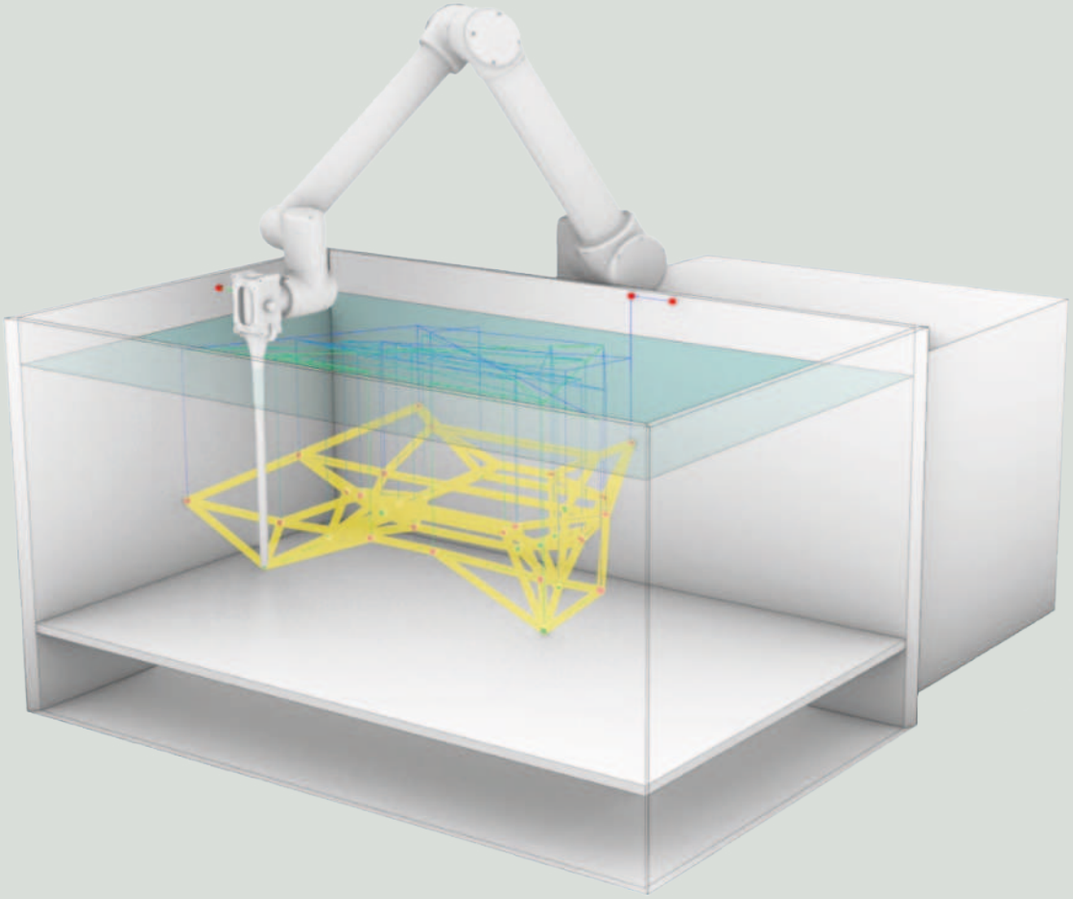
Segmentation

To accommodate the limited workspace of the robot arm, it became necessary to divide the original bridge into five segments. These individual segments were then manufactured using the I3DCP method. The division of the original geometry resulted in topological and geometric adjustments in the overall bridge design. During the segmentation process, it was crucial to maintain static equilibrium in the global geometry. Achieving this required a careful interplay between the vector-based form and force diagrams. Specifically, the force diagram was strategically cut at specific locations to ensure the desired outcomes.

Structural optimisation

To meet structural and manufacturing requirements, the bridge‘s segments underwent optimisation to adhere to both topological and metric constraints. In terms of topological constraints, the maximum node valence was limited to 6. This ensured that the number of connections at each node was within acceptable manufacturing limits. Regarding metric constraints, the geometry of the bridge‘s segments was optimised using the VGS tool to achieve strut lengths ranging from 0.06 to 0.54 meters. Additionally, the angles between the struts were constrained to fall between 17 and 180 degrees, ensuring appropriate angular relationships within the segments.

Figure 3 / Left side / Global geometry of the bridge designed using the Combinatorial Equilibrium Modeling (CEM) and Vector-based Graphic Statics (VGS).
Top: form diagram, side view.
Center: form diagram, top view.
Bottom: force diagram, top view.



FABRICATION

Injection concrete 3D printing of the bridge's segments

Preliminary investigations examined the rheological properties of the fresh concrete and the limestone carrier fluid. On the one hand, the fresh concrete printed in the low yield stress carrier fluid has a higher flowability, making the printed struts easier to join at the nodes. However, in this condition, the struts can bend non-negligibly during the concrete hardening process due to the lack of bearing capacity of the carrier fluid. On the other hand, the carrier fluid with high yield stress can improve the struts' performance and geometric precision. However, joining the fresh concrete struts at the nodes becomes more difficult because the concrete must overcome the higher resistance of the carrier fluid. The final composition of the 3D-printed concrete and the limestone carrier fluid required a thoughtful calibration of the material properties to achieve the requested geometric quality and structural performance.

Manufacturing of the joints

To ensure meticulous accuracy, all the segments underwent a thorough 3D scanning process, resulting in high precision meshes. This step served as a crucial preparation for the subsequent design and generation of joints. By capturing the intricate details of each segment through 3D scanning, a comprehensive digital representation was obtained, allowing for precise analysis and measurements. The bridge's segments were meticulously adjusted to their precise locations after importing all the 3D scanned meshes into the 3D modeling environment. In this stage, special attention was given to designing the joints, which were strategically modeled to align with the connection points of the adjacent segments. These joints served as crucial elements for ensuring structural integrity and stability. To bring the joint designs to life, advanced 3D printing techniques were employed, utilising TPU (Thermoplastic Polyurethane) material. This material selection was based on its desirable properties, such as flexibility, durability, and resilience, which were vital for the effective functioning of the joints. This intricate process seamlessly integrates the segments and joints, forming a robust and reliable structure.

Assembly

Once the five segments of the bridge, joints, and two support bases were successfully 3D printed, a meticulous assembly process took place. The various parts were carefully joined together, ensuring precise alignment and secure connections. Additionally, the two support bases were firmly fixed to the ground, providing a stable foundation for the bridge. The assembly sequence of the bridge's segments followed a methodical approach, starting from one of the support bases and gradually progressing toward the other base. Each segment was positioned and connected in a systematic manner, considering the predetermined design specifications and structural considerations. Throughout the assembly process, careful attention was given to ensuring that each segment seamlessly integrated with its neighboring segments, creating a unified and robust structure.

Figure 4 / Left side / Injection 3D Concrete Printing Process.

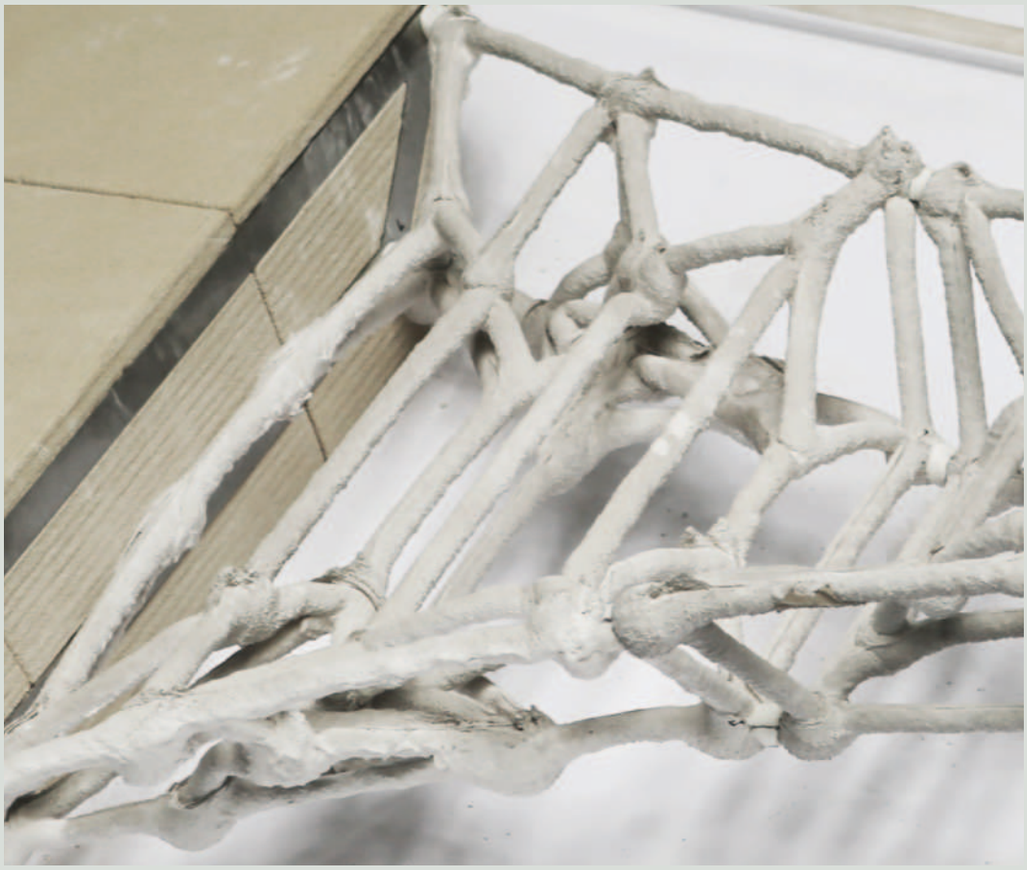
Figure 5 / Assembly process

RESULT

The constructed bridge prototype measures 4.2 meters in length, 0.5 meters in height, and 1.8 meters at its widest point. Its overall weight, including the abutments, amounts to 312.5 kilograms, while the five components manufactured through I3DCP have a combined mass of 50 kilograms. 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. Additionally, it validates the effectiveness of Vector-based Graphic Static (VGS) in designing structures using this fabrication method.

This project introduced a methodology for the Injection 3D Concrete Printing technique to generate reliable structures at the early design phase by combining the constraints that have been detected during the fabrication process and information gained from the structural analysis. The bridge successfully fulfills the constraints that have been set for the optimisation process and demonstrates the potential to apply the proposed approach to I3DCP. Concerning the geometrical aspects, more printing experiments will be carried out to tackle the fabrication constraints, such as the distance between edges with the robot path planning.

Figure 6 / Left side / Top view of the completed bridge



TECHNICAL DATA

Construction system
The compression-only modular grillage system

Process
Injection 3D Concrete Printing (I3DCP), Particle bed 3D printing by Selective Cement Activation (SCA)

Integrated functions
Light-weight arch structure

Material
Concrete, limestone, stainless steel, thermoplastic polyurethane

Density
Concrete for the main structure: 1.982 × 103 kg/m^3

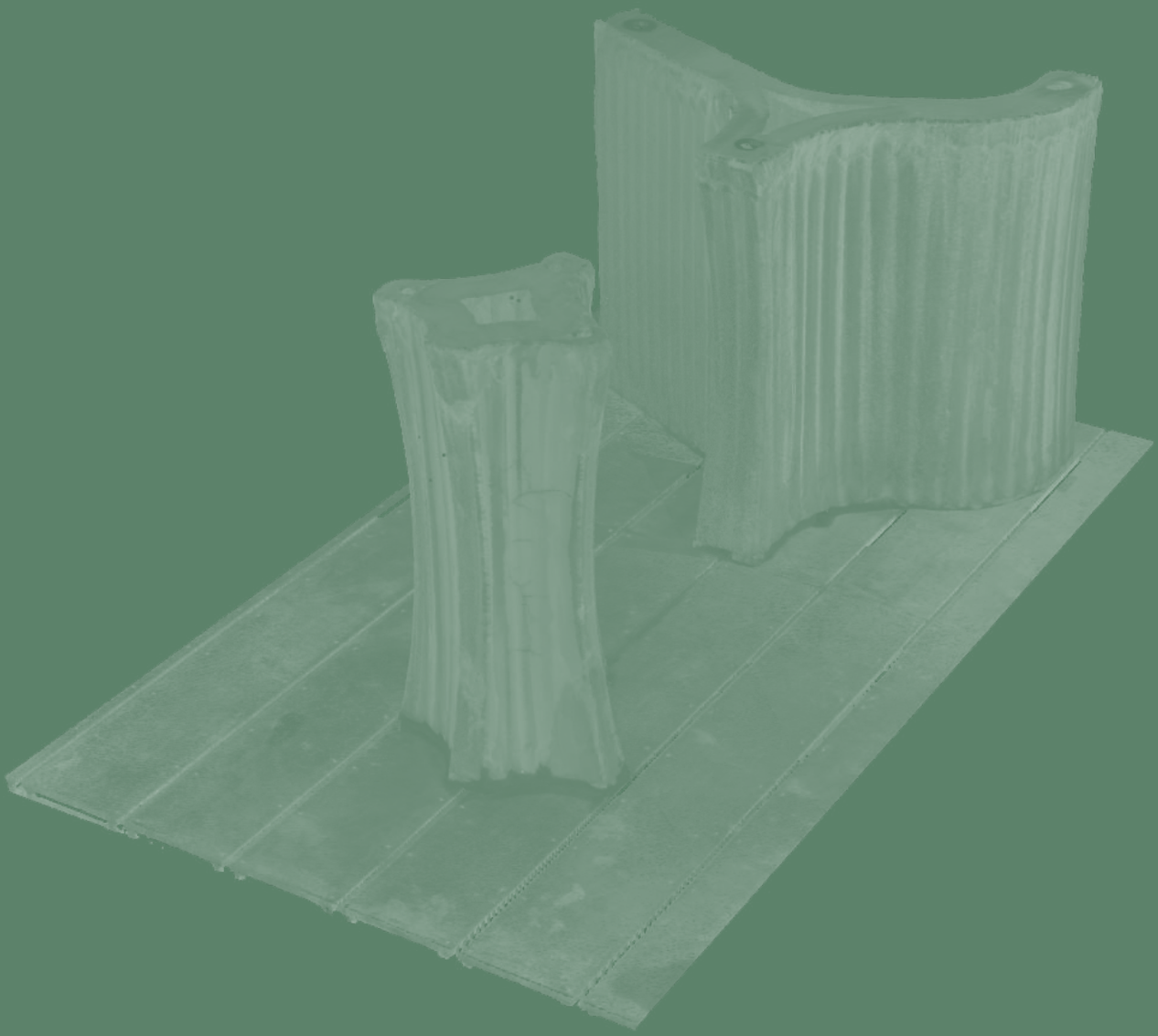
Length x Height x Width
4.20 m x 0.50 m x 1.80 m

Volume
The entire bridge: 0.174 m^3
Volume of the main structure: 0.027 m^3

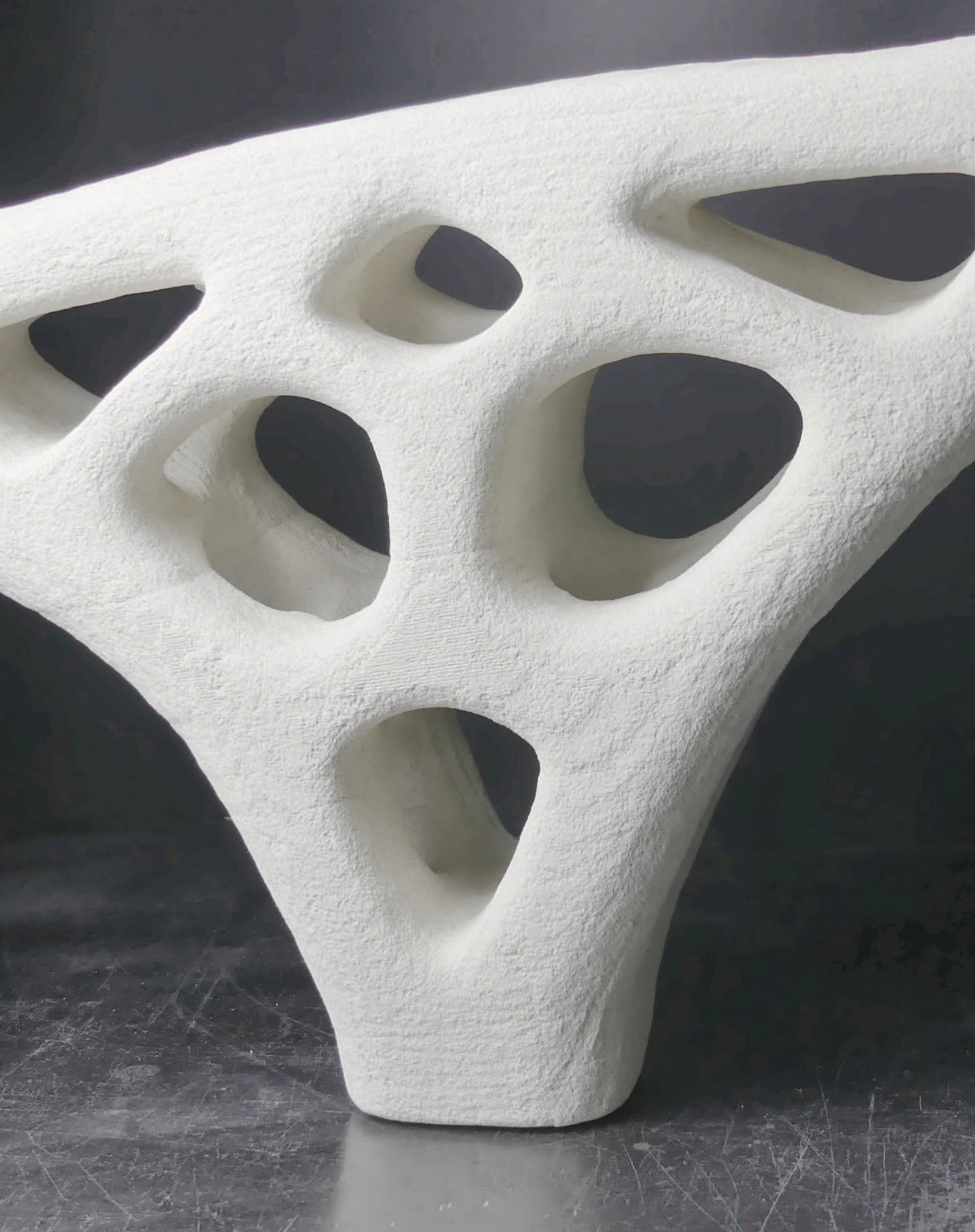
Weight
312,5 kg

Manufacturing time
Construction period: 2,5 months
Printing days: 4 days
Demolding days: 3 days
Assembly: 1 day

Figure 7 / Left side / Detail of the final demonstrator



DEMONSTRATORS FOR BUILDING CONTEXT



PARTICLE-BED 3D PRINTING BY SELECTIVE CEMENT ACTIVATION

Particle-Bed 3D Printing by Selective Cement Activation (SCA) – Particle Surface Functionalisation, Particle-Bed Compaction and Reinforcment Implementation. This project focusses on high-resolution particle-bed 3D printing of reinforced cementitious composites as a novel technology in the construction industry. To pioneer the understanding of governing mechanisms affecting the material-process interaction, basic interdisciplinary research addressing particle surface functionalisation, tailoring of particle size distribution, particle-bed compaction, liquid intrusion, interparticle and interlayer bonding, active structural build-up control of the matrix, high precision geometries as well as reinforcement integration will be conducted.

Project Leaders

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Prof. Dr.-Ing. Inka Mai
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Dr.-Ing. Harald Zetzener

AMC TRR 277 Project

A01

Associated Design Project

Breuer X AM

BREUER X AM

Collaborators:

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Friedrich Herding (materials Lead)
Niklas Meier (materials)
David Briels (building physics)
Hendrik Weigel (structural design)
Abtin Baghdadi (structural design)
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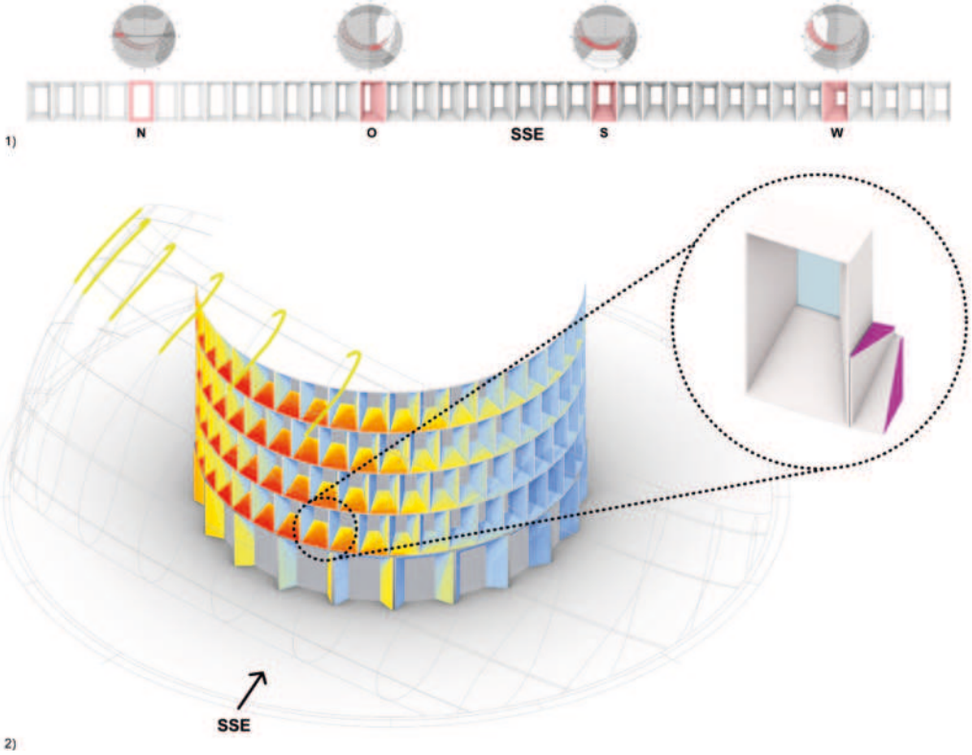
Prof. Dr.-Ing. Patrick Schwerdtner

Industry Partners
additive tectonics GmbH
Bruno Knychalla
Christian Wiesner
Christian Thaler
Max Braun
Kilian Fruth

Figure 1 / Left side / Exterior perspective Ägidienmarkt


1)
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2)
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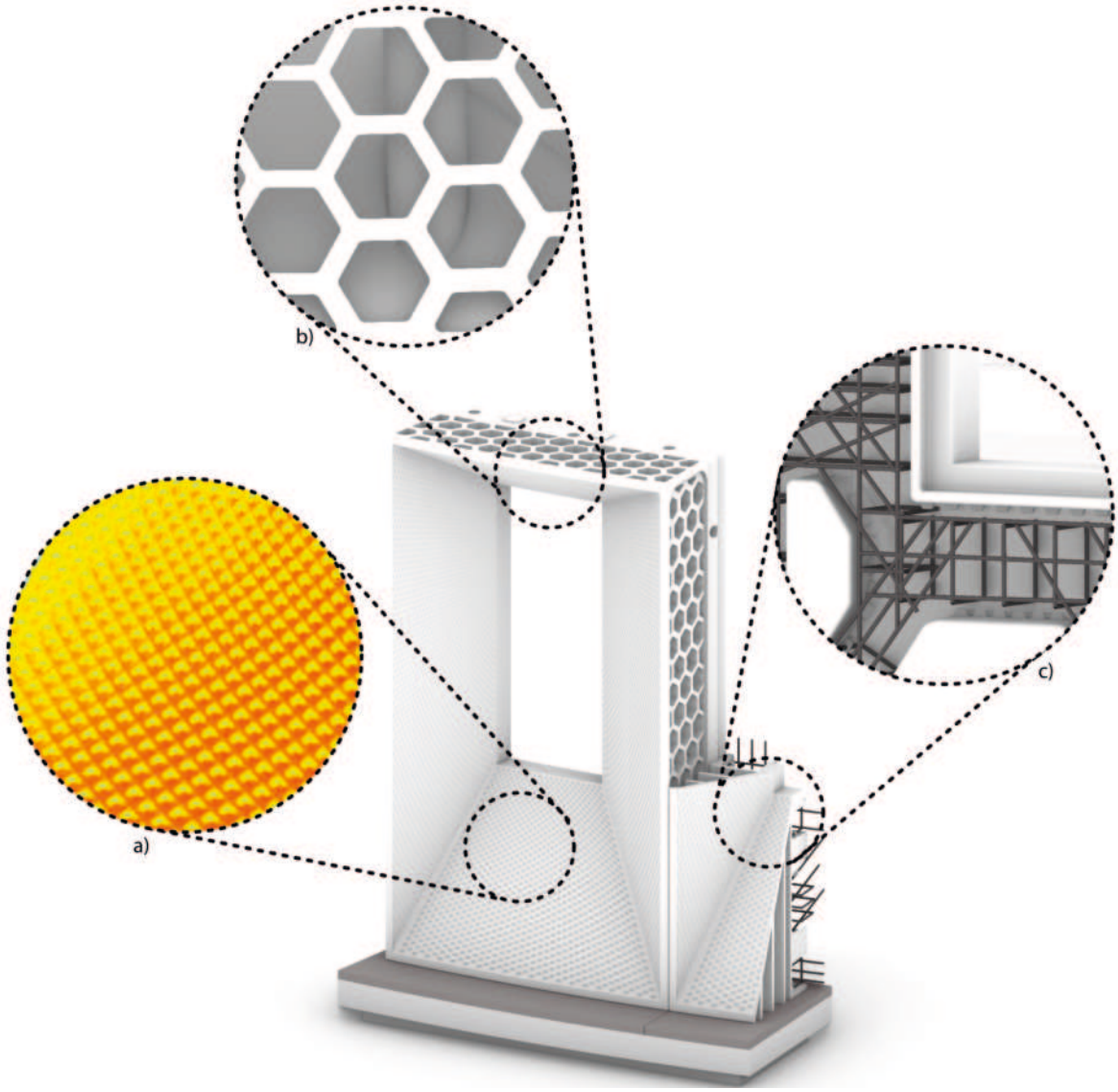

a)
b)
c)

INTRODUCTION

Architect Marcel Breuer developed innovative solutions for a novel industrial approach of modular construction methods at the IBM Research Center in LaGaude, France (1960-1962). By using prefabricated, standardised concrete building elements, load-bearing functions and solar control could be combined in one building element, avoiding the need for multi-layered building systems. However, the standardised manufacturing method at that time was not yet capable of customising building elements to address local requirements within the building envelope or to differentiate the inner structure due to the concrete casting methods available at that time.

Today, Additive Manufacturing technology for Construction (AMC) provide a high degree of design freedom, capable of combining complex local requirements with streamlined manufacturing processes. Therefore, 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 method Selective Cement Activation (SCA), this design project aimed at expanding traditional industrial construction methods towards non-standard, mass-customised, and resource-efficient alternatives.

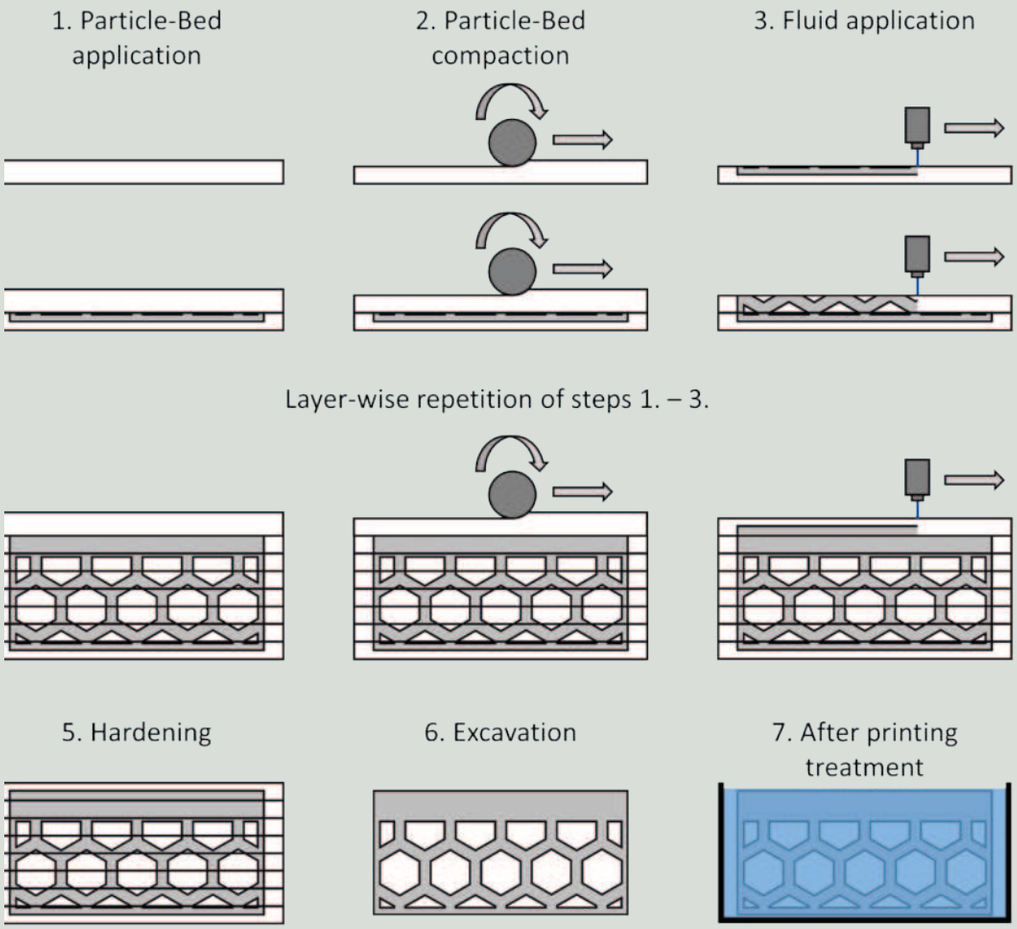
The collaborative demonstrator, which originated in the Breuer x AM design proposal developed within the design studio “From AM to Architecture”, was designed and planned to validate a) the general applicability of the design approach for multi-scale, customized, and site-specific building envelope elements; 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 2).

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

Figure 2 / Left side / Solar control aspects serve as input parameters for the computational algorithm driven design process tailoring the glazed area in depth, width and height to unlock self-shading properties. The design parameters are adapted to minimize overheating for the interior spaces. 2) But this phenomenon can barely be prevented for the south-west orientation and consequently represents the most challenging case for further design investigations.

Figure 3 / Left side / Dedicated functionally graded self-shading building envelope section for the real-scale demonstrator with a) geometric differentiated surface undulation to reduce thermal loads b) insulating zone (~50 cm) with a graded cellular structure (cell wall thickness and cell size) towards the edges, and c) a load-bearing zone as permanent formwork to cast in the reinforcement (~20 cm). The total weight of the demonstrator is 2.2 t, while the SCA part covers 1.05 t at a density of 1.2 g/cm3.


1. Particle-Bed application
2. Particle-Bed compaction
3. Fluid application
Layer-wise repetition of steps 1. – 3.
5. Hardening
6. Excavation
7. After printing treatment

METHOD

SCA AM method

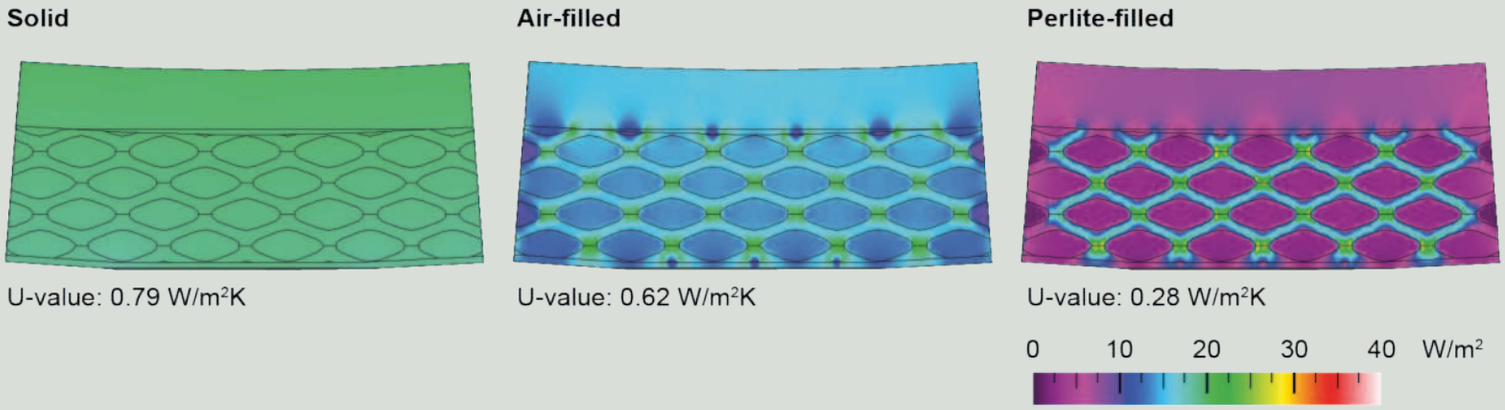
Using the SCA method, dry particles of cementitious material are deposited in thin layers on a print bed and selectively activated with liquid. Depending on the used material of the Portland cement the print resolution features an accuracy of 1.5mm, enabling the AM of arbitrarily complex internal and external geometries without the need of additional formwork. Nevertheless, the SCA method comes along with the constraint of a complex de-powdering process of non-bonded material, particularly in the case of closed cell geometries as well as a generally lower compressive strength compared to extrusion-based 3D printing (Figure 4).

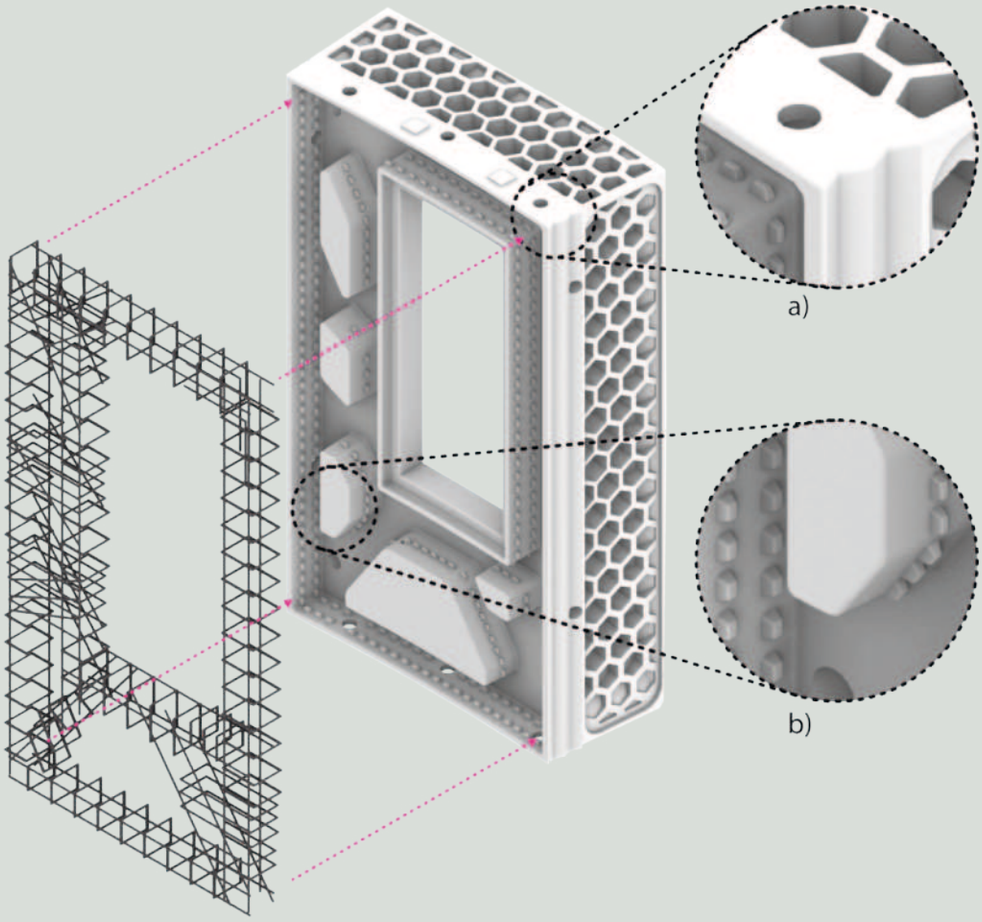
Solar controlled shape design

While the overall shape of the building elements and their openings is derived from daylight studies, the adoption of microstructures presents the potential of being a more precise and selective design method once large-scale self-shading effects are no longer effective to improve the thermal load. Therefore, the south-southeast oriented building envelope element serves as a case study crostructures to reduce the direct solar radiation of the adjacent glazed areas surfaces. The implementation of high-resolution solar to further develop strategies for geometrically differentiated miradiation simulation serves as input parameters for the geometric differentiation capable in adaptation of size, depth, and angle. Integrating passive solar control strategies within the building envelope element, considering self-shading effects, surface tuning, and glazing placement at different spatial scales, addresses hyperlocal requirements and aims to enable the reduction of solar heat gain and cooling loads.

The particle mixture is scattered onto the whole construction chamber (1) and smoothed counterclockwise using a rotating roller to increase the packing density of the particle bed (2). A fluid binder is then selectively sprayed into the particle bed activating particles with the binder (3). This process steps are repeated for each layer, resulting in the design target geometry. Depending on the particle properties, the printed geometry hardens for some hours / days (5) before being excavated from the construction chamber by removing the inactivated particles with e.g. an industrial vacuum cleaner (6). After the printing treatment a high pressure cleaner cleans off the remaining adhesive particles increasing the strength by partially activating the activated binder (7).

Figure 4 / Left side / The particle mixture is scattered onto the whole construction chamber (1) and smoothed counterclockwise using a rotating roller to increase the packing density of the particle bed (2). A fluid binder is then selectively sprayed into the particle bed activating particles with the binder (3). This process steps are repeated for each layer, resulting in the design target geometry. Depending on the particle properties, the printed geometry hardens for some hours / days (5) before being excavated from the construction chamber by removing the inactivated particles with e.g. an industrial vacuum cleaner (6). After the printing treatment a high pressure cleaner cleans off the remaining adhesive particles increasing the strength by partially activating the activated binder (7).


Solid
Air-filled
Perlite-filled
U-value: 0.79 W/m²K
U-value: 0.62 W/m²K
U-value: 0.28 W/m²K
0 10 20 30 40 W/m²


a)
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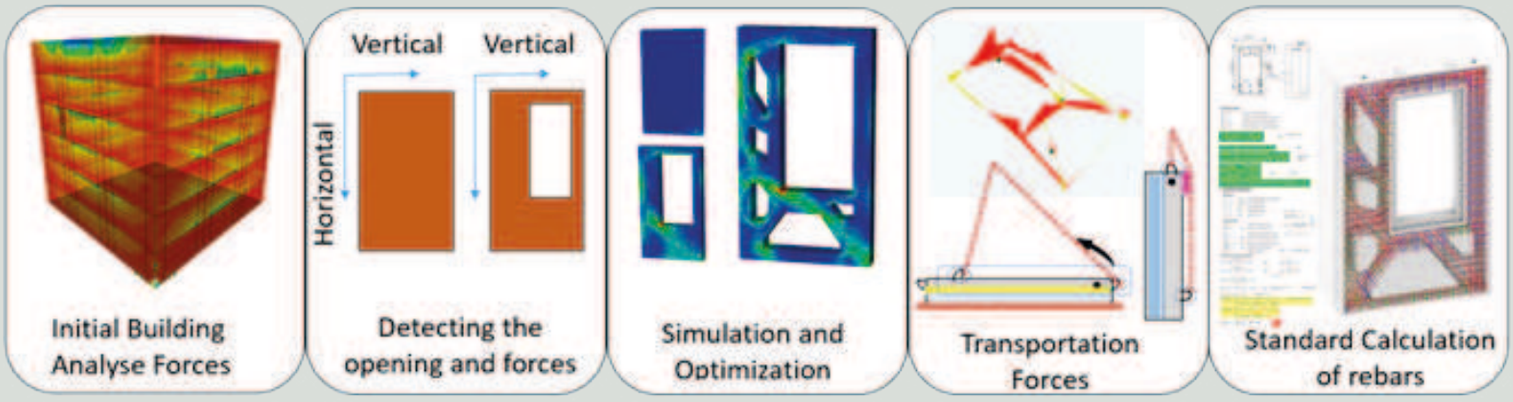

Initial Building
Analyse Forces
Vertical
Vertical
Horizontal
Detecting the
opening and forces
Simulation and
Optimization
Transportation
Forces
Standard Calculation
of rebars

METHOD

Thermal zone design

The use of lightweight aggregates and the customisation of the internal structure aim to significantly improve the thermal properties of the building envelope element to adapt Breuer‘s building envelope concept to the increased requirements on thermal quality (u-value: 0.28 W/m²K; German legal requirements acc. §19 Anlage 3 GEG). A separate simulation-based parametric design approach serves to tailor the cellular structure.

The used SCA material already provides an improved thermal conductivity of 0.6456 W/m2K (st. dev. 0.0475) due to the added lightweight aggregates (expanded glass granulate), measured according to ISO 22007-2. The further integration of a graded cellular structure is meant to enhance the insulating properties considering the following fabrication-related constraints for the design capabilities: a) a minimum cell size of around 100 mm to extract the unbound material, b) no possibility for closed cells and c) a cell wall thickness of around 20 - 40 mm for sufficient rigidity. A parametric study revealed inadequate results for an air-filled open cellular structure with u-values around 0.6 W/m²K. To improve the insulation properties, one approach pursues filling the cavities with insulation material (e.g. perlite or cellulose) after the assembly of the elements on-site. This allows to achieve the required U-value of 0.28 W/m²K (Briels et al. 2023).

This performance feedback was fed back into the design process of the demonstrator for thermally enhancing the internal structure The thermal insulation performance of the final demonstrator design was again simulated using layer-wise 2D heat flux simulations. Calculating an arithmetic mean of all twenty layers, the overall U-value of the facade element accounts for 0.977 W/m2K. This is due to the geometric variation across the element height coming from the window opening and due to the integration of a load-bearing zone using a material with higher thermal conductivity.

Structural zone design

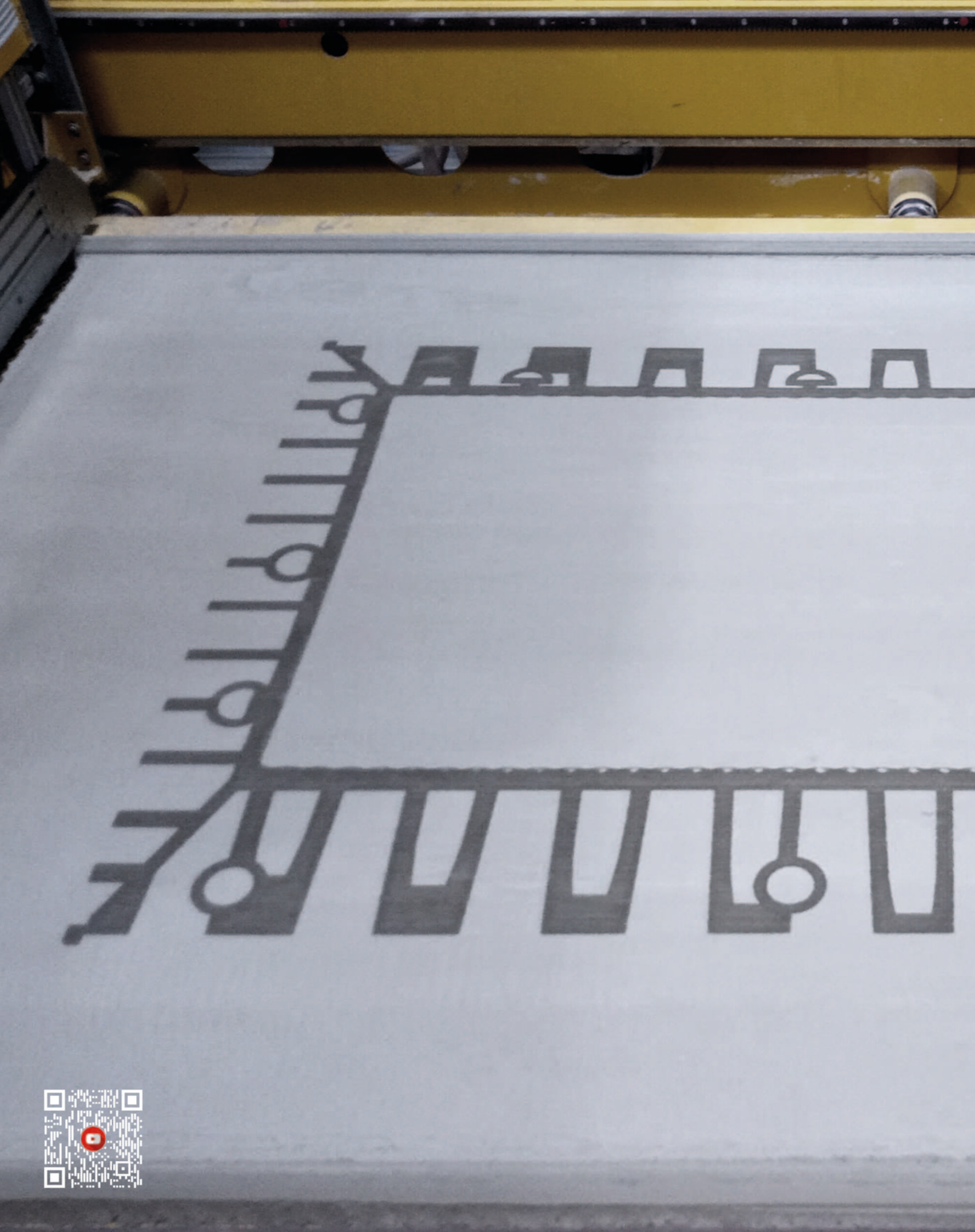
The load-bearing zone is intended as a permanent formwork for placing a prefabricated rebar mesh and for casting grouted concrete. Preliminary tests investigate the general applicability and the bond between the grouting and the SCA concrete. Therefore, the sides of the permanent formwork are evenly notched to wedge the grouted concrete to the SCA material. Based on the idea of the force-flow, redundant material has been selectively extracted to only place the reinforcement and cast the grouted concrete where it is needed (Figure 7). Two different types of dry joints serve to connect adjacent building envelope elements.

The design integrates on the top and bottom truncated pyramids and triangulated connectors along the vertical length of the sides within the area of the permanent formwork (Figure 6).

Figure 5 / Left side / Results of 2D heat flux simulations for a horizontal section through the facade element, comparing a solid element, with a possible typology of internal cell structure for the insulating zone, encapsulating air or blow-in insulation material (e.g., perlite) (Briels et al. 2023b).

Figure 6 / Left side / The design of the permanent formwork is interpreted to match the forces entering from above. This allows optimizing the casting material quantity while reducing the print material. Furthermore, a) dry joints in pyramid shape on the top and bottom and in triangular shape on both sides of the permanent formwork hold the adjoining building envelope elements in place when assembling on site. B) close-up of the notches on the inner sides of the permanent formwork for better bonding between the printed SCA material and the grouting concrete.

Figure 7 / Left side / Workflow for the structural analysis of the building envelope element



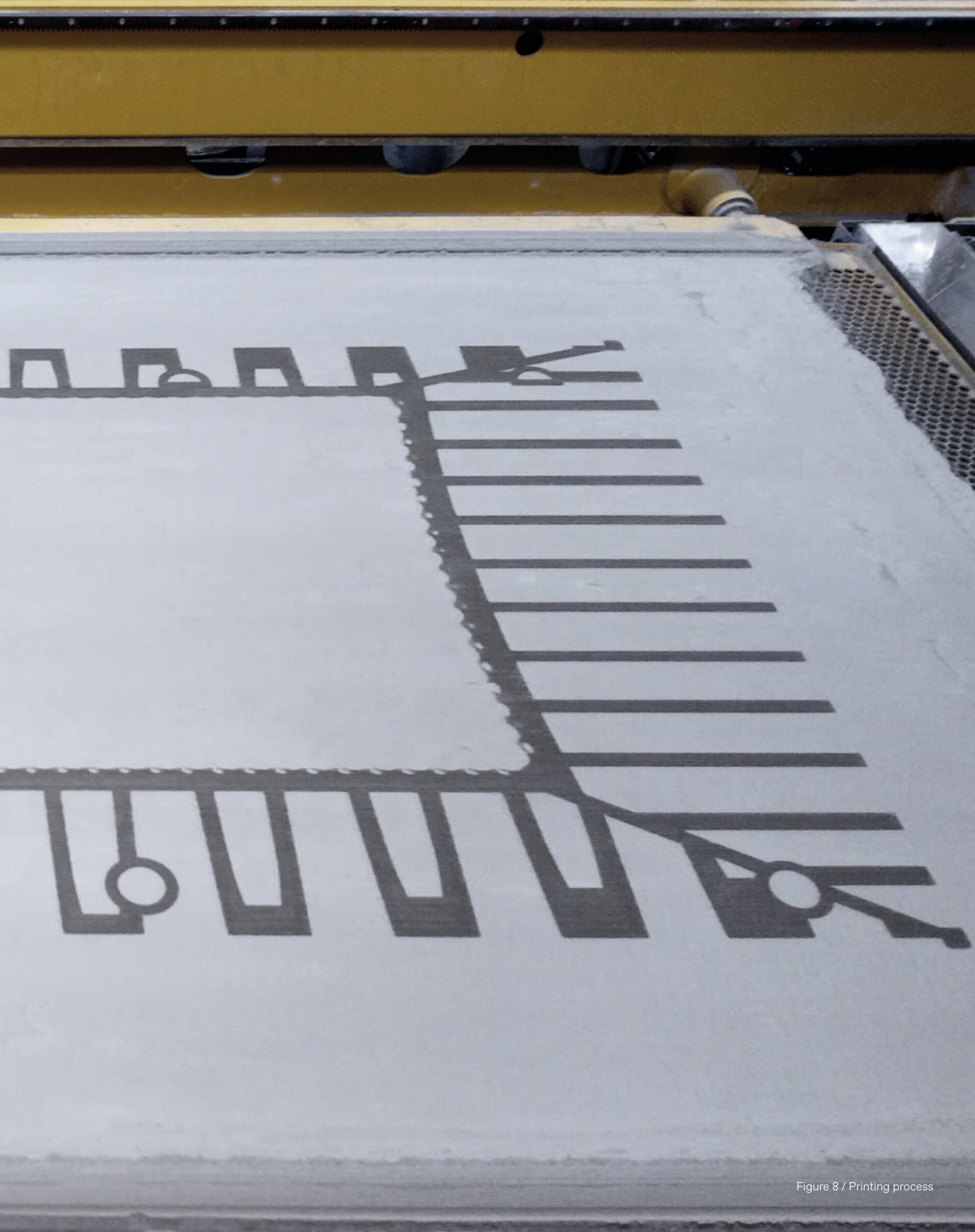


Figure 8 / Printing process


AMC

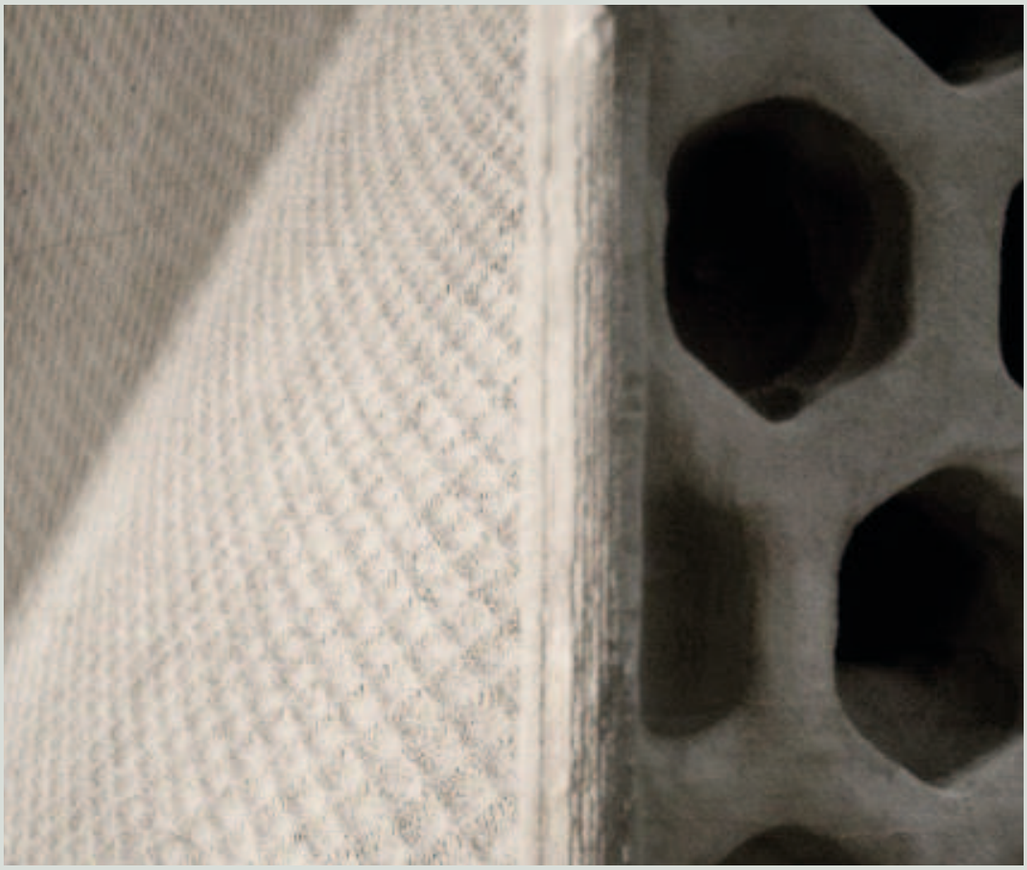
RESULT

The collaborative demonstrator was manufactured at Additive Tectonics GmbH in the Big Future Factory (BFF) using the particle-bed setup with Portland cement and lightweight aggregates as printing material. Due to the provided build space of 4.00 m x 2.00 m x 0.90 m (L x W x H) and additional handling elements such a transportation steel frame, the overall dimensions of the demonstrator were defined to ensure the building envelope element being manufactured in one piece.

In contrast to small scale laboratory printing processes, the manufacturing of the large scale demonstrator offered unknown challenges increasing the preparation time in the BFF laboratory resulting in recurring design iterations. Especially since the handling of the demonstrator resembled a black box, it required detailed planning and additional production steps to support the manufacturing process.

The demonstrator was printed in one piece, horizontally with the front side facing down. This allowed them to excavate the permanent formwork first and to reinforce the building envelope element before any further moving and any further excavation. This front facing down printing setup increased the potential for cracks since due to the curved front side the weight is only derived over the filigree edges. Another aesthetic disadvantage consisted in the reduction of the print quality and thus the resolution of the microstructure caused by the water flowing downwards into the particle bed. In the process of casting, even a foil ensured not to activate excessive unbound particles of the unbound material, causing clogging. Given the weight and size of the building envelope element, together with the rather unknown conditions outside the laboratory, it was finally considered necessary to build a steel frame, supporting the tensile strength of the building envelope element preparing for operation and transportation.

Figure 9 / Left side / final Demonstrator



TECHNICAL DATA

Construction system
Lost formwork with grouted steel-reinforced mortar to distribute vertical and horizontal forces needed throughout the diverse manufacturing phases

Process
Particle bed 3D printing – Selective Cement Activation

Integrated functions
Solar controlled shape design, Thermal zone design, Structural zone design

Material
Portland cement with lightweight aggregates (expanded glass granulate)

Density
Portland cement 1,2 g/cm³

Length x Height x Width
1,80 m x 3,00 m x 0,75 m

Volume
3,01 m³

Weight
Portland cement 1,0332t

Manufacturing time
9:38:33 hours

Figure 10 / Top / Detail of the final Demonstrator

References

D. Briels, M. Renz, A. Nouman, and T. Auer, Heat flux simulations for the insulation concept of the AM facade demonstrator „Breuer X AM“, Munich: TUM, 2023. [Dataset]. Available: https://doi.org/10.14459/2023mp17165068. [Accessed: July 24, 2023].
Bertagna, F., Piccioni, V. and D'Acunto, P. (2023) 'Geometry-based Graphical Methods for Solar Control in Architecture: A Digital Framework.', Frontiers of Architectural Research.
Fleckenstein, J. et al. (2023) 'Revisiting Breuer' Proceedings of the 41th Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2023), status: accepted
Baghdadi, A. et al. (2023) 'Experimental and Numerical Assessments of New Concrete Dry Connections concerning Potentials of the Robotic Subtractive Manufacturing Technique', Buildings, 13(1). doi: 10.3390/buildings13010210.
Fleckenstein, J. et al. (2022) 'Climate-Resilient Robotic Facades: Architectural Strategies to Improve Thermal Comfort in Outdoor Urban Environments using Robotic Assembly', Frontiers in Built Environment, 8. doi: 10.3389/fbuil.2022.856871.
Briels, D. et al. (2022) 'Thermal Optimization of Additively Manufactured Lightweight Concrete Wall Elements with Internal Cellular Structure through Simulations and Measurements', Buildings, 12(7). doi: 10.3390/buildings12071023.
Herding, F., Mai, I. and Lowke, D. (2022) 'Effect of Curing in Selective Cement Activation', in, pp. 283–288. doi: 10.1007/978-3-031-06116-5_42.
Lowke, D. et al. (2022) 'Material-process interactions in particle bed 3D printing and the underlying physics', Cement and Concrete Research, 156, p. 106748. doi: 10.1016/j.cemconres.2022.106748.
Dielemans, G. et al. (2021) 'Additive Manufacturing of Thermally Enhanced Lightweight Concrete Wall Elements with Closed Cellular Structures', in. Journal of Facade Design and Engineering, 9(1), 59–72., p. 14. doi: https://doi.org/10.7480/jfde.2021.1.5418.

PARTICLE-BED 3D PRINTING BY SELECTIVE CEMENT PASTE INTRUSION

Particle-Bed 3D Printing by Selective Cement Paste Intrusion (SPI) – Particle Surface Functionalisation, Particle Synthesis and Integration of WAAM Reinforcement. Selective paste intrusion (SPI) is a particle-bed-based additive manufacturing technology in which aggregates are spread in thin layers and bonded by cement paste. To qualify SPI for structural concrete elements, the inclusion of reinforcement is mandatory. The innovation introduced here is that reinforcement will be implemented simultaneously in the SPI process using Wire and Arc Additive Manufacturing (WAAM). Different active and passive cooling strategies, e.g. particle surface functionalization and the synthesis of new particles, will be developed to deal with the high temperatures during WAAM.

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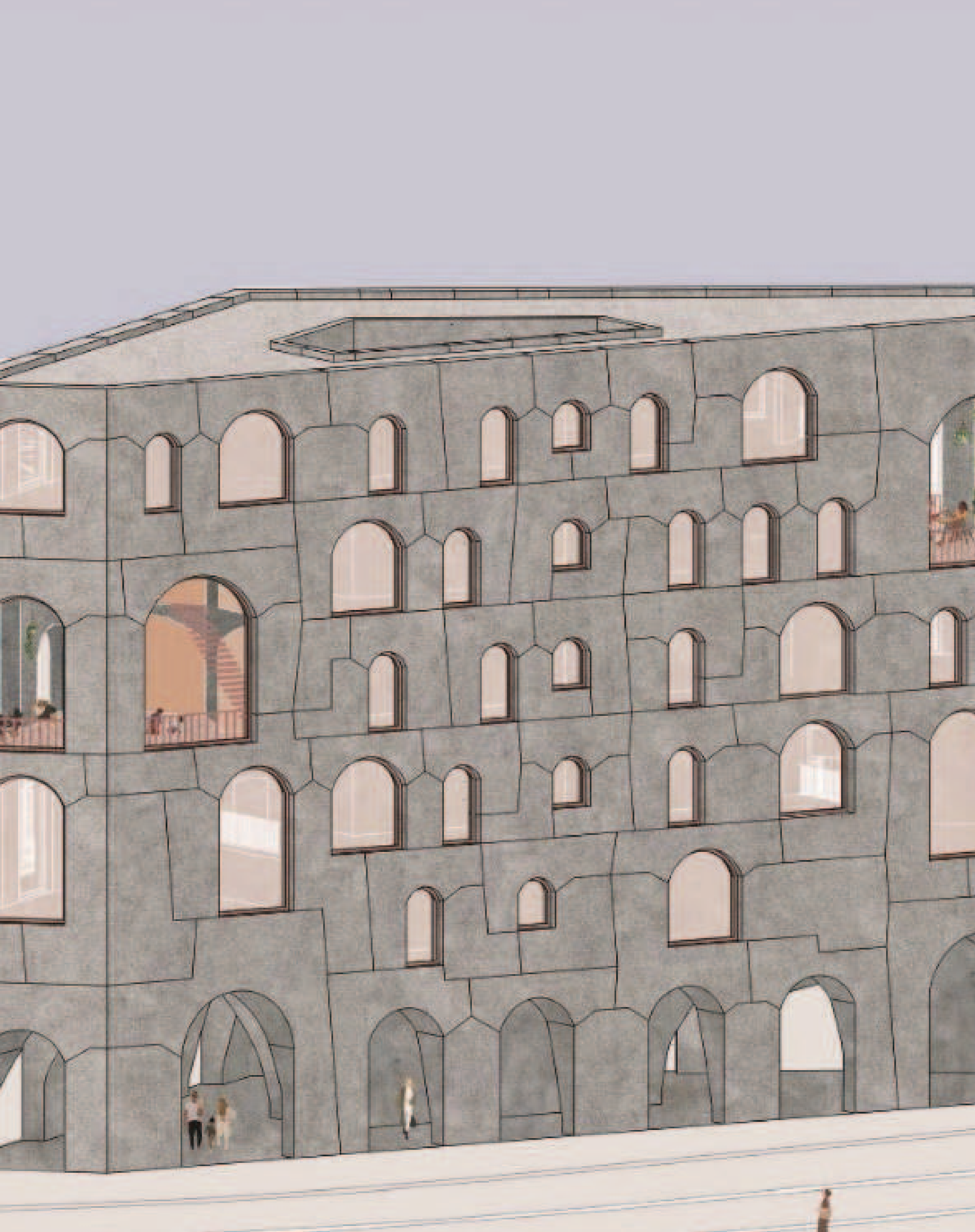
AMC TRR 277 Project

A02

Associated Design Projects

Playing with blocks
Bridge the Gap



PLAYING WITH BLOCKS

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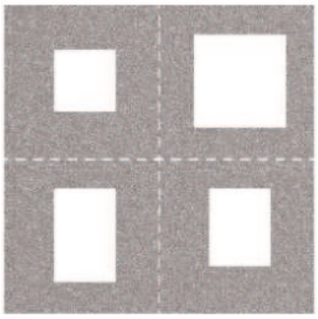
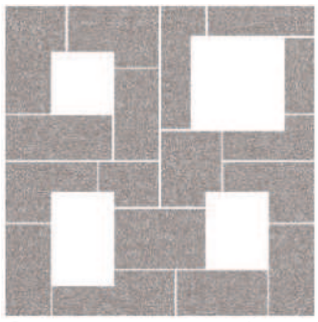
Prof. Dr.-Ing. Christoph Gehlen
Prof. Thomas Auer

Figure 1 / Left side / Design proposal



Design outline

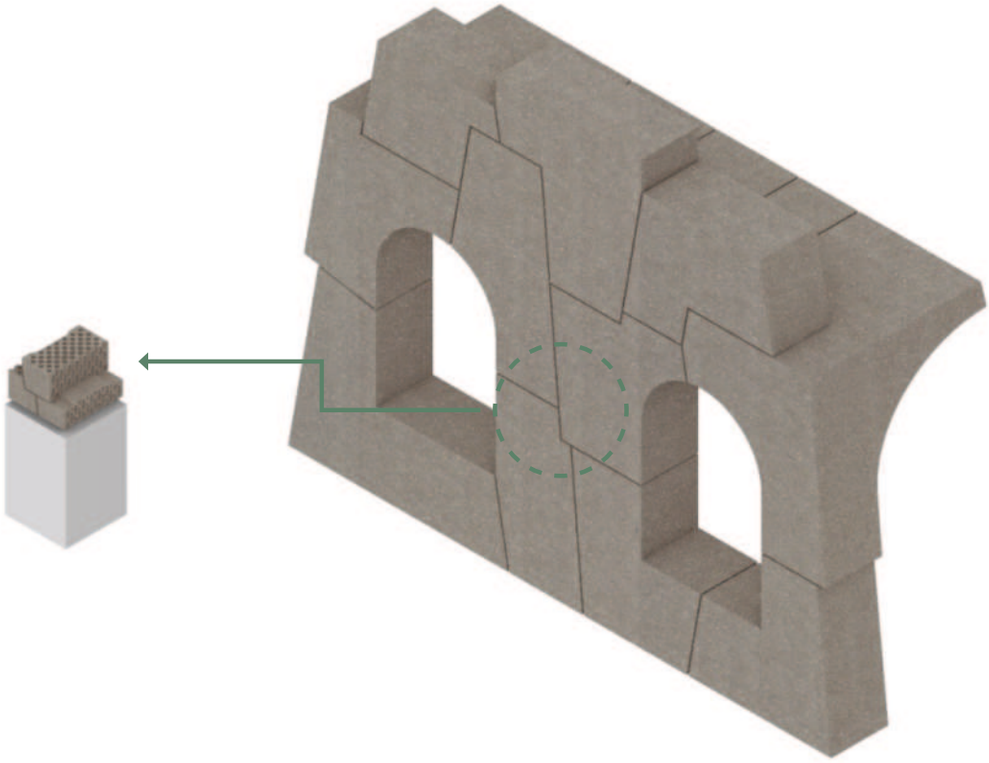


Segmentation according to printer size

Compression dominant shape adjustment

Assembly sequence

Topological interlocking



INTRODUCTION

Design proposal

“Playing with Blocks” explores design strategies for a multi-storey building with the design freedom and functional integration potential provided by the Additive Manufacturing technology Selective Paste Intrusion (SPI) (Figure 1). The SPI method enables aggregates to be selectively bound with a cementitious paste for the prefabrication of large-scale and functionally hybridized building components.

In this design proposal, the use of lightweight aggregates (e.g., foamed clay or glass, perlite, etc.) with a low thermal conductivity was explored, which opens up the possibility to trap the unbound material within the bound structure and its cavities as an insulating material (Figure 4). The inner composition of the closed cells can be varied and functionally graded to fulfil both the structural and thermal requirements within a single building component.

The overall shape of the components follows traditional compression-dominant construction principles. The design foresees that once the elements are prefabricated, they can be transported on site, assembled, and connected through custom, interlocking joints, additionally supported by post-tensioning cables.

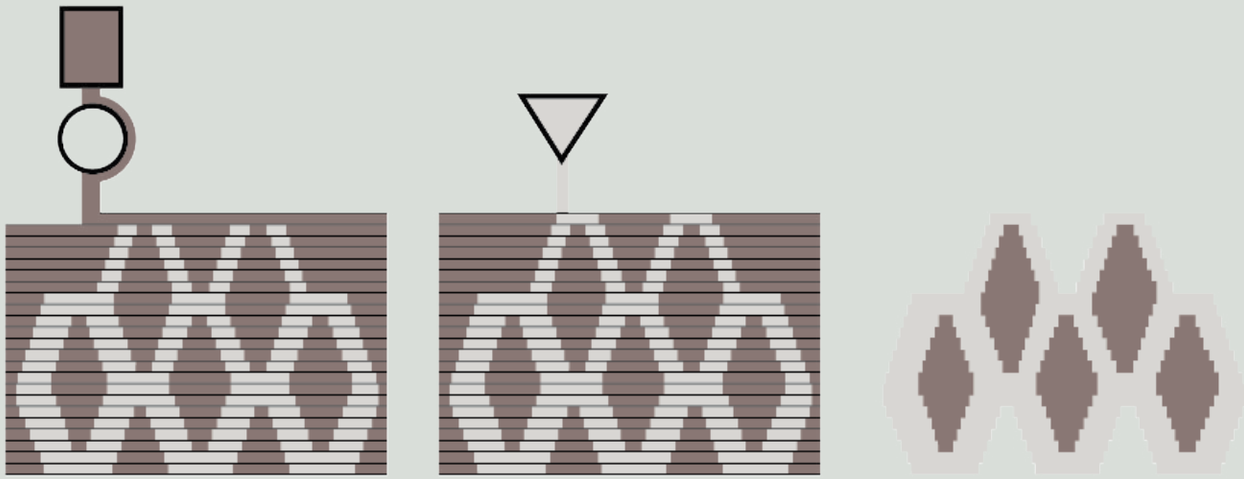
Global topology and selected segment for demonstrator

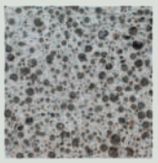
The global design of the prefabricated blocks adheres to a strategy illustrated in the following conceptual scheme. The first step involves establishing a building outline that can be modified and segmented. Following is an initial segmentation, which separates the building into blocks, in accordance with the size constraints of the SPI printer. Subsequently, the blocks are modified to ensure optimal transfer of compression forces, with a further adjustment to account for assembly sequence, resulting in slanting rather than straight blocks. Lastly, the blocks are modified to interlock topologically.

The demonstrator was selected as a cut-out of a larger designed structure, showing a section of the outer wall in 1:1 scale, while exposing the main conceptual features of the project. This includes the prefabrication and assembly of large-scale blocks, with interlocking joints and a graded internal network of the bound and unbound aggregate. In order to realise a section of the global design in the form of a 1:1 demonstrator, it was necessary to develop the selected building components, their internal structure, and joints system in a level of detail surpassing the scope of the original design studio. Moreover, a deeper understanding of the fabrication method and the resulting constraints and tolerances was crucial for the modelling and simulation of the final object and its properties.

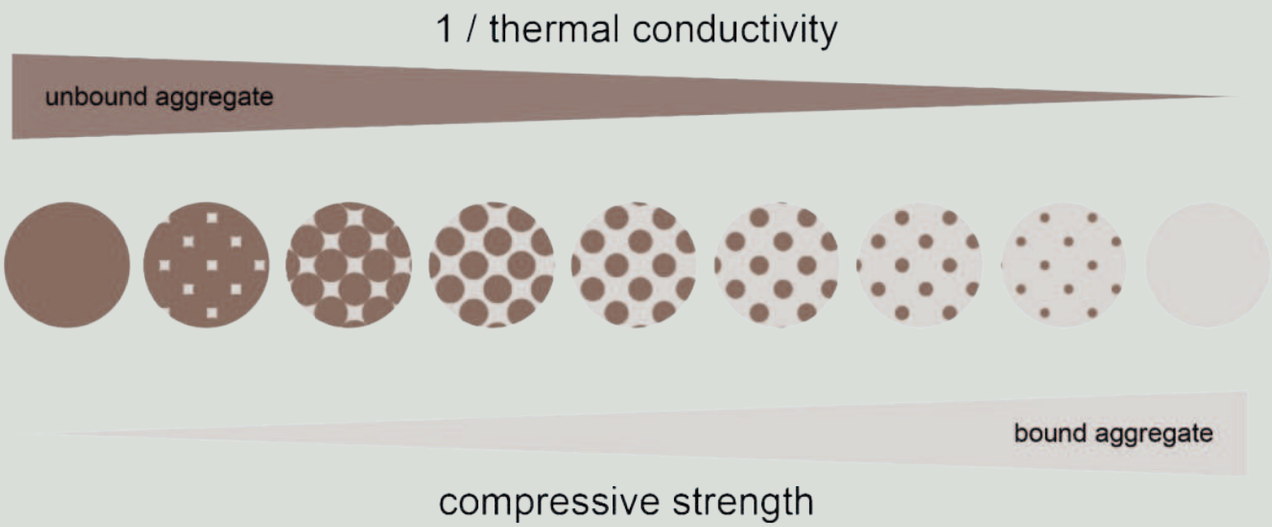
Figure 2 / Left side / Development of the design from the wall

Figure 3 / Left side / Selected wall section for the demonstrator





	Bound LECA (0-2mm, cement binder)	Unbound LECA (0-2mm)	Infraleichtbeton 1-2mm, 2-4mm (Blähglasgranulat) 2-6mm (Blähton)
Density [kg/m3]	1250	700	725
Thermal conductivity [W/mK]	0,5732	0,1233	0,185
Compressive strength [MPa]	27,2	---------	8



METHOD

Selective Paste Intrusion (SPI) using lightweight aggregates

The SPI method consists of two multiple repeated steps, the deposition of a layer of aggregates in a particle bed followed by the selective binding with penetrating cement paste. The surrounding unbound aggregates thereby act as support structure for the built concrete element. This allows to produce complex and free-form geometries without the need for a conventional formwork. The structure is then cured in the particle bed and can subsequently be excavated. This design project employs the method while expanding its intended application. By using a light-weight aggregate, unbound material can become part of the printed architectural building components. Trapped within the bound structure and its cavities, the lightweight aggregates can provide thermal insulation, while the bound areas provide the loadbearing function.

This principle has been inspired by the Einfach Bauen research, which seeks to reduce the complexity of building through the use of monomaterial structures that possess specific properties to provide adequate compressive strength and thermal insulation. In particular, a case study building composed of light-weight concrete (Infraleichtbeton), which featured load-bearing walls of 625 mm thickness served as a reference for this design proposal (Jarmer et al. 2021).

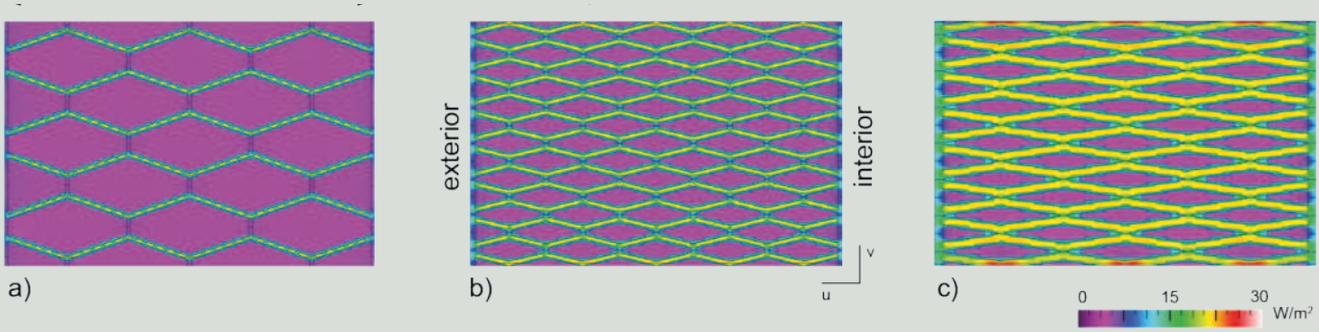
In Figure 5, the physical properties of the fully bound LECA aggregate (expanded clay), resulting from an SPI process, the unbound. LECA aggregate in its loose state, as well as Infraleichtbeton are shown. The bound LECA contains a cement binder, making it suitable for loadbearing purposes with a measurable compressive strength. Due to the contained lightweight aggregate, the bound material has a thermal conductivity comparably lower than common concrete. The unbound LECA, enclosed within cells, is expected to not take loads, but can serve as a thermally insulating material due to its low thermal conductivity.

However, while traditional Infraleichtbeton is cast and thus exhibits uniform material properties, in light-weight aggregate SPI (such as expanded glass and expanded clay), the unlimited geometric freedom and the potential for combining both bound and unbound aggregate in one component can be utilised. This opens the possibility for functional grading and applying material only where its structurally and thermally needed. The properties of functionally graded materials vary gradually in composition and structure over volume, allowing them to be customised for specific functions and applications. The “Playing with Blocks” project entails creating this variation by adjusting the ratio of bound and unbound aggregate and its distribution within a component. Increasing the ratio of bound to unbound aggregate generally results in higher density, compressive strength, and thermal conductivity. Consequently, the grading process involves a trade-off between structural strength and thermal insulation performance, as depicted in Figure 6.

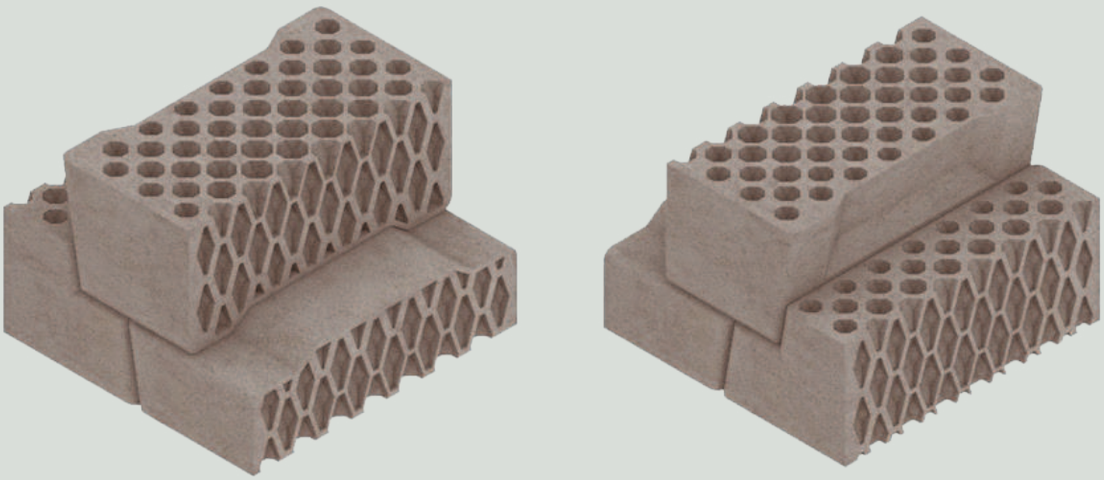
Figure 4 / Left side / SPI method utilised for the AM of closed-cell geometries, which trap lightweight aggregates inside the cells.

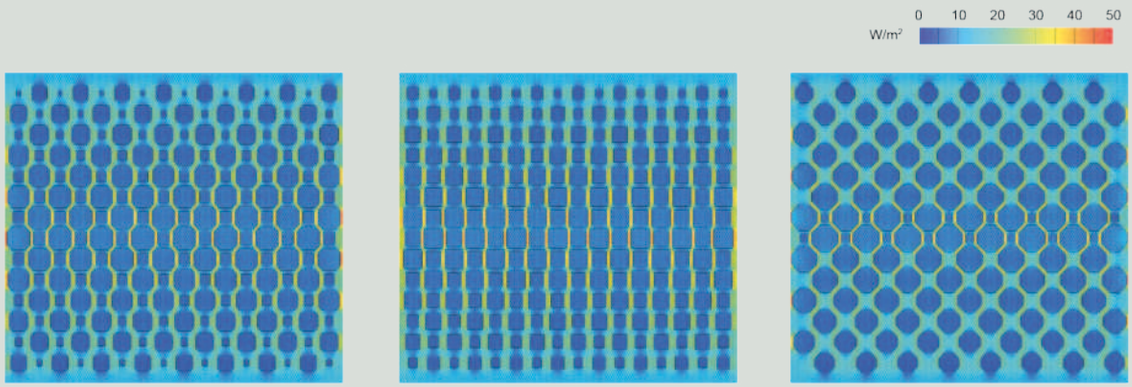
Figure 5 / Left side / Table comparing physical properties of bound and unbound lightweight aggregates with Infraleichtbeton as used in (Jarmer et al. 2021).

Figure 6 / Left side / Functional grading through th.e variation of bound vs unbound aggregate.



	a)	b)	c)
Cell count u / v	3 / 3	5 / 7	3 / 7
Cell wall thickness	6 mm	8 mm	14 mm
U-value	0.27 W/m²K	0.40 W/m²K	0.53 W/m²K
Cell area	87.5 %	67.4 %	47.1 %





METHOD

Parameter Studies

To evaluate how the negotiation between the amount of bound and unbound aggregates affects thermal insulation performance, 2D heat flux simulations were conducted (Briels et al. 2023). Using generatively designed geometries, an algorithm is slicing the geometries horizontally, meshing it and automatically transferring it to a Finite Element Method (FEM) heat transfer simulation engine (LBNL THERM). By that, the heat transfer through a horizontal section is calculated, the heat flux can be visualised, and the u-value can be determined.

With this approach, a parametric study was conducted for a hexagonal pattern, varying the size and shape of the hexagonal cells corresponding with a "cell count" in u-direction and v-direction for wall elements with a total wall thickness of 600 mm. Additionally the cell wall thickness of the bound material was varied from 6 to 14 mm. Overall the thermal insulation performance ranges from 0.27 W/m²K to 0.53 W/m²K, demonstrating the potential of SPI wall elements with lightweight aggregates complying with the German legal minimum requirements for insulation performance of 0.28 W/m²K (acc. GEG §19 annex 3) (Briels et al. 2023).

Modelling and fabrication method

To depict the concept of the enclosed unbound aggregate, a 3D cellular pattern was designed, based on a framework of spatially tessellating truncated octahedrons. Deriving from a repetitive grid, variations in individual cell sizes allow a graded distribution of material based on thermal and structural requirements. The minimum thickness of the bound aggregate given by the fabrication constraints of 5 mm is considered. While the basic cell dimensions were informed by the parameter studies evaluating the insulating capacities, the grading demonstrated in the object did not follow any specific structural simulation but rather serves as an initial proof of concept. To determine the thermal performance of the graded 3D pattern in the demonstrator, various 2D sections were analysed using thermal simulations. The resulting U-values ranges from 0.40 W/m2K to 0.43 W/m2K for the designed cell count and size grading (Figure 10).

The SPI printer of the A02 project selected for the printing of the collaborative demonstrator, situated in Achering, allows for the AM of elements with maximum dimensions of 600 × 300 × 250mm, taken as restriction for the size of the elements chosen for printing (Figure 8).

Figure 8 / Left side / Thermal simulation samples

Figure 9 / Left side / Assembled blocks

Figure 10 / Left side / Layerwise heat flux simulations of the graded 3D cellular pattern

Figure 12 / Selective Paste Intrusion process

RESULT

Initially, the cement paste was prepared, consisting of water, cement, and a fluidizing agent. Upon preparation, the cement paste underwent a quality control check, including a mini-slump flow test and a funnel flow time measurement according to DIN EN ISO 2431. In both tests, the cement paste met the quality standards and was deemed suitable for the fabrication of the demonstrator.

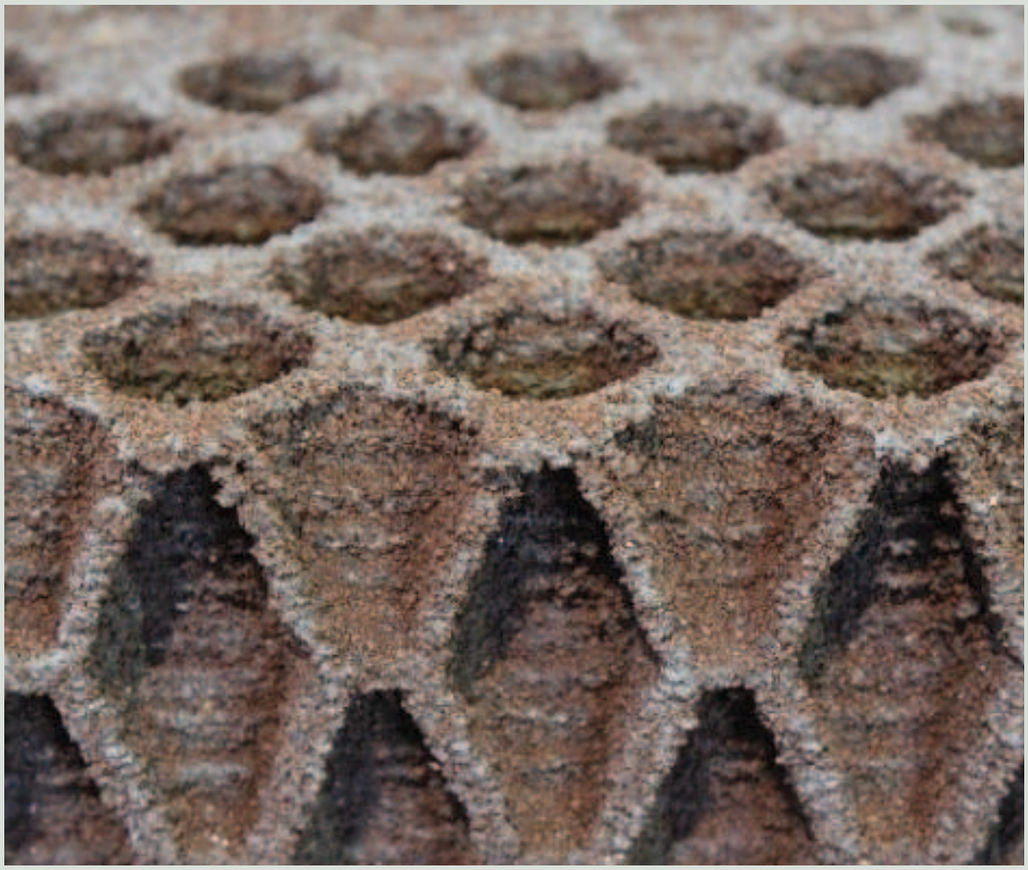
Simultaneously, the SPI printer was prepared. Settings such as printing speed (movement in the x-direction at 220 mm/s), spreading roller speed (300 RPM), and spreading speed (100 mm/s) were adjusted. The spreading roller setting is particularly crucial for distributing a sufficient amount of expanded clay to form a 3 mm layer.

The CAD file was loaded into the SPI-specific software and sliced. After conducting a functional check of the printer (verifying that all nozzles opened and the pump operated correctly), the cement paste was filled into the SPI printer, and the printing process began. The printing environment was maintained at 21°C with 55% relative humidity, which had no noticeable impact on the print quality.

The printing process for all three demonstrator components proceeded smoothly. With the selected settings, the printing speed was approximately one minute per layer (depositing the aggregate, leveling the layer, and printing the layer with cement paste). For components with a height of 250 mm (83 layers), the pure printing process took nearly 90 minutes. For the demonstrator with 180 mm height, the printing time alone was approx. 60 minutes. Additional time was spent on preparations (cement paste production, quality control, SPI settings, and functional check), pauses during printing for material refilling, and cleaning the equipment afterward. As a result, the entire printing process for each component took about three hours. The components were allowed to cure for approximately 16 hours overnight.

The day after fabrication, the component was excavated from the particle bed and lifted out. Subsequently, excess expanded clay particles were vacuumed off with a vacuum cleaner.

Figure 13 / Left side / Final Demonstrator after assembly



TECHNICAL DATA

Construction system
Load transfer through compression

Process
Selective Paste Intrusion

Integrated functions
Form-optimised cell structures for high thermal insulation

Material
Concrete with expanded clay as aggregate

Density
1030 kg/m³ (40% unbound with 700 kg/m³; 60% bound with 1250 kg/m³)

Length x Height x Width
0,60 m x 0,41 m x 0,57 m

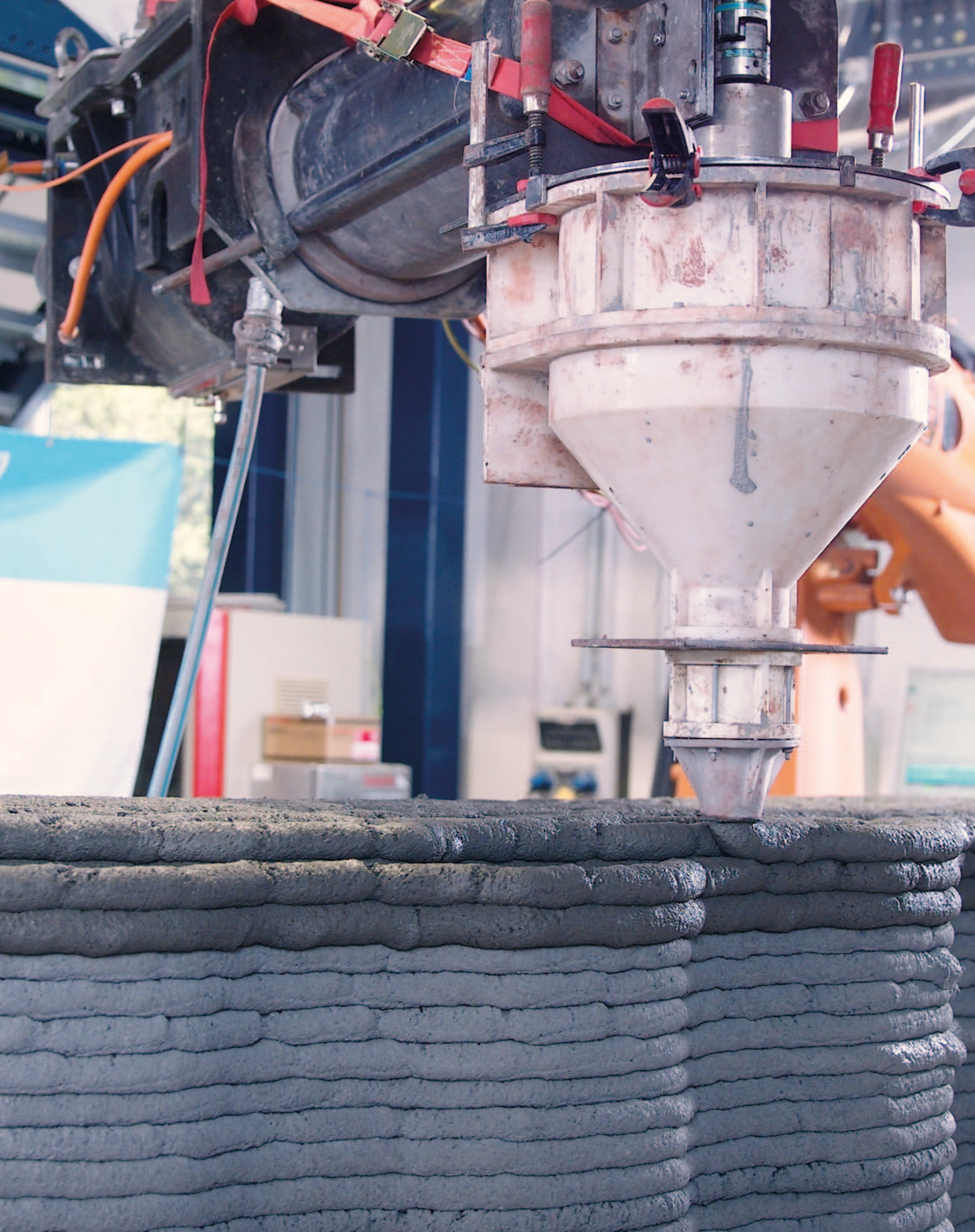
Volume
0,103 m³

Weight
107 kg

Manufacturing time
4 hours pure printing time per component, 12 hours including preparation and cleaning time

Figure 14 / Left side / Detail of the final demonstrator

References
D. Briels, M. Renz, A. Nouman, and T. Auer, Parametric heat flux simulations for the insulation concept of the AM facade demonstrator „Building with Blocks“, Munich: TUM, 2023. [Dataset]. Available: https://doi.org/10.14459/2023mp1716506. [Accessed: July 24, 2023].
Straβer, A.; Matthäus, Carla; Weger, D.; Kränkel, T.; Gehlen, C.: (2022) “Selective Paste Intrusion: Stability of Cement Paste Mixtures Towards Changing Ambient Temperature.” In: Third RILEM International Conference 296–301
Weger, D.; Gehlen, C. “Particle-Bed Binding by Selective Paste Intrusion—Strength and Durability of Printed Fine-Grain Concrete Members.” Materials 2021, 14, 586. https://doi.org/10.3390/ma14030586
Jarmer, T.; Niemann, A.; Franke, L.; Varga, Z.; Diewald, F.; Nagler, F.; Auer, T.: (2021) “Einfach Bauen 2 – Planen, Bauen, Messen.“ https://doi.org/10.14459/2021md1617984



EXTRUSION OF NEAR-NOZZLE MIXED CONCRETE

Extrusion of Near-Nozzle Mixed Concrete –Individually Graded in Density and in Rate of 3D Fibre Reinforcement. The gradation of material properties in concrete extrusion allows more efficient use of resources and multifunctional design of components, but represents a particular challenge in pump-based extrusion systems. Therefore, an innovative near-nozzle mixing system, called gradation ready extruding system (GRES), is being developed in A03 which enables immediate gradation of the material properties. This allows to locally extrude different materials ranging from normal to lightweight concrete. Furthermore, the short conveying distances for the fresh concrete facilitate the extrusion of e.g. more sustainable materials that cannot be processed in previous extrusion systems due to impeded workability compared to normal 3D printing materials. The combination of multi-material printing with an automated vertical rebar insertion strives for high performance as well as a precise adjustment of material properties to the local needs and thus for a more sustainable material use.

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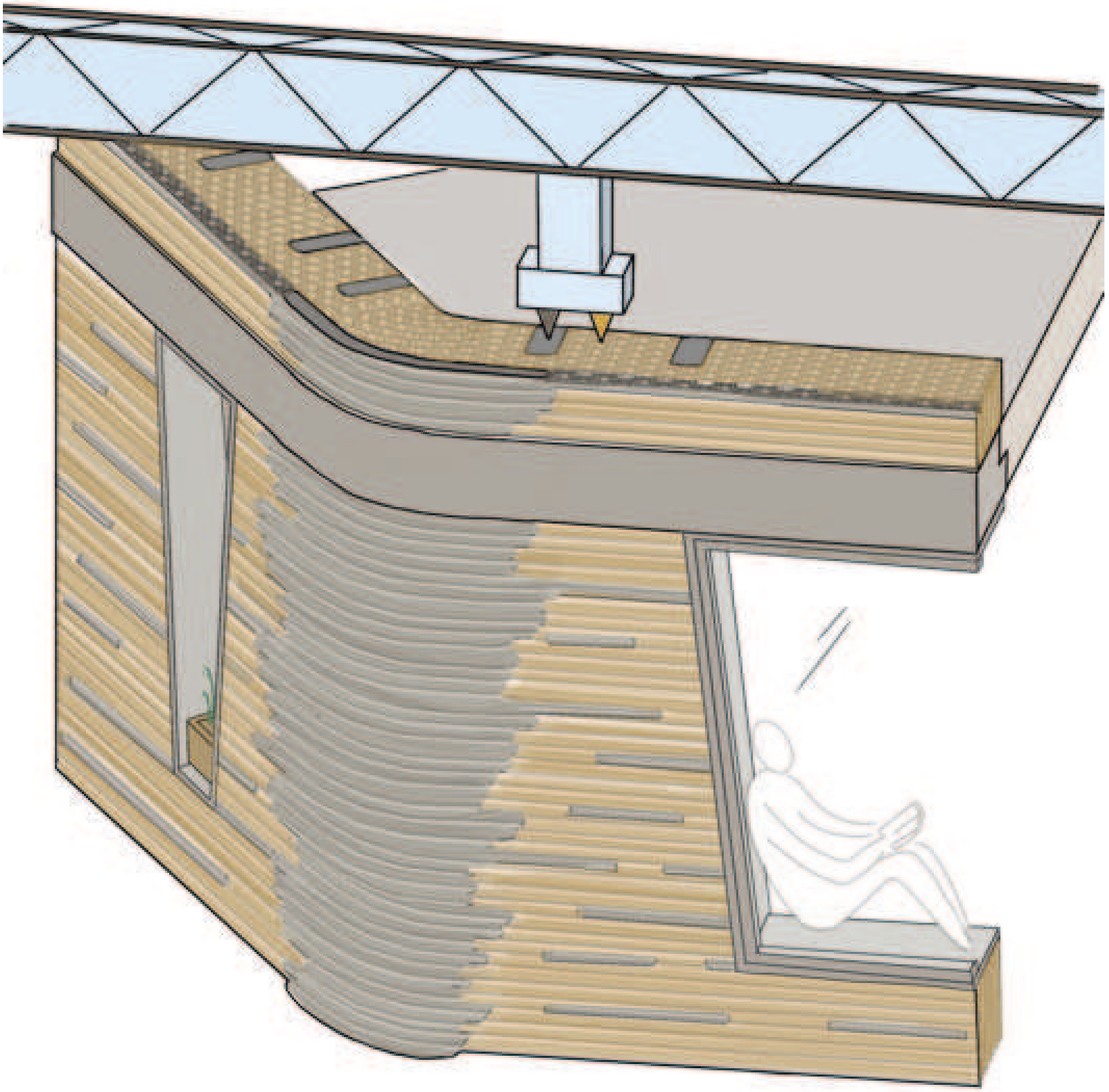
AMC TRR 277 Project

A03

Associated Design Projects

Marriage of two Materials



MARRIAGE OF TWO MATERIALS

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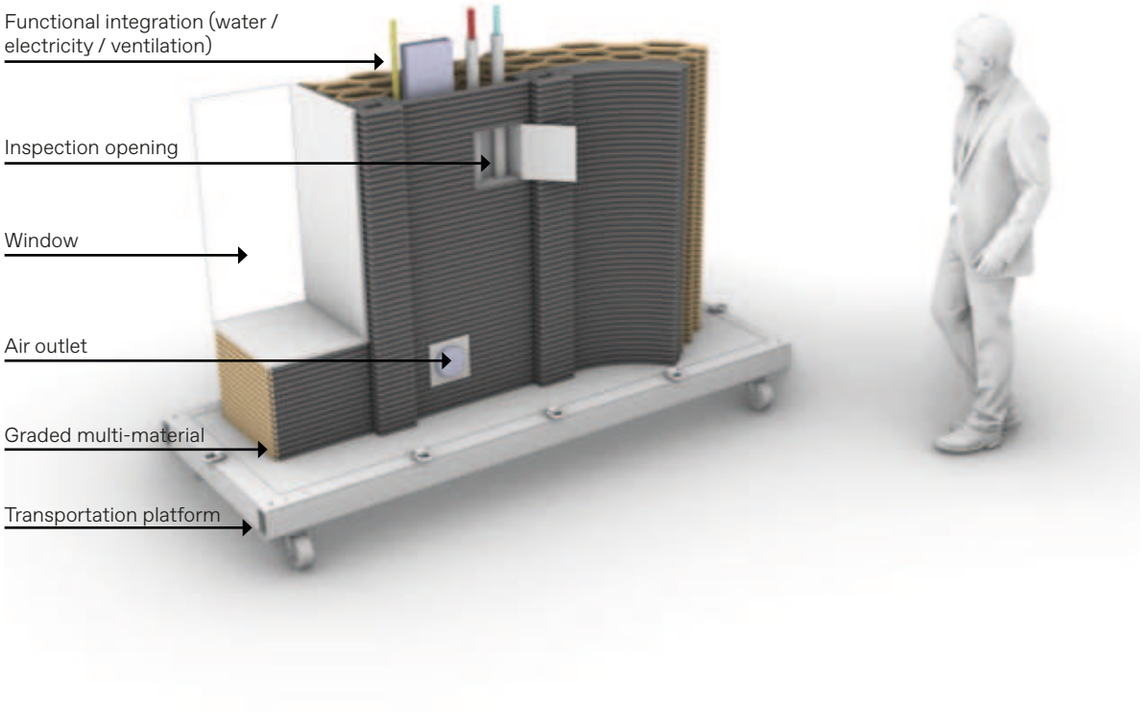
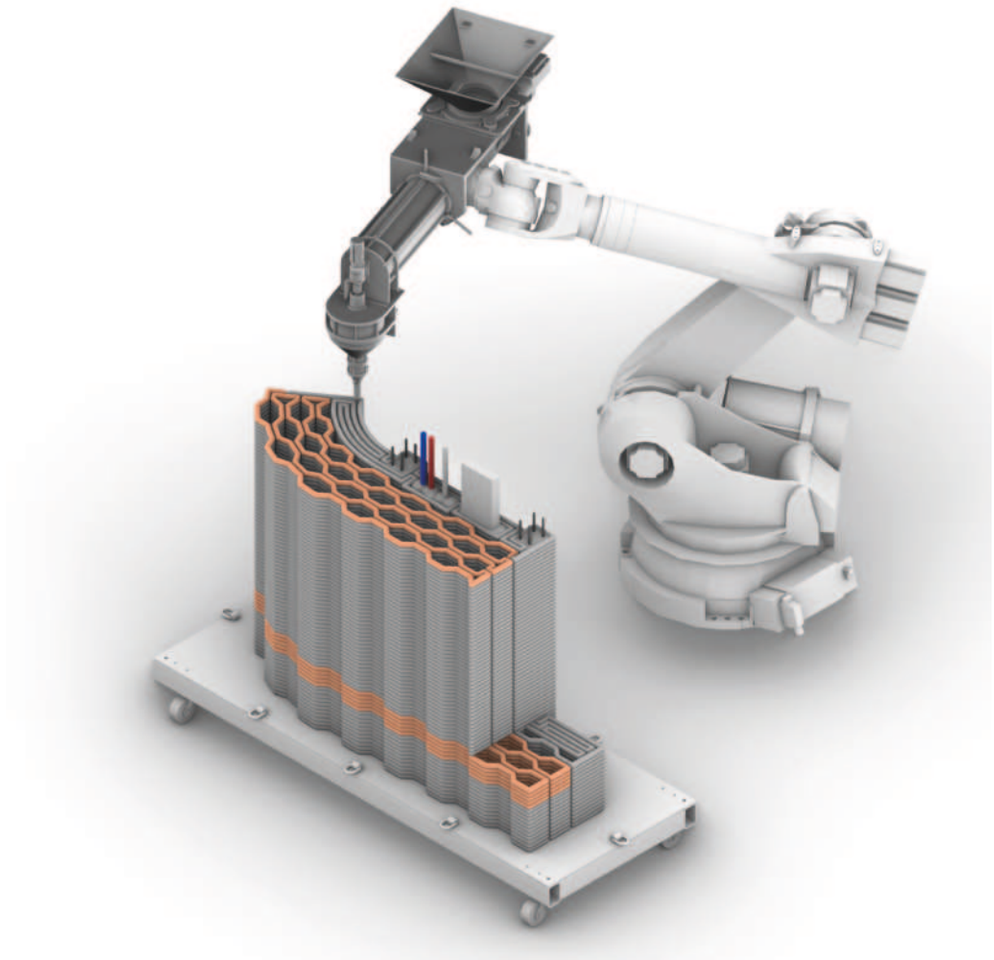
Scientific Supervision
Prof. Dr.-Ing. Johannes Fottner
Prof. Dr.-Ing. Christoph Gehlen

Figure 1 / Left side / Schematic 3D visualisation of a corner with Dual-Nozzle printing System


Functional integration (water / electricity / ventilation)
Inspection opening
Window
Air outlet
Graded multi-material
Transportation platform



INTRODUCTION

Design proposal

The project aims at a simple construction using a dual-nozzle 3D concrete printer extruding earth and concrete. By capitalising on the benefits of each material, the limitations of one material can be compensated by the other. Through the simultaneous printing process of both materials, each layer supports the other and allows for greater geometric freedom. The on-site production of all vertical elements is supplemented with prefabricated horizontal elements. The concrete in the columns is a load-bearing system designed for self-stiffening due to their slight inclination to minimise the required reinforcement. Furthermore, it also provides erosion protection for the earth. The earth meets the building physics requirements and offers the possibility of component activation. The walls are printed with an internal hexagonal structure, creating a thermal insulation effect and reducing material consumption. The building is intended to stay functional without further surface treatments, saving labour time and costs and creating a southern facade.

Demonstrator Selection

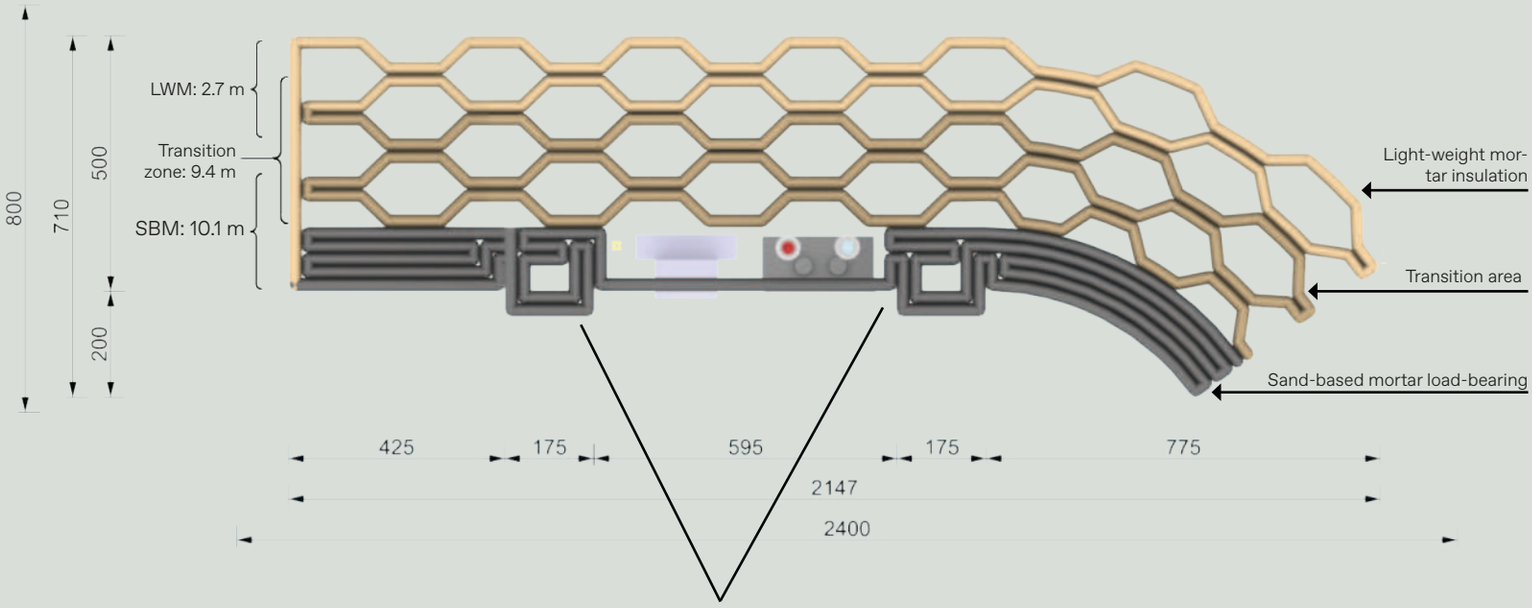
As already demonstrated in the historical example, the design in Braunschweig also shows that when building with two different materials, such as stone and earth, the building corners require special attention. In the case of the design proposal, at this part of the building, facades from two directions come together, which makes the geometry of the wall and the load-bearing structure more complex. Furthermore, due to the cut-out size, two floors are represented, which show the connection point of the vertical components printed on site and the prefabricated horizontal components of the building. In addition, small and large window openings, have the window positioned inside and outside. Other unique features of the design, are printed erosion barriers into the earth, a cellular structure and thermal mass. Thus the corner section was selected as the demonstrator model giving an overview of Design and Technology (Figure 1).

Modifications

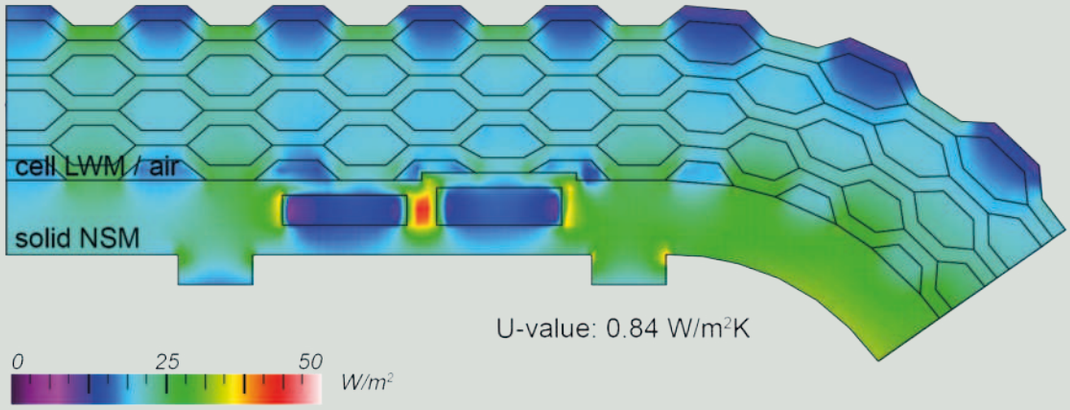
Adjustments in geometry, length, width, and height had to be made due to changing the process from the dual-nozzle approach to the promising Near-Nozzle-Mixing Method, enabling full material control, for example, switching from lightweight mortar to natural sand-based mortar. Several test geometries showed possible improvements in the Demonstrator's Design. The transition area's length and a simplified path planning with a continuous printing path have been selected. To avoid overhangs, columns are designed to be vertically reinforced with steel rebars for transport safety and structural strength. In addition, the external erosion barriers and corner reinforcements are not embedded. A larger nozzle diameter reduces cell quantity due to wider material strains and increases the demonstrator's overall load-bearing capacities. MEP / HVAC components were directly incorporated into the design and path planning, namely a ventilation duct including a ventilation outlet and water piping including a flush-mounted casing for water meters with an inspection flap. Due to space and transportation constraints, the overall dimensions of the demonstrator have been scaled down to the size of two Euro pallets.

Figure 2 / Left side / overview over the final demonstrator

Figure 3 / Right side / Rendering of GRES V1.3 printing "Marriage of Materials" Demonstrator, Credit: cbm, fml TUM



Columns:
Inner structure hollow, to be filled with rebars and concrete



SBM: λ = 1.00 W/mK
Transition zone: λ = 0.61 W/mK
LWM: λ = 0.22 W/mK
U-Value: 0.92 W/m²K

METHOD

During the first funding period, a novel extrusion-based fabrication method called NNM was developed, tested, and successfully tried and tested during the printing of the large-scale demonstrator.

GRES can grade mortars by altering the aggregates from lightweight to natural sand in predefined areas or optimising the material regarding external influencing factors by adjusting machine parameters and thus the mix design. The high degree of material independence allows using easier to handle and more sustainable materials than in conventional processes. This is because Near-Nozzle-Mixing does not require a pumping process significantly reduces workability requirements. In addition, GRES allows new design approaches, efficient use of resources, and tailored product properties by choosing the optimal material for either load-bearing- or thermally optimised sections.

A simulation-based parametric design approach is pursued to raise the potential of integrating functional features into highly differentiated monolithic AM elements. Path planning is based on a specifically developed generative algorithm that parametrically creates the internal structure, consisting of an insulating hexagonal pattern, considering integrated building services and a load-bearing segment. Using this approach, the generative geometry can be used to perform parametric studies of thermal heat flow through the element to assess the thermal insulation performance of the design.

To maximize the potential of GRES, it is crucial to develop exact component models that accurately depict an object‘s geometry, encompassing precise details of manufacturing steps, processes, machinery, and material parameters. The Fabrication Information Modeling (FIM) methodology was developed in the first funding period to achieve this. FIM leverages generative algorithms to derive manufacturing information from BIM models, enabling a high level of detail and platform-independent accessibility.

Figure 4 / Left side / Material Distribution

Figure 5 / Left side / Thermal Simulation

Figure 6 / Printing process


Construction (AMC)
AMC
Additive
in Constr
C Design and Construction

RESULT

Near-Nozzle-Mixing

The Near-Nozzle-Mixing (NNM) process has emerged as a highly robust solution for handling different material mixes in the construction industry. Its ability to calibrate new materials within days enables rapid adaptation and streamlines production. For instance, incorporating an inline-mixer is crucial for achieving continuous large-scale demonstrator production, which not only eliminates multi-day printing requirements but also improves the outer surface quality of the final product.

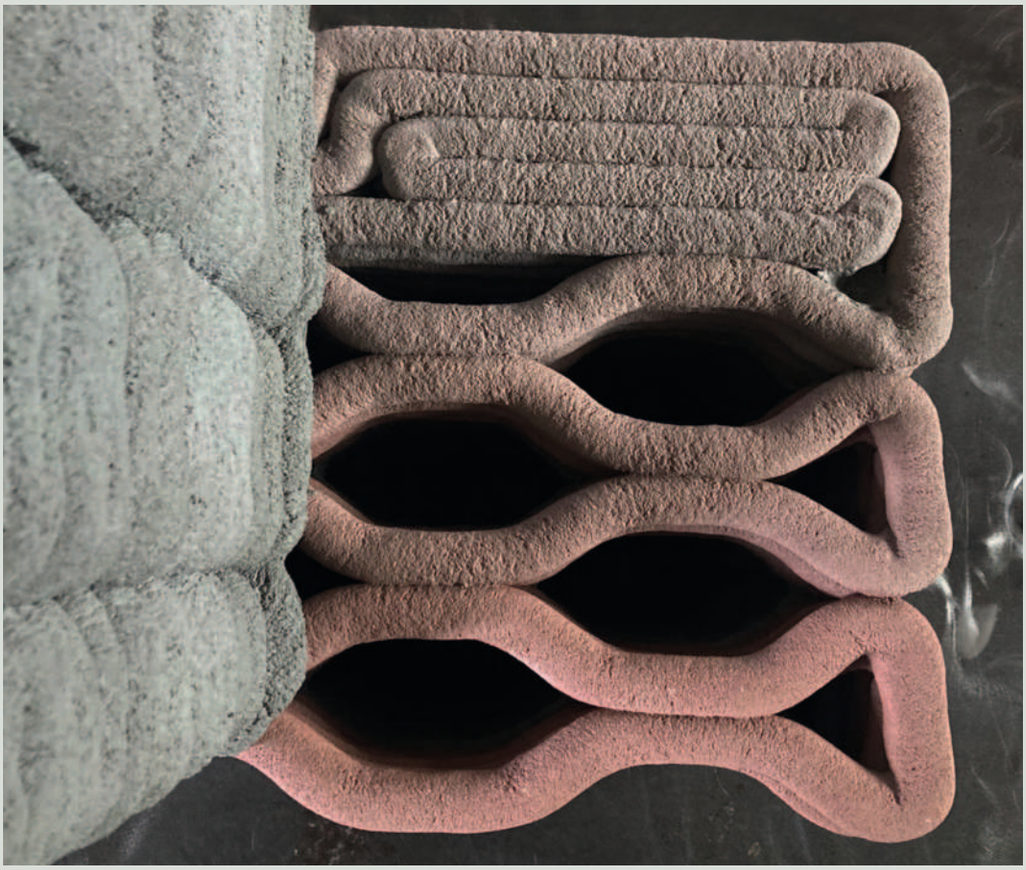
However, it is essential to recognise that variations in material properties, such as flowability and hydration state (due to aging), can significantly impact the processability of materials and, consequently, the quality of the end product. In this context, GRES has shown promising results, particularly with the design and analysis of various mortar types, including lightweight mortar (LWM), natural sand mortar (NSM), and recycled aggregate mortar (RAM). These mortars have been specifically designed for use in NNM processes within extrusion based 3D concrete printing (E3DCP), a cutting-edge approach that has successfully demonstrated its ability to handle a wide range of materials while maintaining homogeneity in material properties.

The NNM process‘s versatility and adaptability are further highlighted by its capacity to work effectively with recycled aggregates. This approach not only guarantees acceptable performance but also represents a more environmentally friendly and sustainable alternative to traditional construction techniques. As a result, the NNM process has the potential to contribute significantly to E3DCP.

Thermal performance of the printed demonstrator:

Using the final print paths, the geometry of the printed demonstrator was used to run heat flux simulations, assessing the overall thermal insulation performance of the component (Briels et al. 2023). To showcase the effect of the overall approach, using the NNM process with graded material properties (LWM and NSM), as well as the cell structure. There are three simulation variants: a solid NSM structure, a combination of solid NSM and LWM, and the realised combination of solid NSM with a cell structure consisting of LWM and air-filled cells. The U-value for the solid NSM element accounts for 2.28 W/m²K (solid NSM), whereas using LWM reduces the U-value by more than 60%, achieving 0.91 W/m²K. Adding an air-filled cell structure into the LWM insulation zone further enhances the thermal insulation effect by almost 8%, resulting in a final U-value for the printed demonstrator of 0.84 W/m2K. Even though this value is still above the German minimum legal requirement for the building envelope (0.28 W/m²K, acc. §19 Anlage 3 GEG), these results show the high potential for functionally hybridized, monolithic building elements using the NNM process with graded material properties and an insulating internal structure, combining load-bearing and insulating functions. Continuing developments in the NNM process will enable finer geometries, paving the way further to improve the thermal insulation effect of the cell structure.

Figure 7 / Left side / Demonstrator “Marriage of two Materials”



TECHNICAL DATA

Construction system
Two steel cages

Process
Extrusion-based concrete printing (E3DCP) with Near-Nozzle-Mixing Process

Integrated functions
Graded multi-material honey comb wall element, copper water pipes (hot and cold), ventilation duct , inspection opening, air outlet

Material
Natural-sand mortar, Light-weight mortar

Density
2,2 kg/dm³ (NSM), 1,18 kg/dm³ (LWM)

Length x Height x Width
2,16 m x 1,24 m x 0,70 m

Volume
707,76 m³ (actual printed material approx. 1000 m³)

Weight
1,16 tons (excl. function)

Manufacturing time
36 h (incl. preperation 72h)

Figure 8 / Top / Inlayer gradation detail from the final demonstrator

References

D. Briels, M. Renz, A. Nouman, and T. Auer, Heat flux simulations for the AM facade demonstrator „Marriage of two Materials", Munich: TUM, 2023. [Dataset]. Available: https://doi.org/10.14459/2023mp1716509. [Accessed: July 24, 2023].

INTEGRATION OF INDIVIDUALIZED PREFABRICATED FIBRE REINFORCEMENT IN ADDITIVE MANUFACTURING

Integration of Individualised Prefabricated Fibre Reinforcement in Additive Manufacturing with Concrete. 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. The aim of this project is to develop textile-based reinforcement strategies for additive manufacturing with concrete and to utilise the advantages of textile reinforcement (e.g. corrosion resistance and material flexibility) for the production of material-efficient, individualised structures.

Project Leaders

Prof. Dr. Norman Hack
Prof. Dr.-Ing. Christian Hühne

Contributors

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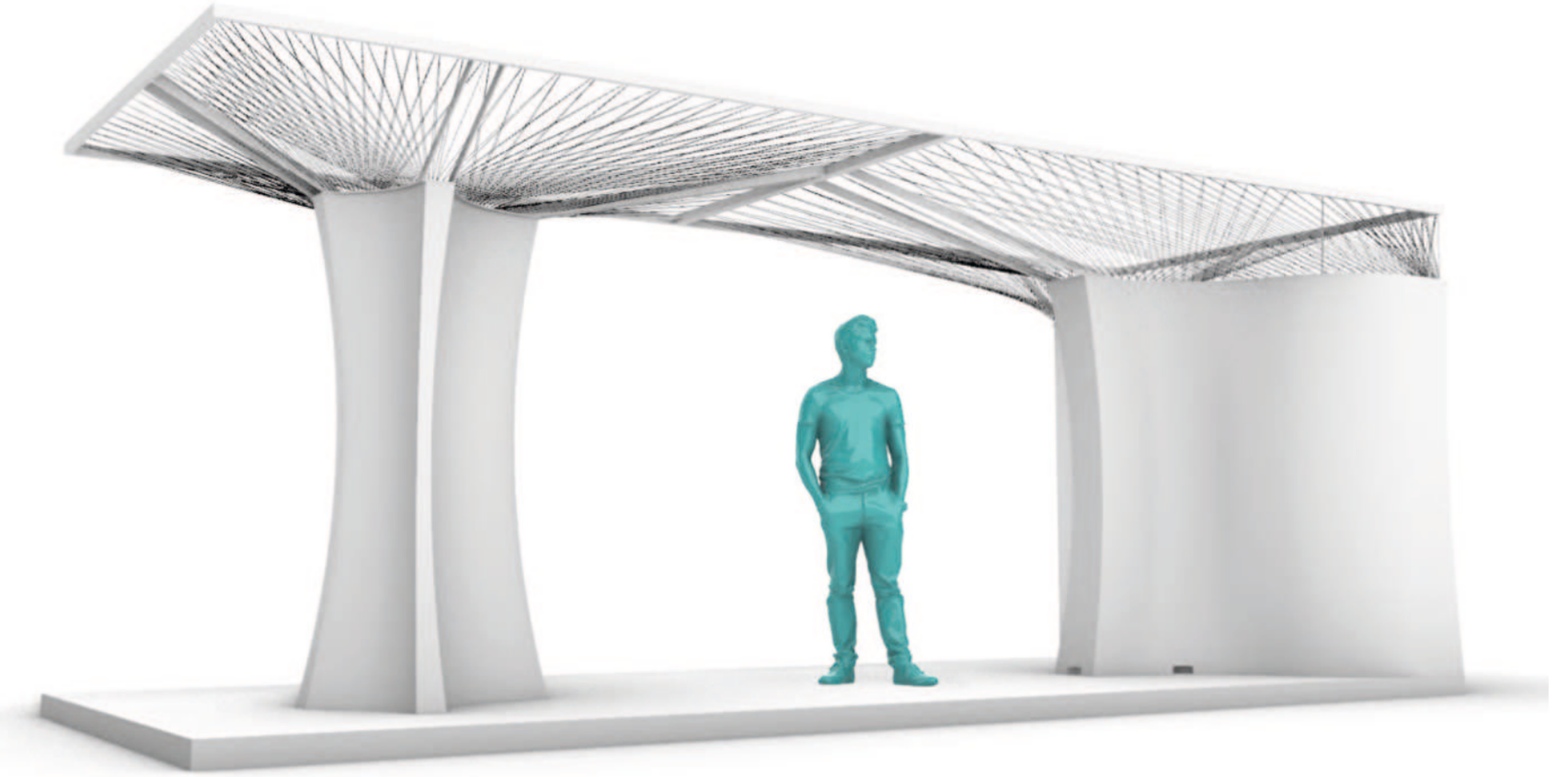
M. A. S. Noor Khader
M. Sc. Tom Rothe

AMC TRR 277 Project

A05

Associated Design Project

Shelltonics
Robotic KnitCrete



SHELLTONICS

Collaborators:

Research, Planning- and Realisation
Robin Dörrie (design lead - project lead)
Stefan Gantner (design lead - project lead)
Niklas Freund, Jennifer Rudolph (manufacturing support)
Fatemeh Amiri, Tom Rothe, Martin David (reinforcement intergration)
Lukas Lachmayer (online control)
Oguz Oztoprak (simulation)
Ahmad Nouman (functional integration)
Abtin Baghdadi (simulation, dry joints)
Gerrit Placzek, Karam Mawas, Carsten Jantzen (scan, AR)
Tobias Ludwig, Birger Buschmann, Daniel Talke (monitoring)

Architectural Design
Thilo Schlinker & Leon Kremer
AMtoARC – Course supervised by Prof. Helga Blocksdorf,
Prof. Dr. Kathrin Dörfler, Prof. Dr. Norman Hack, Prof. Florian Nagler

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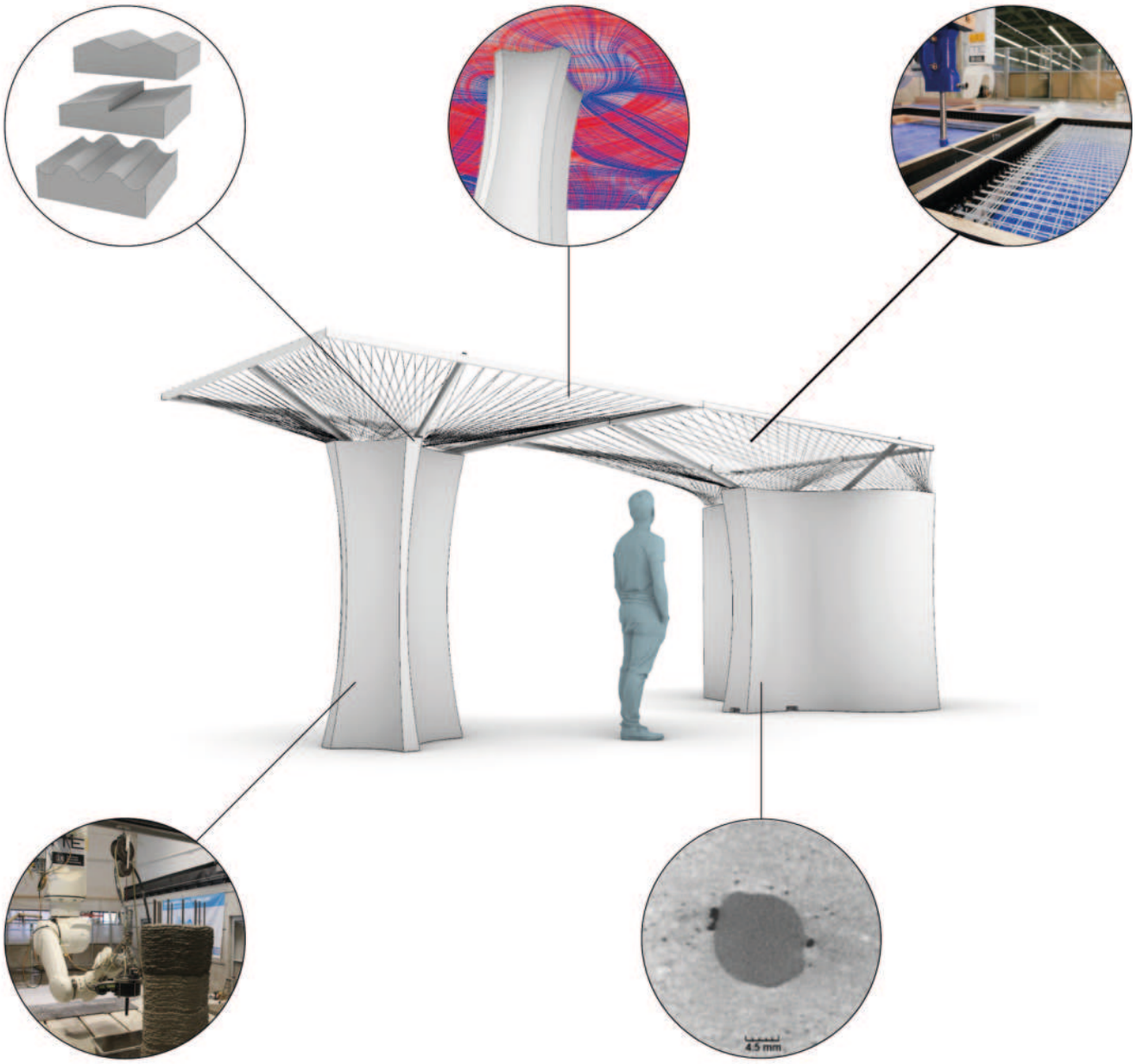
Prof. Dr. Klaus Dröder
Prof. Dr. Norman Hack
Prof. Dr. Christian Hühne
Prof. Dr.-Ing. Christoph Gehlen

Figure 1 / Left side / Perspective from the planned object


4.5 mm

INTRODUCTION

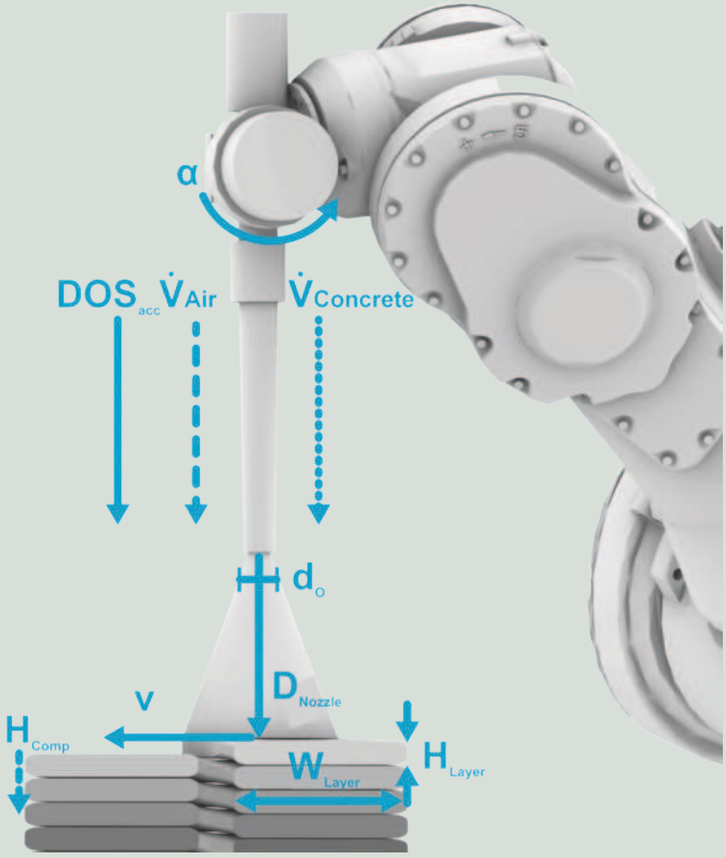
The conception of the design is based on the tectonics of a shell structure: a thin and elegant element that transfers bearing loads to the ground in a material-efficient way. Fabrication with Shotcrete 3D Printing and Fibre Winding reinforcement make it possible to achieve the demanded aesthetic quality whilst sustaining a resource-efficient production. Here, the shell is translated into vaulted ceilings and columns that are arranged within the building in a modular manner, creating flexible and possibly multi-functional spaces. Lightweight wood is used as a complementary material and can be found in separation walls as well as in the façade. The additive manufactured parts are prefabricated in a controlled environment and then assembled on site with dry joints, creating a super-light load-bearing structure that also braces itself.

This AMC Demonstrator is based on the design of the AMtoARC Shelltectonics design. The selected segment from the digital model showcases the key building components in a large cutout: the column, the wall, and the vaulted ceiling with bracing ribs. It is not, however, just a copy of the original design. the design changed over time to make the cutout stand for itself. The right form was carefully chosen based on a Grasshopper-scripted 3D model, maintaining its elegant textile character. Its elegant textile character still remains. The concrete sculpture contains various different techniques from different fields of the AMC. It represents the capabilities of the team today.

For the realisation and manufacturing of the demonstrator certain process limitations as well as specific machine limitations had to be regarded. Hence, the design was adapted accordingly. In a first step the geometry was reworked to fit the limitations of the DBFL. The wall and column path width, curve radii, overhangs and the position of integrated parts was adjusted to data from previous experimental investigations. Furthermore the print strategy was changed regarding the necessary reinforcement and build-up rate. In this case the building components were segmented into 15 cm sections to include the reinforcement automatically and subsequently after every section into the concrete structure.

Lastly, based on the new design, the reinforcement structure was optimised according to a force-flow analysis of the concrete components. This way a design loop was initiated to continuously enhance the manufacturing process of the demonstrator.

Figure 2 / Left side / Shelltonics Demonstrator: AM-Section of building construction


α
DOS acc
V̇Air
V̇Concrete
d o
D Nozzle
v
H Comp
W Layer
H Layer

METHOD

The demonstrator project involved the utilisation of cutting-edge technology and advanced software tools to achieve remarkable results. The initial design phase took place in Rhino 3D, a powerful software, complemented by the versatility of its Plug-In Grasshopper, which enabled the creation of intricate and complex geometries with ease.

In order to ensure structural integrity and analyze the force-flow within the element, Finite Element Method (FEM) software was employed. This allowed for meticulous simulations, providing valuable insights into the behavior of the structure under different loads and helping to optimize the reinforcement structure accordingly.

To effectively plan the manufacturing process, the team relied on the use of the Plug-In „Robots“, a tool that enabled precise control over the robot‘s path and the process parameters. This level of control and automation ensured the accuracy and efficiency of the printing process.

The actual manufacturing took place at the esteemed Digital Building Fabrication Laboratory (DBFL). This state-of-the-art facility is equipped with a 6-axis Stäubli Robot, enabling a wide range of motion and flexibility in the printing process. Additionally, a 5-Axis mill attached to a gantry system enhances the laboratory‘s capabilities, further expanding the potential for intricate and precise fabrication.

To complete this fully automated printing process, the DBFL incoporates an automated concrete mixing plant. This integration allowed for a seamless workflow, as the mixture could be consistently prepared and supplied to the printing system without manual intervention. The synergy between the robotic technology, the milling capabilities, and the automated concrete mixing plant resulted in a streamlined and efficient manufacturing process.

Overall, this project showcased the fusion of advanced software tools, cutting-edge robotics, and automated systems in the field of construction and fabrication. By harnessing the power of technology, the team successfully demonstrated the potential for automated and precise manufacturing processes in the creation of complex structures.

Figure 3 / Top / Robot Parameters

Figure 4 / Production process


Sykuli

RESULT

The Shelltonics project demonstrates, at a 1:1 scale, the latest advancements in additive manufacturing in construction, specifically focusing on precise material control, intricate component designs, and automated reinforcement integration. The SC3DP printing process was initially subjected to simulation in order to comprehend the material behaviour throughout the printing process. Based on these insights, the process was subsequently controlled in real-time to ensure a stable deposition of layers for the doubly curved geometries. Furthermore, automated horizontal and vertical reinforcement placement, along with robotically wound fiber 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 exposed concrete-like finishes and render the component ready for transportation. Shelltonics effectively connects three inseparable research domains-design, material, and process- and serves as a compelling showcase of the SC3DP's capabilities for manufacturing large-scale reinforced concrete components, thereby fostering a more expedient and sustainable construction industry.

Figure 5 / Left side / final Demonstrator at the DBFL

TECHNICAL DATA

Construction system
Load-bearing reinforced concrete member reinforced by automatically integrated short bar reinforcement and interlayer reinforcement and robotically wound fiber reinforcement

Process
Shotcrete 3D Printing

Integrated functions
Anchoring systems, thermal component activation, piping for installations, electrical installations

Material
MC Bauchemie - Nafufill KM 250 (maximum grain size 2mm)

Density of the material
Ca. 2,1 kg/m^3

Length x Height x Width
6,35 m x 2,40 m x 2,40 m

Volume
Wall: 1,56 m^3
Collumn: 0,55 m^3

Weight
Ca. 6 tons

Manufacturing time:
Wall: approx. 9.5 h printing time, incl. reinforcement integration, incl. surface finishing
Column: approx. 5.5 h printing time, incl. reinforcement integration

Figure 6 / Left side / Detail of the final Demonstartor

STRUCTURAL TIMBER BY INDIVIDUAL LAYER FABRICATION

In project A08 a novel fabrication process named ‘individual layer fabrication (ILF)’ is being investigated, which allows the use of wood in the additive manufacturing of structural elements. In this process the parts are built up by laminating successive layers of individually contoured panels that are additively manufactured by selective binding of wood particles. As each layer is fabricated separately, mechanical pressure can be applied in the production of these bespoke wood composite panels, leading to a significant reduction of binder content and an increase of mechanical strength.

The renewable resource wood is becoming increasingly popular as feedstock material for additive manufacturing. Reasons for this can be environmental aspects, cost reduction or the enhancement of material properties. The aim of project A08 is to facilitate additive manufacturing of wood composite parts that are, in terms of scale and material properties, suitable for an application in construction.

Project Leaders

Dr. rer. nat. Frauke Bunzel
Dr.-Ing. Klaudius Henke

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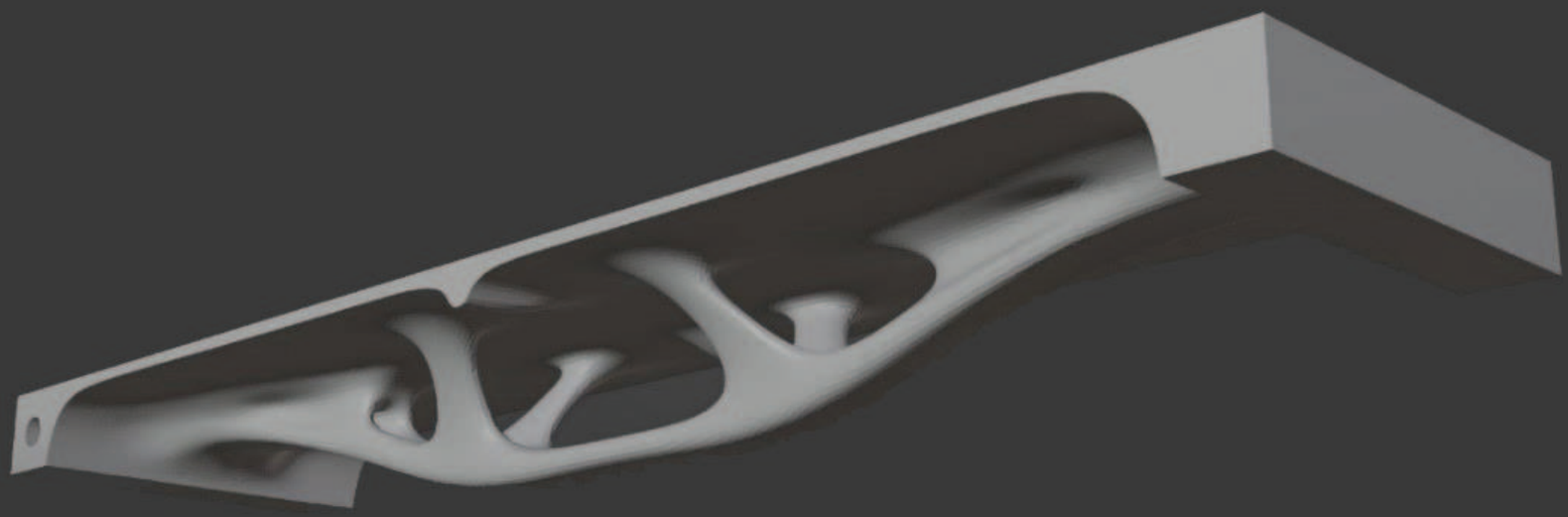
M. Sc. Birger Buschmann
M. Sc. Daniel Talke

AMC TRR 277 Project

A08

Associated Design Projects

ILF Slab



ILF SLAB

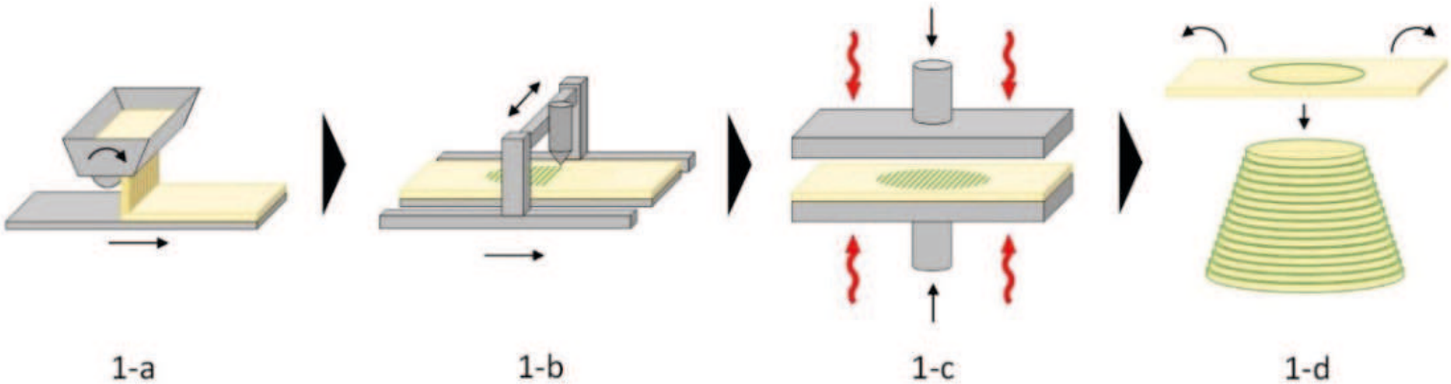
Collaborators:

Research, Planning- and Realisation
Birger Buschmann (planning and fabrication)
Dr.-Ing. Reza Najian Asl (planning and design)
Daniel Talke (planning)
Carsten Aβhoff (planning)

Architectural Design
Design is based on structural optimisation methods developed by project C02 and original idea from Klaudius Henke.

Scientific Supervision
Dr. -Ing. Klaudius Henke
Dr. rer. nat. Frauke Bunzel
Prof. Dr.-Ing. Kai-Uwe Bletzinger

Figure 1 / Left side / Final design of ILF-slab Demonstrator
(optimisation by Reza Najian Asl, C02)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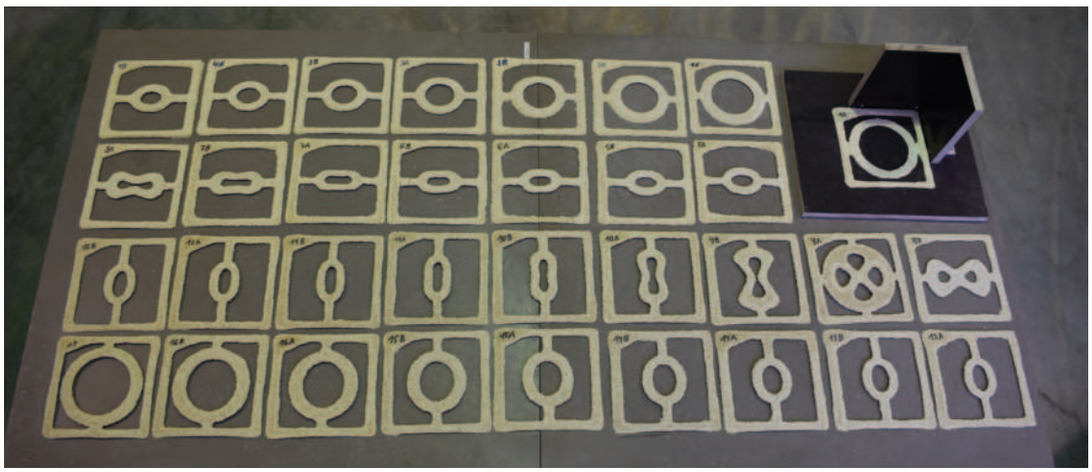
1-d



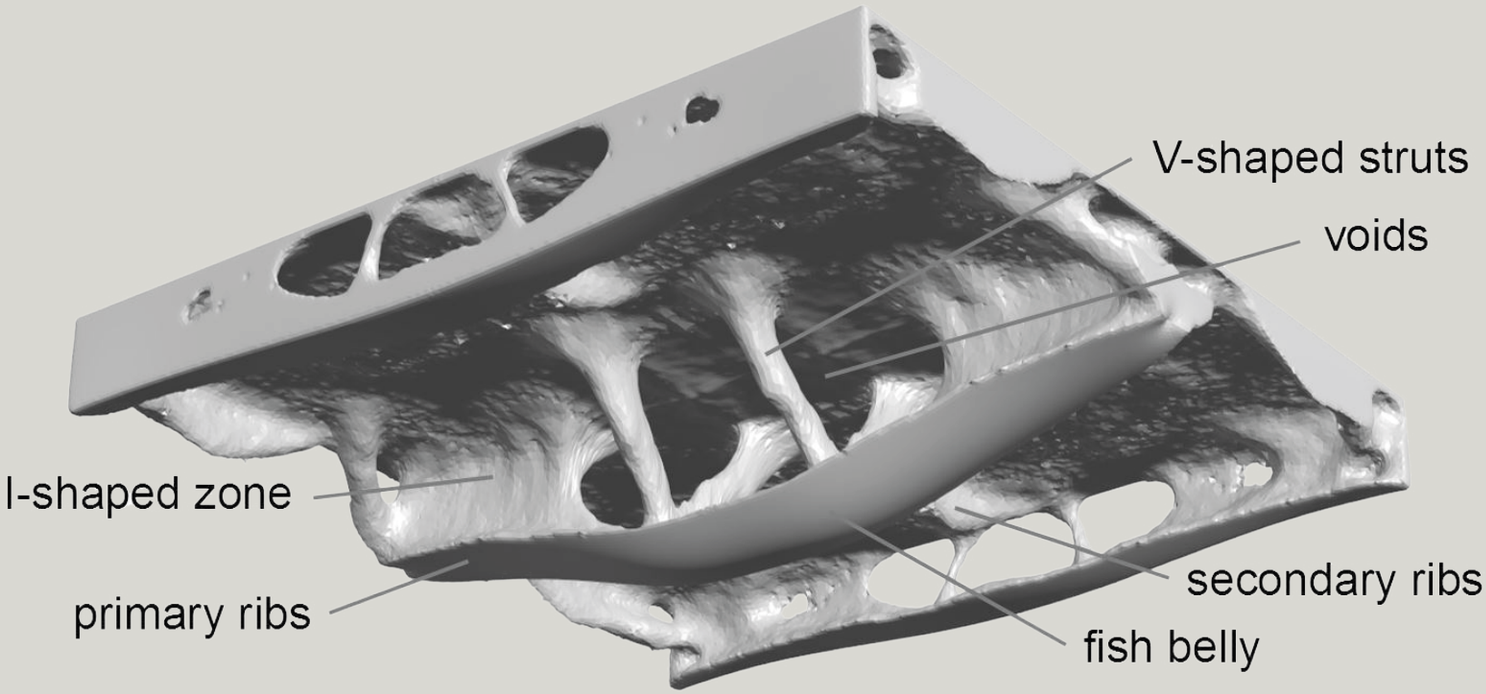
INTRODUCTION

In project A08, a novel fabrication process named ‘Individual Layer Fabrication (ILF)’ is being investigated, which allows the use of wood in the additive manufacturing of structural elements. In this process, parts are built up by laminating successive layers of individually contoured panels that are additively manufactured by selective binding of wood particles. As each layer is fabricated separately, mechanical pressure can be applied in the production of these bespoke wood composite panels, leading to a significant reduction of binder content (less than 20 wt%) and an increase in mechanical strength (up to 50 MPa).

The general principle of the ILF process is depicted in Figure 2. It can be divided into the following work steps. Wood particles are scattered on a base forming a thin layer (1-a). Adhesive is then applied onto this layer, locally limited to those areas where, according to the target geometry of the object, the particles are intended to be bound (1-b). The resulting hybrid layer is pressed under heat, curing the adhesive (1-c). Finally, the unbound material is removed, and the panel of bound particles is laminated onto the stack of previously produced panels (1-d). An object manufactured this way and the different panels employed for its fabrication are shown in Figure 3. It should be noted that the described process chain represents the ILF process in its basic version. The order of work steps may be altered, or single step sequences may be repeated several times before advancing to the next step.

Figure 2 / Left side / General principle of the ILF process

Figure 3 / Left side / Individually contoured panels of of an object (left) and the object after lamination (right)


V-shaped struts
voids
I-shaped zone
primary ribs
secondary ribs
fish belly

METHOD

To illustrate the potential of the ILF process for the fabrication of structural elements, a wooden ceiling element was designed and fabricated, reminiscent in terms of load-bearing behaviour of ribbed concrete slabs. The 'ILF-Slab' demonstrator was designed in close collaboration between projects A08 and C02.

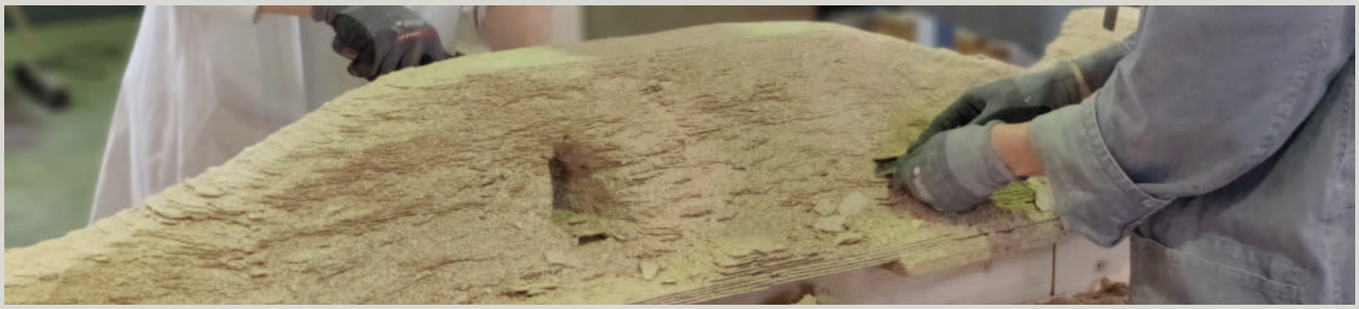
In a first iteration several optimisations were calculated for slabs with different dimensions and support situations. In this step topology optimisation was applied as well as concurrent topology and shape optimisation. The optimisation objective was mass minimization under a uniformly distributed load of 10 kN/m². It could be observed that the results of these optimsations always showed similar characteristics. The significant features of these characteristics are depicted in Figure 4. On this basis, a simplified version of the slab was modelled in consideration of the manufacturability of the demonstrator.

In a second iteration, this simplified design was again subjected to an optimisation routine, in this case solely shape optimisation (Figure 5). Finally, to showcase the possibility to integrate further functionalities into structures fabricated by ILF, internal ducts for the housing of e.g. cables and plumbing were inserted into the massive parts of the slab. On this model, shape optimisation was performed one more time.

The final design of the demonstrator to be fabricated by ILF is shown in Figure 1. The dimensions of the resulting part and further technical data are compiled at the end of this document.

Figure 4 / Left side/ Structural optimisation using concurrent (topology and shape) optimisation applied to ILF-slab (left, optimization by Reza Najian Asl, C02)

Figure 5 / Left side / Simplified redesign of ILF-slab, before (top) and after shape optimisation (bottom, optimisation by Reza Najian Asl, C02)



METHOD

By slicing the 3-dimensional digital model of the slab, 2D geometries were generated for each individual layer. As the panel size is currently limited by the size of the heat press, each layer of the demonstrator had to be composed of several panels. A panel size of 450 mm x 450 mm was chosen and the panels of each second layer were placed with an offset of 225 mm resulting in a staggered arrangement (Figure 7).

After the work steps of particle scattering and adhesive application, heat pressing was applied to the partly wetted particle layers resulting in hybrid panels, consisting of bound and unbound regions (Figure 6).

As a modification of the default process described above, for the fabrication of the ILF-slab demonstrator, the unbound particles were not removed immediately after heat pressing. They were rather retained to serve as support material during lamination. Due to the fact, that the unbound particles also gain some solidity by the pressing, the hybrid panels could each be handled easily as one solid piece. By using the 2D geometries of the individual layers to control a gantry system, adhesive was once more applied to these panels. After that they were stacked and laminated (Figure 7). Only then were the unbound particles removed to reveal the targeted physical part (Figure 8).

Figure 6 / Left side / Panels after heat pressing

Figure 7 / Left side / ILF-slab demonstrator during lamination of panels

Figure 8 / Left side / Unpacking - Rough Removal

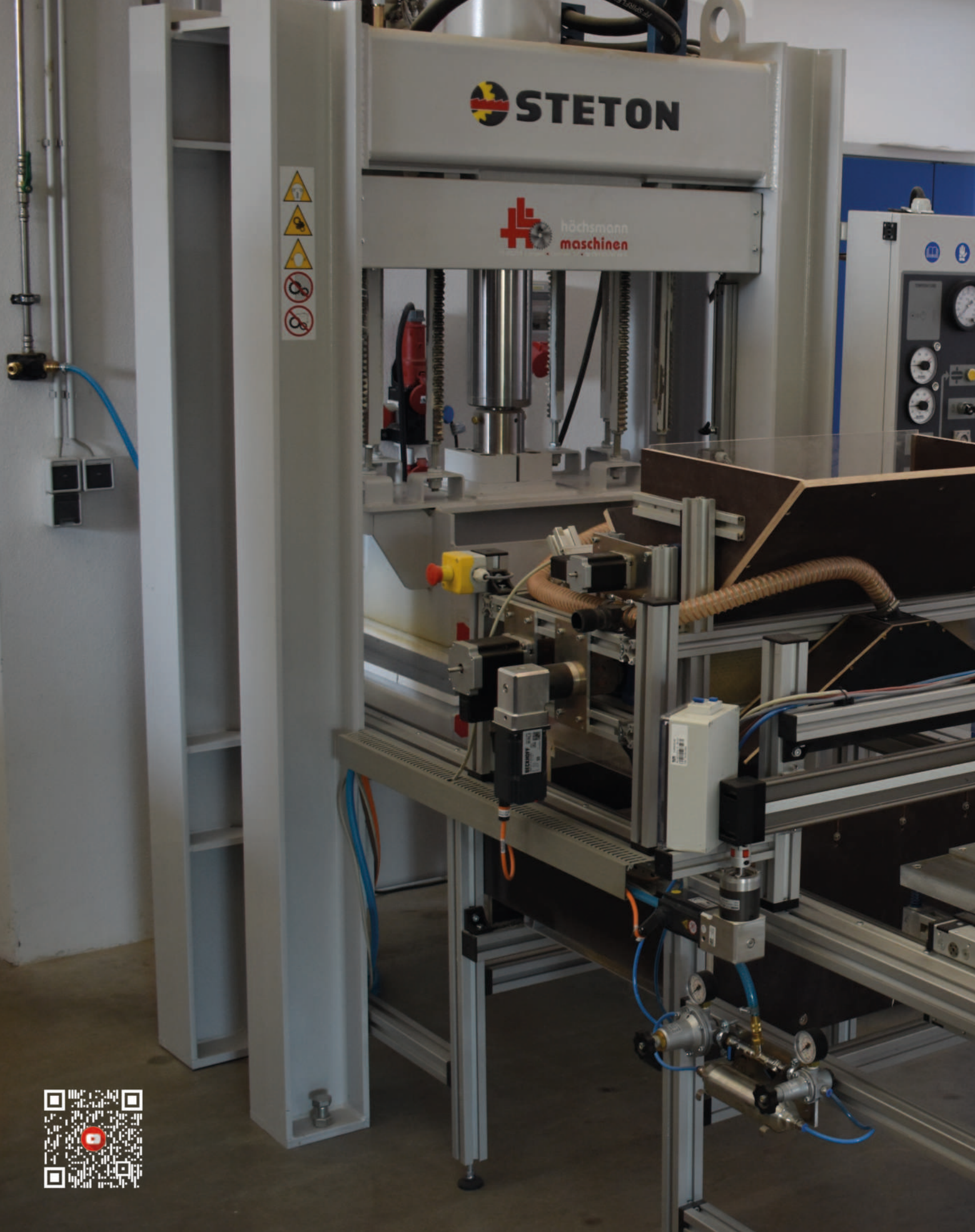

STETON
höchsmann
maschinen

Figure 9 / Printing process

RESULT

In the course of project A08 of TRR 277, the feasibility of the ILF process has already been proven by several small scale demonstrators. With the ILF-slab, it could be shown that the process can also be scaled up to full architectural scale. The concept of fabricating objects larger than the build chamber by composing each layer by a number of panels proved viable. While almost all fabrication steps of the process have already been automatised, laminating and unpacking still have to be executed by hand. Future modifications and automation of these steps will lead to a better bonding between layers and increased shape accuracy. The ILF-slab demonstrator makes apparent that for architectural applications, resolution and surface quality still have to be improved. However, it notably illustrates the potential of the ILF process to additively manufacture topology and shape optimsed structural elements with integrated functionalities from wood.

Figure 10 / Left side / ILF-slab demonstrator after removal of unbound particles

TECHNICAL DATA

Construction system
Ceiling element

Process
Individual Layer Fabrication (ILF)

Integrated functions
Internal ducts for installation

Material
wood composite (85 wt.% wood)

Density
0,9 g/cm^3

Length x Height x Width
1,90 m x 0,20 m x 0,45 m

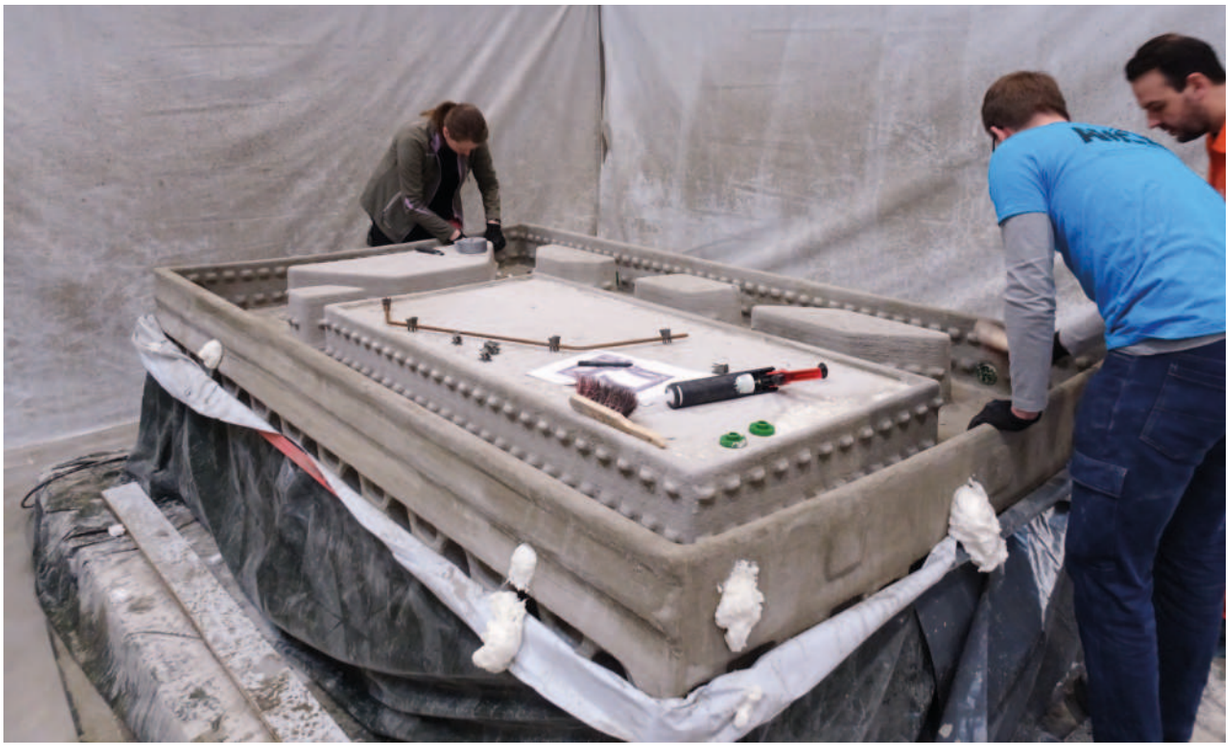
Volume
33 l

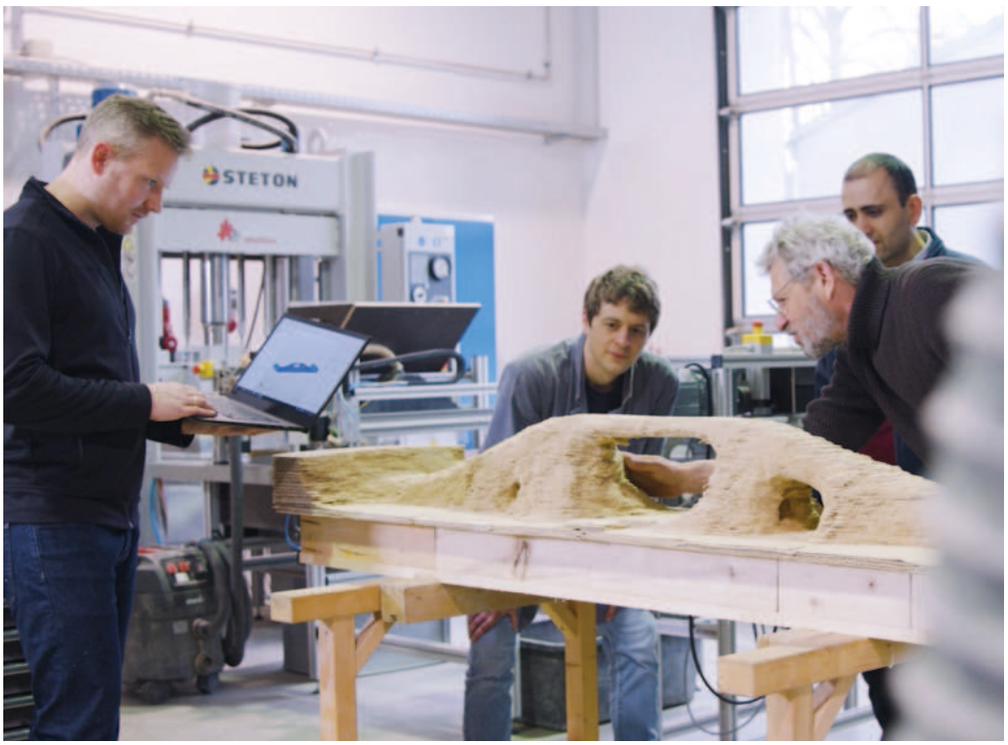
Weight
30 kg

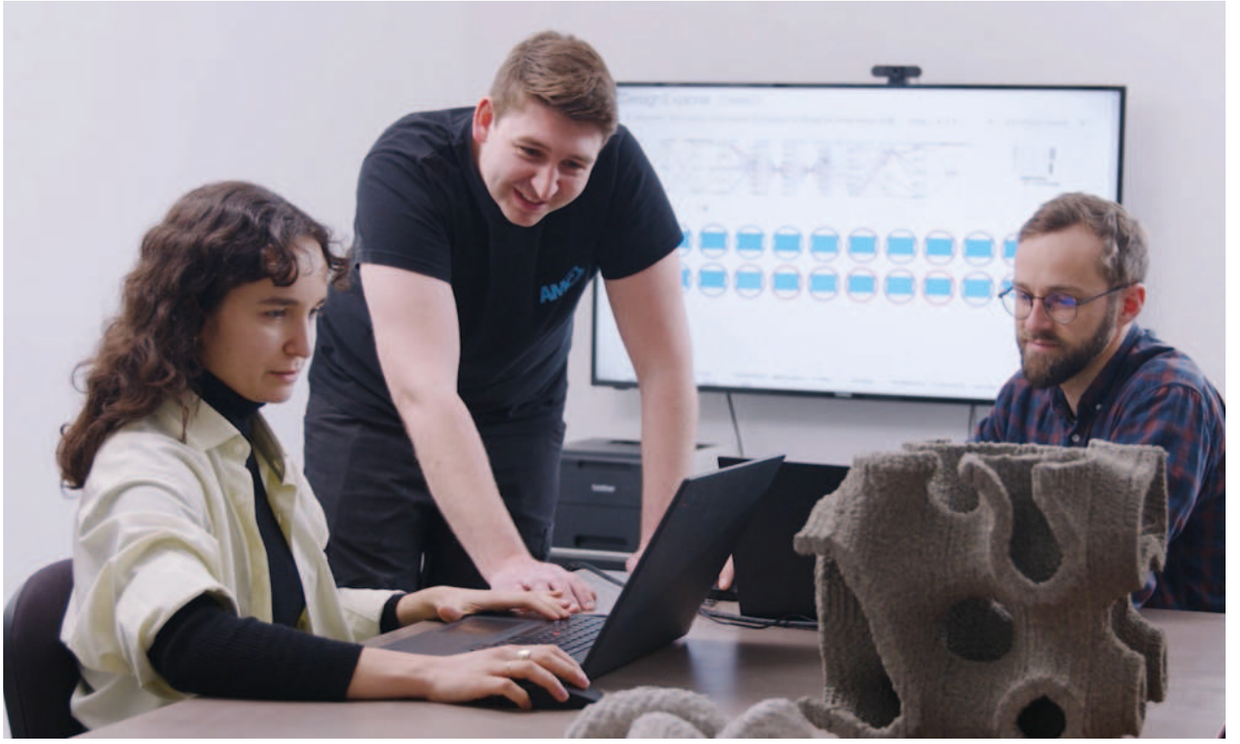
Manufacturing time
3 weeks

Figure 11 / Left side / Detail of the final Demonstrator

MAKING OF





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Additive Manufacturing in Construction
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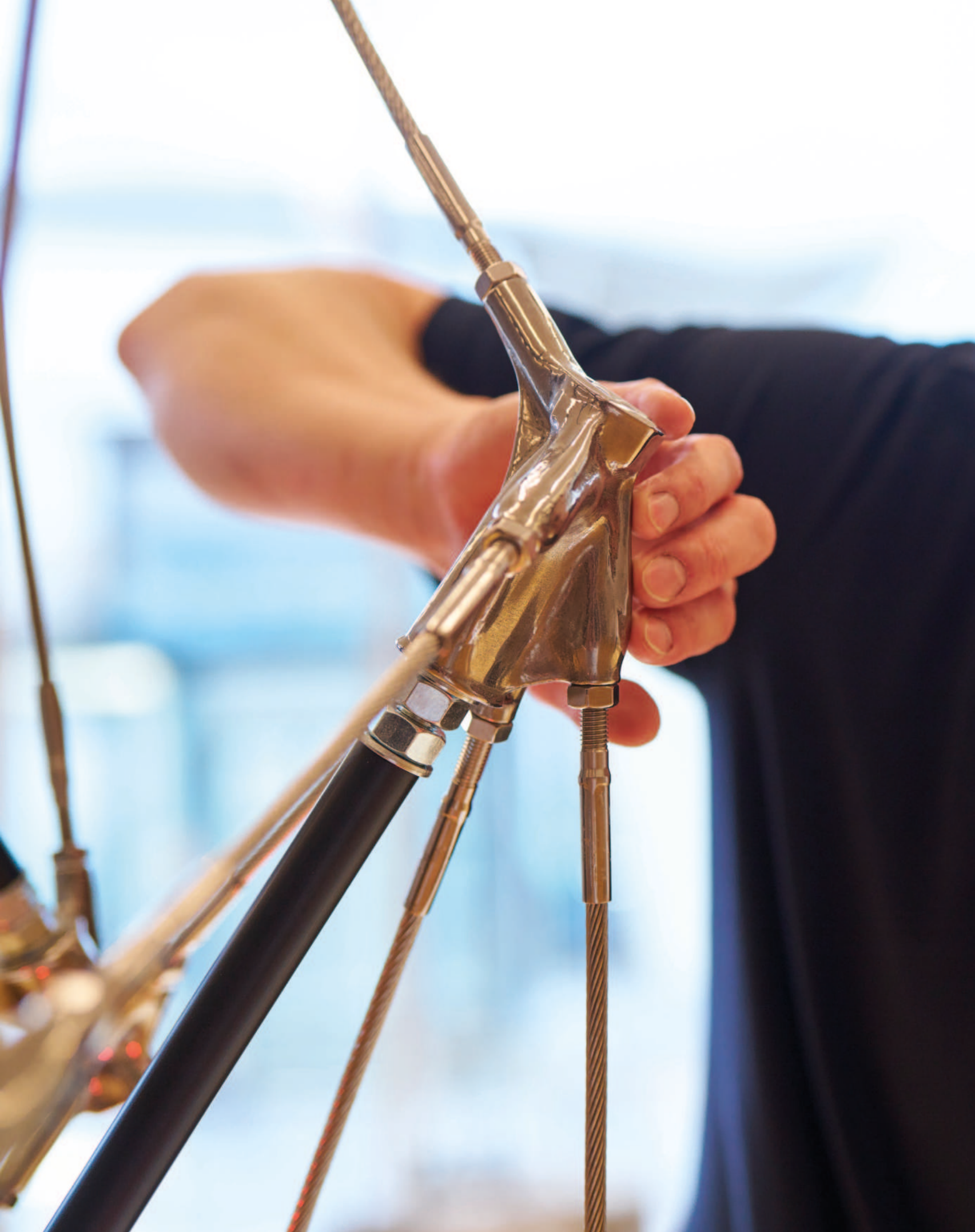
Arbeitsraum




SCIENCE CONGRESS
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BY MARRIOTT
Additive Manufacturing in Construction (AMC)
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TUM


SCIENCE CONGRESS CE
Sammel-
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COURT


Munich


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REFLECTION & FORECAST

Building is one of the fundaments of human socialisation and part of our cultural development. We have always built with the materials that are available to us through natural resources. As in society as a whole, we are also at a „turning point“ with building. In an article in the FAZ of 14.5.2023 on the occasion of the opening of this year‘s Architecture Biennale in Venice under the motto „Laboratory of the Future“, Niklas Maak writes of the „paradox of building in times of climate change“. He pointed to the fact that the building sector already consumes 50% of the world‘s natural resources and that construction is responsible for 11% of CO2 emissions, with the operation of buildings even accounting for more than 40%. The paradox is that as the world‘s population continues to grow, we must continue to build, both in building and infrastructure construction. So the question of the future is: how can we build for more people with less material and fewer emissions?

With additive manufacturing, the perfect construction technology is ready at the right time. Why? Firstly, in additive manufacturing, a component is built up layer by layer and brought into its three-dimensional form during the process: mould construction, industrial pre-processes or complex forming or adaptation processes of semi-finished products are not necessary; completely new design freedoms are created. With additive manufacturing in construction, we have the freedom to design the material application according to load-bearing, functional and/or design criteria, and thus the great opportunity to rethink material, process, structural design, construction and joining. Ingenious and architectural creativity thus once again takes on a completely new meaning. Additive manufacturing has the potential to bring about a paradigm shift in the building industry, namely to put the value of the material back in the foreground and not the human working time. 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. The sequential processes of planning and manufacturing and the unilateral goal of „as built as planned“ are being given the opportunity to be interactively controlled in the process through digitalisation. Through online control, information can be fed back into planning and thus production speeds and qualities can be increased.

The researchers of TRR 277 Additive Manufacturing in Construction (AMC) see additive manufacturing as a key digital technology to provide our 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. AMC has the potential to bring about digital manufacturing technologies that are tailored to the individual needs of construction. In addition to possible applications in building construction, AMC can also enable completely new approaches to individualised construction in infrastructure construction. In coastal protection, for example, shape-optimised structures are conceivable that do not so much oppose the attacking energies with their massive components, but can absorb these energies to a large extent through shape and material structure. In addition, shapes and surfaces can be designed in such a way that renaturation through the settlement of fauna and flora is an integral part of the design. In the area of the growing need for inner-city traffic infrastructure, digital planning methods and additive manufacturing technologies also open up completely new approaches for the three-dimensional integration of cycle paths and pedestrian routes in highly frequented and structurally complex inner-city spaces, for example. By arranging transport infrastructures at height, a new type of „elevated mobility“ can be created that takes into account the requirements of different mobility groups without consuming more space. In addition to research into new innovative technologies, the development of creativity among young people and the intergenerational assumption of responsibility for our social future is crucial for social change.

Harald Kloft

Figure 1 / Left side / FLOWall ecological and individual urban coastline structure

Figure 2 / Left side / Elevated mobility

CREDITS

Acknowledgements

Special thanks to the research associates, postdoctoral researchers and professors of the Collaborative Research Center, Additive Manufacturing in Construction, TRR 277 during the years 2022 and 2023 and to everyone who contributed to the success of this project and this book publication.

The authors would like to express their sincere gratitude for the support provided by the German Research Foundation (DFG) within the framework of the Collaborative Research Center Transregio 277 – Additive Manufacturing in Construction (AMC) – TRR 277/1 2020, project number 414265976. This funding has significantly contributed to enabling and advancing our research and work.

Book Cover Illustration

Yinan Xiao

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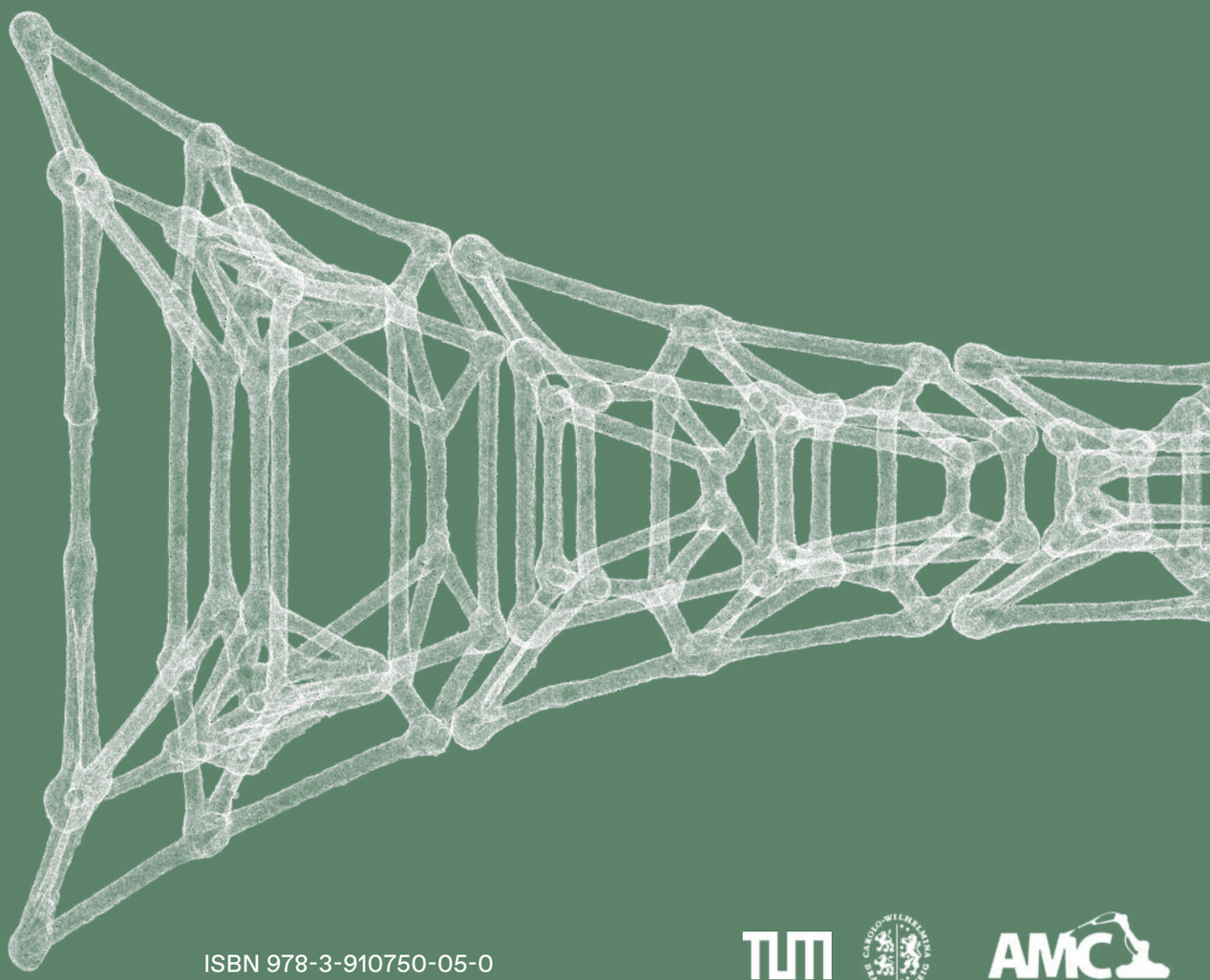

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ISBN 978-3-910750-05-0

TRR 277