Chapter Title: BREUER X AM FUNCTIONAL HYBRIDISATION IN CONCRETE BUILDING ENVELOPE ELEMENTS THROUGH ADDITIVE MANUFACTURING
Chapter Author(s): JULIA FLECKENSTEIN, BRUNO KNYCHALLA, DAVID BRIELS, ABTIN BAGHDADI, GERRIT PLACZEK, FRIEDRICH HERDING, PATRICK SCHWERDTNER, THOMAS AUER, DIRK LOWKE, HARALD KLOFT and KATHRIN DÖRFLER

Book Title: Fabricate 2024
Book Subtitle: Creating Resourceful Futures
Book Author(s): PHIL AYRES, METTE RAMSGAARD THOMSEN, BOB SHEIL and MARILENA SKAVARA
Published by: UCL Press. (2024)
Stable URL: https://www.jstor.org/stable/jj.11374766.29

BREUER X AM
FUNCTIONAL HYBRIDISATION IN CONCRETE BUILDING ENVELOPE ELEMENTS THROUGH ADDITIVE MANUFACTURING

JULIA FLECKENSTEIN[1] / BRUNO KNYCHALLA[2] / DAVID BRIELS[3] / ABTIN BAGHDADI[4] / GERRIT PLACZEK[5] / FRIEDRICH HERDING[6] / PATRICK SCHWERDTNER[5] / THOMAS AUER[3] / DIRK LOWKE[6] / HARALD KLOFT[4] / KATHRIN DÖRFLER[1]
[1] PROFESSORSHIP OF DIGITAL FABRICATION, TECHNICAL UNIVERSITY OF MUNICH, GERMANY
[2] ADDITIVE TECTONICS GMBH
[3] CHAIR OF BUILDING TECHNOLOGY AND CLIMATE RESPONSIVE DESIGN,
TECHNICAL UNIVERSITY OF MUNICH, GERMANY
[4] INSTITUTE OF STRUCTURAL DESIGN, TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG, GERMANY
[5] INSTITUTE FOR CONSTRUCTION, ENGINEERING AND MANAGEMENT,
TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG, GERMANY
[6] INSTITUTE OF BUILDING MATERIALS, TECHNISCHE UNIVERSITÄT BRAUNSCHWEIG, GERMANY

Introduction

Additive Manufacturing in Construction (AMC) provides a high degree of design freedom, capable of integrating complex functional requirements with streamlined manufacturing processes. In traditional industrial construction, adherence to standardised practices often necessitates the division of building functions across multiple layers and materials. This is done to comply with structural and functional guidelines outlined in building codes, as well as to incorporate active and passive heating and cooling systems in building envelopes.

In the 1960s, architect Marcel Breuer introduced pioneering methods to address the complexities of multi-layered building systems. His visionary approach, exemplified in projects like the IBM Research Center in La Gaude, France, sought to synthesise building services, installations, and passive solar protection measures into a single modular precast façade panel. His design approach involved the manual calculations of solar angles and graphical methods to obtain desirable shading properties for the building envelope elements. However, the manufacturing constraints imposed by concrete casting techniques posed limitations on the ability to create bespoke variations, necessitating an excessive reliance on standardised production of identical elements (Fig. 2).

AMC technologies offer unique design flexibility to address both the need for functional integration and adherence to building codes and non-standard and bespoke production possibilities by leveraging geometric differentiation. Going beyond multi-layered and multi-material building systems, functional integration and hybridisation in mono-material building systems further enable the attainment of sufficient dismantlability and circular material utilisation at the end-of-life stage of building envelope elements. Within this context, this research explores how AMC technology can be utilised to expand the concept of prefabrication of concrete elements towards functionally integrated and hybridised building envelope elements while reducing the materials used. As such, this research comprises: a) a bespoke volume and surface design of individual building envelope elements in an overall building envelope, b) the structural zone design, and c) the thermal zone design of the internal structure of these bespoke elements (Fig. 3). The proposed methods were experimentally tested and validated by producing a 1:1-scale demonstrator using the AMC technology of Selective Cement Activation (SCA).

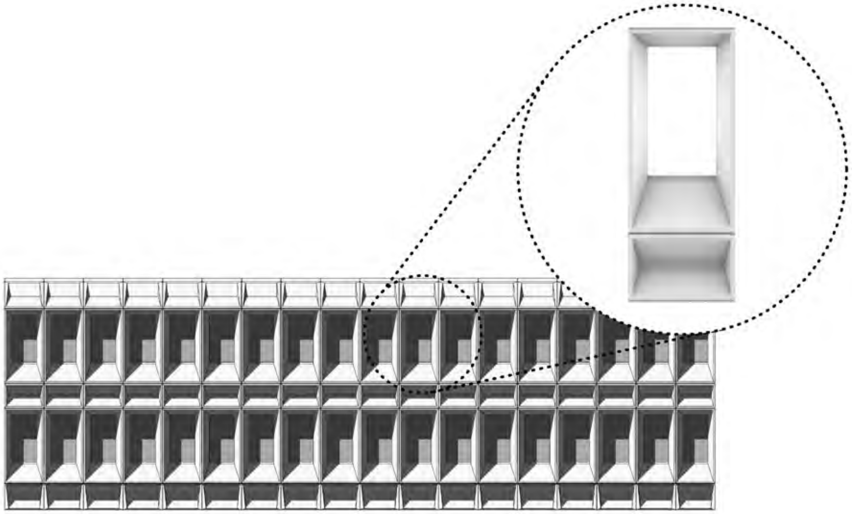
1. Drone image of the 1:1-scale demonstrator, oriented in south-southeast direction, set up on 5 June, 2023 at 13:30 at the Galileo in Garching bei München, Germany. © Janna Vollrath / TUBS.


AMC
AMC TRR277

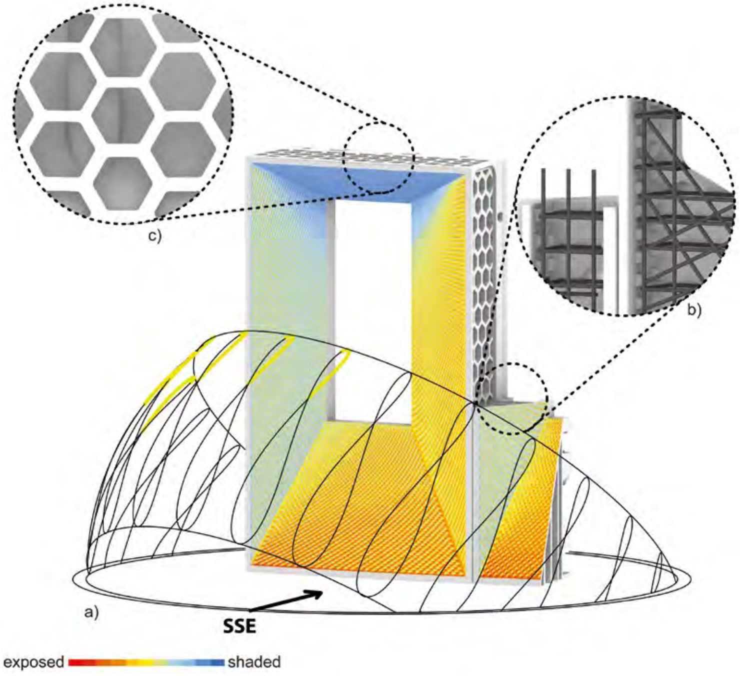
Functional hybridisation potentials through SCA

Novel AMC technologies such as particle-bed 3D Printing (PB3DP) have transitioned from experimental setups in academia towards large-scale applications in the construction industry (Asprone *et al.*, 2018). SCA, a distinct PB3DP process, involves applying a liquid activator to compressed layers of a mix of dry aggregate and mineral binder, such as dry cement, typically comprising fine grains <1mm, with a layer height of approximately 1.5mm. This technology, with high-resolution capabilities ranging from 1 to 3mm, allows for precise material deposition tailored to local structural and functional needs. It offers a durable, low-waste prefabrication method with expansive design freedom and without the need for formwork (Meibodi *et al.*, 2018; Herding *et al.*, 2022). This innovation not only serves the purpose of automation, industrialisation, and increasing resource efficiency, but also enables innovative approaches such as the integration of functions and their hybridisation through high-resolution geometric detailing (Agustí-Juan *et al.*, 2019).

In a broader context, large-scale SCA is well suited for prefabricating concrete elements. However, the production of large-scale SCA building elements also presents considerable challenges, primarily due to material shrinkage and the potential for cracking, as well as the mechanical properties inherent to the material system. These complications are coupled with the intricacies of part handling throughout the process, including the extraction and transportation of printed elements from the powder bed. At present, SCA exhibits a lower mechanical strength, featuring a flexural strength of 2.5MPa, compressive strength of 12.0MPa, and a density of 900kg/m^3 (Richter and Jungwirth, 2023) compared with cast concrete elements with a similar density, such as infra-lightweight concrete, which boast a flexural strength of 3.0MPa, compressive strength of 13.0MPa, and a density of 780kg/m^3 (Schlaich and Hückler, 2012). This discrepancy in strength contributes to the occurrence of early-stage cracking. Given the necessity for prefabricated load-bearing building elements to withstand high stresses during transport and structural application, one potential solution is the combination of lightweight SCA, applied locally as a stay-in-place formwork for cast reinforced concrete, to enable robust structural implementations. However, it is worth noting that the density and mechanical strength of lightweight SCA material systems closely approach the upper limit for state-of-the-art infra-light concrete defined in the German Building Standard DIN EN 206-1.



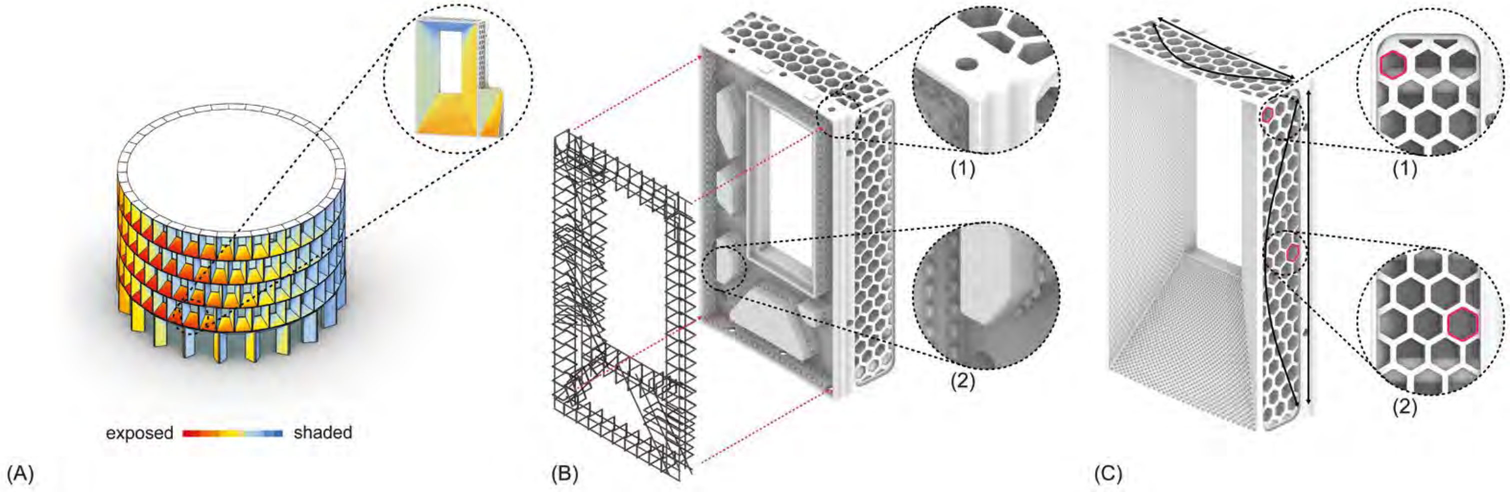
2



3

2. Elevation of architect Marcel Breuer's precast solar-controlled standardised building façade panels.
© M. Düpree, M. Fechner / Professorship of Digital Fabrication / TUM.

3. Functionally hybridised building envelope element of the 1:1-scale demonstrator: (a) Solar-controlled volume and surface design, (b) Structural zone design as a stay-in-place formwork for casting reinforcement (~20cm width), (c) Thermal zone design as a graded cellular structure (~50cm width).
© Julia Fleckenstein / TUM.



4

4. The geometric design of the individual building envelope elements, based on a circular building layout (A) serves as framework for the functional hybridisation of both structural (B) and building physical (C) requirements. In the structural zone (B), dry joints (1) on the outer sides are positioned to support the assembly of adjacent elements onsite. Simultaneously, the zone functions as notched and customised lost formwork (2) for casting a rebar cage and loadbearing anchors. The thermal zone (C) is open to all four sides, featuring cells that vary in both horizontal and vertical directions, providing ample rigidity for the front edges. Here, (1) indicates the smallest cell, while (2) represents the largest cell. @ Julia Fleckenstein / TUM.

Further crucial considerations for the functional integration into SCA building elements involve the removing of inactivated powder from the printed component and the necessity of open-cell structures to prevent cement powder entrapment in closed geometries. It is thus essential to consider only open-cell structures that are easily accessible from the exterior and sufficiently spacious to accommodate the insertion of a suction hose for excavation (Lowke *et al.,* 2022). Achieving proper material adhesion at the interface between activated and deactivated powder also presents a challenge.

While research on AMC processes with SCA has been ongoing, the large-scale integration of SCA into architectural applications and the development of multi-functional design approaches remain significantly unexplored. Consequently, this research aims to investigate the potentials and constraints of utilising SCA for the proposed hybridised design objectives at a 1:1 scale, presenting an expansion of traditional concrete-element prefabrication methods.

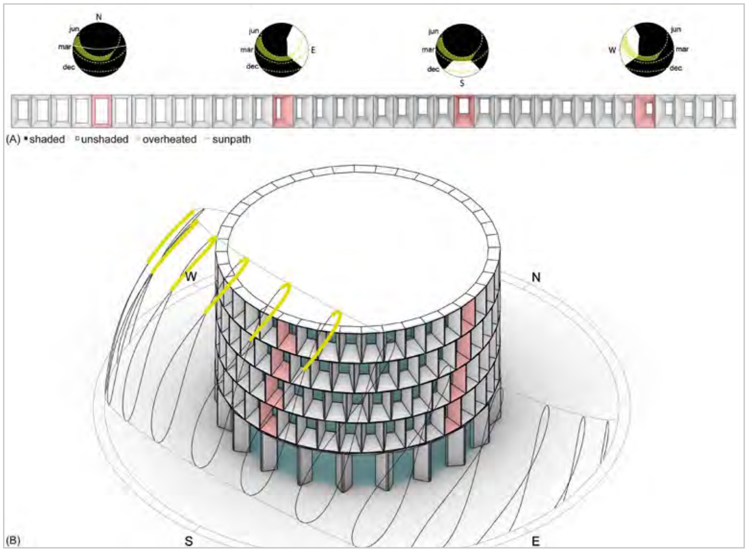
Method

Drawing inspiration from the architectural reference of Marcel Breuer's prefabricated façade system, a method for the design and prefabrication of AMC building envelope components has been developed in this research. This method harnesses SCA technology to overcome present industrial manufacturing constraints and unlock opportunities for localised variations and customisation. This method encompasses the following steps: a) Tailoring the volume and surface design of individual building envelope elements within the overarching building envelope by using graphical methods to respond to specific local solar exposure conditions (Fig. 4A), and, concurrently, designing the internal structure of these elements, which includes integrating the design of b) the structural zone (Fig. 4B), and c) the thermal zone (Fig. 4C).

The development, testing, and assessment of this design-to-fabrication method were undertaken within the context of a case study involving the design of a multi-storey building. Ultimately, a full-scale demonstrator of two building envelope elements from the building design was fabricated using SCA technology. This demonstrator was designed and planned as a functional hybrid to validate the general applicability of the computational design approach of functionally integrating both thermal and load-bearing requirements, as well as the fabricability with SCA technology of such a large-scale building envelope element.

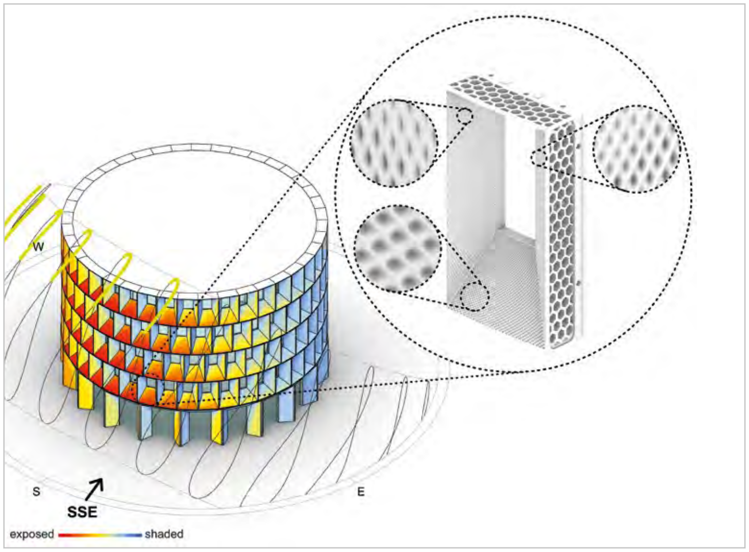
SCA material system

In this research, the AMC technology of SCA was chosen and customised to fit defined requirements, and its boundary conditions were used as key design drivers. First, the layer height of the PB3DP method was set to 1.5mm requiring the use of sub-millimetre aggregates to achieve such a high resolution. The material system was tailored to use locally available ingredients and standardised building products. Therefore, ordinary Portland Cement and unpurified soft water were selected as binding agents because of their wide availability and



5

5. (A) Solar-control aspects serve as input parameters for the algorithm-based design workflow tailoring the glazed area for the north, east, south, and west directions in width, height, and depth as well as in its vertical and horizontal translation to prevent the interior space from overheating. The solar masks above the elements indicate that the glazed area's adjacent surfaces cast enough shade (indicated in black) to prevent thermal overload during the cooling season (yellow), while still allowing sufficient daylight for the interior with the window-to-wall ratio varying for each element according to the sun's orientation. (B) Implemented in the design tool, each of these four elements is customisable to the local requirements, while the elements in between gradually self-align. The outcome of the solar-controlled design method is a building envelope composed of customised, solar-controlled building elements with varying sizes of the glazing area. © Julia Fleckenstein / TUM.



6

cost-effectiveness in the construction sector. The chosen aggregates incorporated expanded glass particles (LEGA) derived from locally sourced glass bottles, thereby extending their life cycle. As ordinary Portland Cement was used as a binder, manufactured parts needed to be hydrated before being fully cured. The necessity of these additional steps demands part handling of the unreinforced green-state element and precise control of temperature and humidity. Additionally, the size of the print element is constrained by the size of the overall build space and varies according to the particle print setup between small and large print jobs, which are linked to different requirements as well.

Solar-control design strategies for the building envelope element's volume

Computational tools provide a precise means of simulating and implementing features that adapt to the varying levels of solar exposure on a building's envelope. In this research, we harnessed solar-control strategies to differentiate the design of the volumetric shapes of building envelope elements, building upon prior work by Bertagna *et al.* (2023). These solar-control strategies leverage graphical methods for shading building envelope elements, using a geometry-based model that relies on climate data as the only input parameter (e.g., Energy Plus Weather (EPW) file), along with the designer's intention for their overall shape. We developed an algorithmic design tool capable of translating design intentions into customisable parameters, granting the flexibility to modify depth, width, and length, as well as the vertical and horizontal positioning of the glazed area in each building envelope element. The objective of adjusting these parameters is to ensure ample daylight for the interior spaces throughout the year while effectively avoiding overheating, particularly during the cooling season. In the proposed case study, a circular building layout served for the exploration of the architectural variations across the overall building envelope design (Fig. 5). Employing the solar-control design method resulted in a building envelope composed of customised elements, featuring varying sizes for the glazed areas that ensure an adequate window-to-wall ratio, taking into consideration their unique orientations.

Solar-control design strategies concerning the element's surface

Additionally, we have adjusted the surface of the customised building envelope elements to incorporate self-shading properties using surface patterns, aiming to mitigate overheating on the surfaces adjacent to the glazed area resulting from the accumulation of solar energy, as discussed by Fleckenstein *et al.* (2022). These surface patterns were strategically designed to harness self-shading effects, effectively reducing solar heat gain and cooling loads based on locally varying requirements. The geometric patterns were carefully adjusted in terms of depth, size, and angle, to align with the prevailing radiation profile. Solar radiation simulations reveal that unmodified surfaces receive higher potentials of solar radiation than those with applied geometries. This implies that geometrically differentiated surfaces tend to have lower surface temperatures as a consequence of inter-reflections that reduce the direct solar exposure through their self-shading capabilities (Fleckenstein *et al.*, 2023) (Fig. 6).

7

6. Elaboration of a building design section facing south-southeast for the AM of a demonstrator in real-building scale. A solar radiation simulation (red = exposed, blue = shaded) visualises the solar exposed surfaces of the building envelope elements tending to overheat during sunny summer days. A south-southeast-oriented building envelope element serves for the further elaboration of the demonstrator to validate the assumptions made from the simulations. Self-shading surface geometries are applied to gradually reduce exposed areas based on the colour codes of the solar radiation simulation. The more exposed the area, the stronger the depth of the pattern, and less exposed and more shaded surface areas feature a lower differentiation. © Julia Fleckenstein / TUM.

7. (left) The load-bearing zone is intended as a lost formwork for placing a prefabricated rebar cage and for casting grouted concrete. Evenly notched sides 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. (right) Triangulated connectors along the vertical length of the building envelope's side effectively secure the adjacent cut building envelope element in place. (left) © Gerrit Placzek / TUBS, (right) © Julia Bergmeister / TUM.

Structural zone design

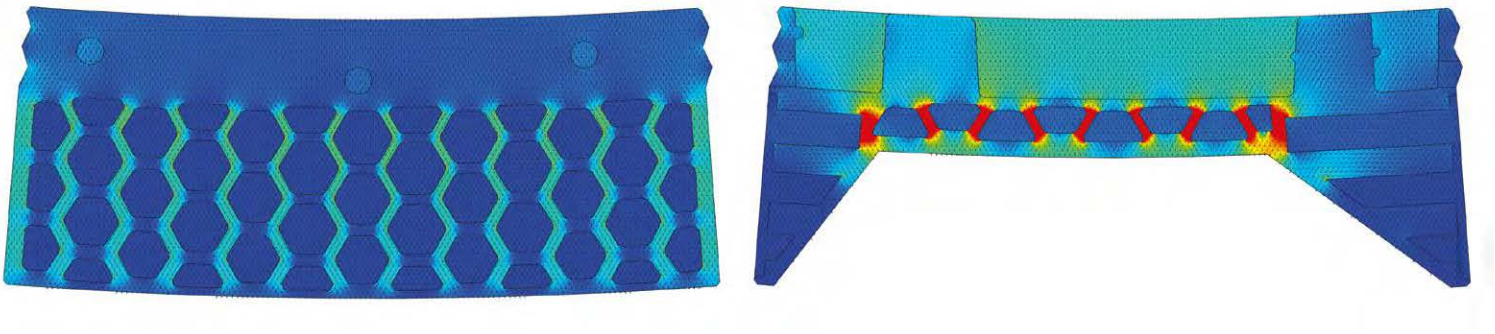
The load-bearing zone, with a width of ~20cm at its deepest, is designed as an additively manufactured stay-in-place formwork, offering the benefits of designing the optimal geometry for incorporating a prefabricated rebar cage as reinforcement and cast grouted concrete into the SCA element. This concept makes it possible to significantly increase the mechanical properties of the final building envelope element at specifically required locations. The stay-in-place formwork is customisable for varying thicknesses and non-prismatic shapes, facilitating the adaptation to non-standard geometries and enhancing versatility for construction projects with distinctive design elements and varying structural requirements. Preliminary tests assessed the general applicability and the bond between the grouting and the SCA concrete. As a result, the sides of the stay-in-place formwork were uniformly notched with the aim of enhancing the bond and facilitating a secure connection between the grouted concrete and the SCA material (Fig. 7).

For the structural zone design, the forces in the building envelope element have been analysed as part of the overall building design – that is, by considering gravity and lateral loads, resulting in a topology-optimised design based on the determined load combination. Subsequently, the applied forces were calculated for the building envelope element's rotation around its centre of gravity from the downward-facing front side to an upright position, and from there to the downward-facing back side. Based on this, the quantity and layout of the rebar were calculated as beam-column elements, resulting in a rebar cage with longitudinal rebar (ϕ0.12m, 1.30m) and stirrups (ϕ0.08m, 0.38m), along with additional necessary anchorages for transportation. To integrate the building envelope elements into the overall building system using a dry-joint assembly, two types of pretested, high-force-resistant geometries were employed: truncated pyramids on top and bottom and triangular connectors on the building envelope elements' sides. Given their simple geometry, they are expected to facilitate and accelerate the assembly process on site while transmitting the forces in the required degrees of freedom. In each area of the structural system, one side of the selected joint carries a specific force to the other side of the joint into the next joint of the adjacent building envelope element. This force transfer depends on the joint's rigidity, influenced by its shape, material, and position. Therefore, the joints were strategically placed within the structural, reinforced zone of the building envelope element and maintained during the topology optimisation (Lanwer *et al.*, 2022; Baghdadi *et al.*, 2023).

Thermal zone design

The insulation zone, extending to 50cm at its widest point, is designed to enhance the thermal performance of the overall building envelope element without the need for an additional layer of insulation. This zone features an open-cell structure, utilising a graded hexagonal cellular shape. The form-finding is supported by a simulation-based, parametric design approach based on two-dimensional heat flux simulations, and has been evaluated and compared in detail with other AMC processes and material compositions (Briels *et al.*, 2023c). To provide ample rigidity at the front edges and to meet the printing needs of the SCA process, the cell size varies between 80 and 100mm and the rib thickness between 20 to 40mm, allowing for the removal of unbound material. The cell structure is recessed by 2cm, creating a continuous cavity between the adjacent building envelope elements when assembled on site, connecting the individual cells. This allows for the injection of blow-in insulation material (e.g., perlite or cellulose) after assembly, significantly improving the overall insulation properties, compared with a solid element and air-filled cells (Briels *et al.*, 2023b). The final design's thermal performance was assessed using a heat transfer coefficient of 0.98W/m^{2}K, which was averaged across 20 layers (Briels *et al.*, 2023a).

The resulting heat flux density is visualised with a coloured mesh of two exemplary horizontal sections of the element in Fig. 7, illustrating the thermal throughput per area through the element ranging from blue (low thermal heat flux density) to red (high thermal heat flux density). The overall thermal performance is limited by the additional load-bearing zone, which has higher thermal conductivity due to its solid composition and the grouting mortar. Additionally, the vertically varying



8

geometry of the window opening results in a reduced thickness of the insulation zone and a higher heat flux density (Fig. 9).

Result

Based on the highest solar radiation profile, a full south-southeast facing (3.00m × 1.80m × 0.75m (h×w×d)) and an adjacent cut building envelope element (1.25m × 0.50m × 0.75m (h×w×d)) from the overall building design were chosen for manufacture as full-scale building envelope elements, aiming to evaluate and showcase the design concept in terms of its manufacturability. Based on the colour code of the solar radiation profile, the self-shading pattern gradually adapts in depth, size, and rotation. Both building envelope elements comply with the initial circular layout, featuring an outer radius of 12m. The cut element primarily served to demonstrate the assembly logic and to validate the tolerance of the proposed building system. Both building envelope elements were manufactured at additive tectonics GmbH within the Big Future Factory (BFF) using a large-scale particle-bed setup with a build space of 4.00m × 2.50m × 0.90m (l×w×h). They were printed in one piece, oriented horizontally, with the front side facing down.

After a total print duration of 9:38:33 hours for the first full building envelope element, the element was lifted in one piece onto an unpacking station, where it cured for four days until it reached its peak hydration temperature. Continuous thermal monitoring was essential to forestall any shrinkage cracks in the green-state element resulting from dehydration. Achieving sufficient green-state strength 24 hours prior to the temperature peak allowed for the excavation of both the structural and the lateral thermal zones. This, in turn, facilitated the placement of the rebar cage, followed by the casting with grouted mortar (Fig. 10).

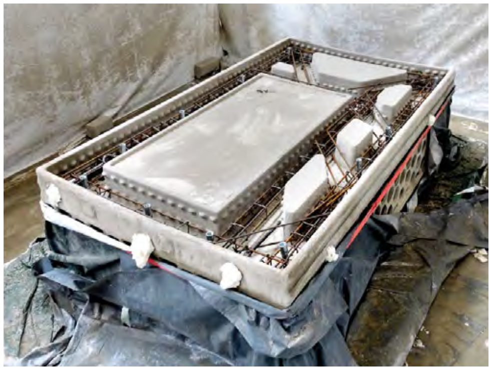
9

8. Two exemplary results of layerwise 2D heat flux simulations, illustrating the respective heat flux density with resulting U-values of 0.34 W/m^{2}K (Layer 01: left) and 0.83 W/m^{2}K (Layer 06: right). © David Briels / TUM.

9. 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. A separate simulation-based parametric design approach serves to tailor the cellular structure. The used SCA material already provides an improved thermal conductivity of 0.65W/m^{2}K due to the added lightweight aggregates. To improve the insulation properties, one approach pursues the filling of insulation material (e.g., cellulose) after the assembly of the building envelope elements on site. © Julia Fleckenstein / TUM.


10.1


10.2


10.3


11.1


11.2


11.3

10. (1) Excavation at the unpacking station after curing. (2) Watering and cleaning of the remaining material. (3) Reinforcement of the lost formwork. © additive tectonics GmbH.

11. (1) Casting grouted mortar with a crane-mounted concrete bucket. (2) Watering and cleaning of the remaining material in the front and post-treatment. (3) Transportation on a semi-trailer and uplifting on site. (1) & (2) © additive tectonics GmbH, (3) © Gerrit Placzek / TUBS.

The grouted mortar was mixed and poured into into a 500l concrete bucket attached to a crane. Then, the material was controlled and poured into the stay-in-place formwork and evenly distributed with a compactor. After 24 hours, the grout had hardened sufficiently to mount a customised supporting steel frame in the structural zone to transmit the tensile forces during the handling processes. After rotating the element in its vertical position, the front side of the element could now be cleaned of the remaining unbound material and made available for post-processing. To guarantee safe transportation, the building envelope element was positioned on a semi-trailer with the structural zone facing downwards to protect the delicate corners of its front side. Upon arrival on site, the element was lifted by a truck-mounted crane and assisted into its vertical position (Fig. 11).

The full building envelope element has a combined weight of roughly 2.2t, out of which approximately 1033.2kg are attributed to the SCA technology, while the remaining weight is distributed among the cast grouted concrete and steel rebar. The cut building envelope element, which was purely fabricated in SCA, weighs approximately 163.2kg (Fig. 12).

Conclusion

The outlined design and manufacturing methods showcase the potential of AMC in replacing intricate, functionally separated multi-layer building systems with customised, functionally hybridised building envelope elements at full building scale (Fig. 1). The building envelope elements not only have the potential to reduce global waste through formwork-free and material-saving manufacturing processes, but also to regulate solar radiation through global shape and local surface customisation. Furthermore, the research validates the approach of using lightweight aggregates within the SCA process and the potential to enhance thermal performance by creating cellular structures filled with blow-in insulation material.

Challenges and potential improvements in the real-scale SCA manufacturing process

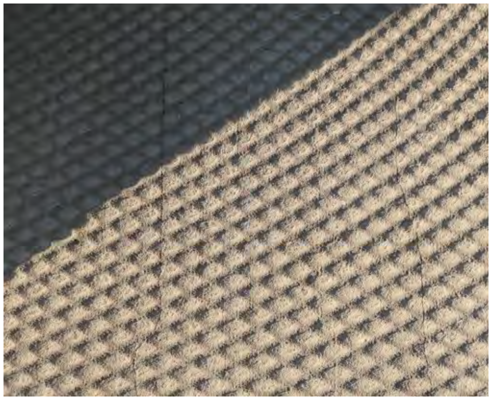
The manufacturing of the full-scale SCA building envelope elements encountered significant challenges. The selection of standard Portland Cement as the binder introduced a serious obstacle arising from its inherent tendency to shrink, potentially leading to the formation of shrinkage-induced cracks over time. Additionally, the diverse geometric profiles within the element, combining fast-drying slender sections with slower-drying massive structures, compounded the complexity of addressing potential cracking issues. The downward orientation of the front face and its curvature increased the risk of cracking from unbalanced weight distribution and a tendency to move within the powder bed. This orientation also affected the façade surface quality, as the jetted water tended to penetrate deeper, resulting in dull edges and a reduced resolution. Additionally, during the cleaning and casting process, excessive water leaked through the element and activated previously dry and non-activated layers, causing small imperfections after the full excavation and rotation.

Further research could focus on advancing the Portland Cement material system, especially since the system used in this project was a pioneering development. Larger lightweight particles up to 2mm in size could improve the resulting material performance; these aggregates could displace more cement paste due to their volume and reduced surface area ratio, diminishing the cement matrix for bonding, potentially resulting in a reduced carbon footprint, simplified excavation, and diminished shrinkage and cracking. Moreover, larger lightweight particles could lower the material density while increasing the structural and thermal performance.

Validation of the global shape and local surface design approach

The building envelope elements were set up in Garching in Munich, Germany, oriented in a south-southeast direction. This allowed on-site measurements of the surface temperature over several days in early June 2023. On a warm and sunny day, 6 June, on-site thermal measurements were conducted. Notably, at 12:30, with an average air temperature of 23°C, the measurements revealed a surface temperature difference of 7°C between the self-shaded (lows) and the solar-exposed areas (highs), indicating that the implementation of surface patterns can effectively unlock self-shading properties and lead to a substantial reduction of the surface temperature. Additional shading studies on the same day revealed that the glazed area was shaded in the morning and partially covered in the afternoon. This adjustment was achieved through the shape customisation that evaluated the size and recessed position of the glazed area. However, as a result of structural requirements and the constraints of the built space, the final shape slightly deviated from the initially simulated one.

12



13.1

13.2

In summary, the produced elements showed two key potentials: a) controlling solar heat gain through shape customisation helping to reduce energy needed for cooling, and b) controlling solar radiation through local surface customisation. However, to validate and to build upon these findings, long-term monitoring and continued thermal measurements are imperative (Fleckenstein *et al.*, 2023) (Fig. 13).

Hybridising structural and building physical design

In addressing the intricate balance between load-bearing and insulating requirements, the integration and hybridisation of these factors becomes pivotal to achieving a more refined and harmonious design.
In pursuit of enhancing structural integrity, advanced simulations with the finite element method would be crucial. This approach would enable precise calculations for the force distribution, accounting for all necessary operational movements, and thereby boosting the efficiency of the printing and casting process. Additionally, employing three-dimensional heat flux simulations enables a comprehensive analysis for both load-bearing and insulating zones, facilitating targeted assumptions to meet both requirements without compromising upon either. Furthermore, including process and handling simulations plays a significant role in identifying potential manufacturing challenges at early design phases, to prevent and address potential for cracking and irregular shrinkage of large-area geometries, and to streamline the transportation and handling processes. Those findings could potentially lead to the segmentation of the building envelope element, along with the development of additional dry-joint assembly methods.

12. Assembly of the full and the cut building envelope element at the BFF after the post-treatment. © additive tectonics GmbH.

13. (1) Close-up of the self-shading surface geometry on 6 June, 2023, at 19:00 and (2) validation with the infrared thermal camera of the self-shading surface geometry on 6 June, 2023, at 12:30 using a FLIR ONE Pro with an average air temperature of 23°C. (1) © Julia Fleckenstein / TUM, (2) © Janna Vollrath / TUBS.

Acknowledgement

This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (Project number: 414265976 – TRR 277 Additive Manufacturing in Construction). Researchers and collaborators for the realisation of the demonstrator include:

Research associates: Julia Fleckenstein, Friedrich Herding, David Briels, Niklas Meier, Hendrik Weigel, Gerrit Placzek, Dr Abtin Baghdadi

Professors: Professor Dr Kathrin Dörfler, Professor Dr Dirk Lowke, Professor Thomas Auer, Professor Dr Harald Kloft, Professor Dr Arno Kwade, Professor Dr Martin Empelmann, University-Professor Dr Patrick Schwerdtner

Project students: Mia Düpree, Mareen Fechner

Industry partner additive tectonics GmbH: Bruno Knychalla, Christian Wiesner, Christian Thaler, Max Braun, Kilian Fruth

References

Agustí-Juan, I., Jipa, A. and Habert, G. (2019) Environmental assessment of multi-functional building elements constructed with digital fabrication techniques. International *Journal of Life Cycle Assessment*, 24(6), pp.1027-1039. https://doi.org/10.1007/s11367-018-1563-4.

Asprone, D., Menna, C., Bos, F., Salet T., Mata-Falcón, J. and Kaufmann, W. (2018) Rethinking reinforcement for digital fabrication with concrete. *Cement and Concrete Research*, 112, pp.111-121. https://doi.org/10.1016/j.cemconres.2018.05.020.

Baghdadi, A., Ledderose, L., Ameri, S. and Kloft, H. (2023) Experimental and numerical assessments of new concrete dry connections concerning potentials of robotic CNC manufacturing technique. *Engineering Structures*, 280, p.115605. https://doi.org/10.1016/j.engstruct.2023.115605.

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*, 12(4), pp.754-774. https://doi.org/10.1016/j.foar.2023.02.006.

Briels, D., Renz, M., Nouman, A. and Auer, T. (2023a) Heat flux simulations for the AM façade demonstrator 'Breuer X AM'. *data.europa.eu*. https://doi.org/10.14459/2023mp1716507.

Briels, D., Renz, M., Nouman, A. and Auer, T. (2023b) Heat flux simulations for the insulation concept of the AM facade demonstrator 'Breuer X AM'. *data.europa.eu*. https://doi.org/10.14459/2023mp1716508.

Briels, D., Renz, M., Nouman, A., Straßer, A., Hechtl, M., Dahlenburg, M., Knychalla, B., Sonnleitner, P., Herding, F., Fleckenstein, J., Krakovská, E., Dörfler, K. and Auer, T. (2023c) Monolithic AM façade: Multi-objective parametric design optimization of additively manufactured insulating wall elements. *Frontiers in Built Environment*, 9. https://doi.org/10.3389/fbuil.2023.1286933.

Fleckenstein, J., Molter, P., Chokhachian, A. and Dörfler, K. (2022) Climate-resilient robotic façades: Architectural strategies to improve thermal comfort in outdoor urban environments using robotic assembly. *Frontiers in Built Environment*, 8. https://doi.org/10.3389/fbuil.2022.856871.

Fleckenstein, J., Molter, P., Chokhachian, A. and Dörfler, K. (2023) Revisiting Breuer through additive manufacturing: Passive solar-control design strategies for bespoke concrete building envelope elements. *Frontiers in Built Environment*, 8, pp.527-538. https://doi.org/10.52842/conf.ecaade.2023.1.527.

Herding, F., Mai, I. and Lowke, D. (2022) Effect of curing in selective cement activation. *RILEM International Conference on Concrete and Digital Fabrication*, pp.283-288. https://doi.org/10.1007/978-3-031-06116-5_42.

Lanwer, J-P., Weigel, H., Baghdadi, A., Empelmann, M. and Kloft, H. (2022) Jointing principles in AMC, Part 1: Design and preparation of dry joints. *Applied Sciences (Switzerland)*, 12(9). https://doi.org/10.3390/app12094138.

Lowke, D., Mai, I., Keita, E., Perrot, A., Weger, D., Gehlen, C., Herding, F., Zuo, W. and Roussel, N. (2022) Material-process interactions in particle bed 3D printing and the underlying physics. *Cement and Concrete Research*, 156, p.106748. https://doi.com/10.1016/j.cemconres.2022.106748.

Meibodi, M.A., Jipa, A., Giesecke, R., Shammas, D., Bernhard, M., Leschok, M., Graser, K. and Dillenburger, B. (2018) Smart slab: Computational design and digital fabrication of a lightweight concrete slab. In: *ACADIA 2018 Recalibration on Imprecision and Infidelity, Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*, Mexico City, 18-20 October, pp.434-443. https://doi.org/10.52842/conf.acadia.2018.434.

Richter, C. and Jungwirth, J. (2023) 'Mechanical properties of concrete components manufactured by selective cement activation', in *Proceedings of the 19th Rapid.Tech 3D Conference Erfurt, Germany*, 9–11 May 2023, pp. 134–143.

Schlaich, M. and Hückler, A. (2012) Infraleichtbeton 2.0. *Beton- und Stahlbetonbau*, 107(11), pp.757-766. https://doi.org10.1002/best.201200033.