LIGHT-WEIGHT HOLLOW ADDITIVE MANUFACTURING

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This article examines additive manufacturing and robotic fabrication methods for hollow, lightweight structures in the field of architecture, engineering, and construction (AEC) industries. This article examines hollow, lightweight mineral building elements and their manufacturing methods. More specifically, this article explains the novel additive manufacturing method Blow Extrusion (BX) in detail. Blow Extrusion is an extrusion-based method for large-scale 3D printing of hollow strand structures. Blow Extrusion (BX) enables the production of lightweight, air-filled, strand-based structures significantly reducing material use while maintaining structural integrity.

Hollow structural elements have historically played a critical role in reducing material consumption, optimizing weight, and improving construction material efficiency in construction. For instance, RotoForm, a sequential robotic casting process for mineral-based materials, is a robotic additive manufacturing method, resulting in hollow building elements. Beside the technical insights, this paper outlines the potentials of additive manufacturing in enhancing reduction material consumption through design and manufacturing procedures for cavities. The paper discusses the mechanical challenges, computational frameworks, prototyping challenges, and future applications of these methods in structural design, prefabrication, and lightweight construction.

INTRODUCTION

Hollow building elements have been long in use in architecture, engineering, and construction (AEC), serving as an essential and straight forward strategy for reducing material consumption, enabling lightweight structures, and optimizing the overall weight of construction. From ancient Roman concrete vaults with embedded voids to modernist explorations in lightweight prefabrication, the principles of hollow construction have continuously evolved alongside architectural and technological advancements.

With the emergence of digital fabrication, robotics and automation, the principles of light weight hollow structures are to be redefined through novel fabrication techniques. The integration of additive manufacturing and robotic construction allows for unprecedented control over material placement, enabling the realization of geometric complex, light-weight hollow structures. These advancements not only enhance material consumption efficiency but also open new design capacities for precise material placement and deposition.

This article examines three emerging material systems and fabrication techniques that harness robotics and additive manufacturing for the creation of lightweight, hollow building components. The first, RotoForm, sequential robotic casting, explores rotational additive manufacturing for shaping hollow building elements within mineral-based materials (Tessmann & Mehdizadeh, 2019). This additive manufacturing method investigates the capacities of activating kinetic behavior through robotic sequential casting and weight distribution inside the cavity. (Mehdizadeh & Tessmann, 2024). The second, Blow Extrusion (BX) in Large Scale reimagines extrusion-based fabrication to form large-scale, air-filled hollow strand 3D printing (Mehdizadeh et. al. 2024) . Through these case studies, this article highlights the capacities of light weight hollow additive technique BX more in detail on mechanical, digital framework developments.

BACKGROUND; PRECAST HOLLOW LIGHTWEIGHT STRUCTURES

The Barrel vault made of terracotta tubes employs the Hollow clay elements have been employed since the Roman Empire for building vaults and ceilings. These elements serve to either minimize the overall weight of the structure or to create large-span vaulted spaces by assembling conically shaped hollow tubes in an interlocking manner (Lancaster, 2015) (Fig.1. a.). By the late 19th century, hollow clay elements gained widespread use in ceiling construction (Fig. 1. b.). The ability to mass-produce these tubes as standardized products was the key factor in their widespread adoption. These tubes were manufactured using drainage pipe presses from the 1870s onward. Their popularity led to the development and patenting of numerous variations in France, England, Germany, and the U.S. up until the 1930s. These innovations focused on improving durability but also on reducing weight through hollow sections. The modular logic of these elements is designed to position the hollow clay tubes and then add reinforcement between them. Afterward, cast concrete is placed on top of them to increase the width of the span between two structural beams (Fischer, 2009) (fig.1. b.). These structural span elements increase the overall load-bearing behavior of span, and at the same time, they serve as lost formwork to cast concrete on top of them.

The hollow-core slab

The hollow-core slab is a widespread precast hollow concrete floor construction system (Fig. 2.a.b.). Due to its cavity, this system provides high material efficiency with significantly less weight. A large machine extrudes the concrete slabs horizontally on the bed (Elliott, 2017). The manufacturing of these elements is very fast and efficient due to the extrusion process. However, the repetitive logic and standardization restrict them to planar shapes, limiting their adaptability.

Both bridge and slab systems provide higher structural performance in relation to material mass. Structural height is achieved through the hollow section without excessive material consumption. The use of cavities formed by plastic balls inside concrete slabs is a common practice, particularly in the 'Cobiax Technologies' (Fig. 2c) system, patented in 2004 (Haag et al., 2005).

'Bones', precast system of Miguel Fisac

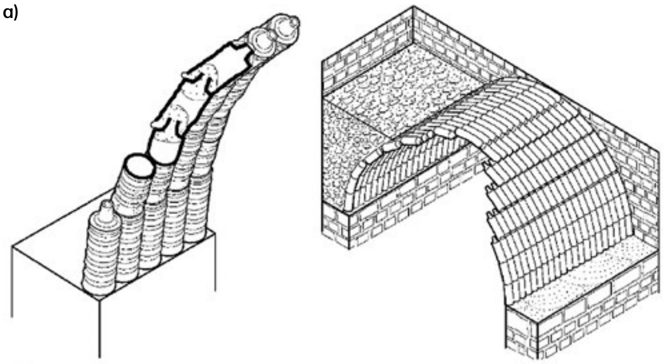
A great example of expanding the design capacities of hollow structural elements is in the work of Miguel Fisac, the modernist architect (*Carbonero*, 2003.) developed a structural system based on lightweight, hollow concrete elements. His patented system, known as 'Bones,' allows for the construction of long-span roofs by utilizing prestressed components that function in both prestressed and post-tensioned states (Fig. 3.a.). Fisac expanded this approach into a broader range of building elements using the same prestressed material principles (Fig. 3.b.) (*Mostafavi*, 2003.). Within the system 'Bones' Fisac had brought the Idea of bringing the water drainage and even light distribution in the spaces under the bone beams and still be light weigh. Geometry satisfies the function integration in this case. Fisac had built Lang post-tension span buildings with his system in 60's such as center of hydrographic studies in Madrid 1960-1963.

A hollow lightweight mineral material system; RotoForm

The emphasis on the role of material behavior and its embodiment into a design procedure describes much of the material system's theoretical framework. This emphasis also includes the machinery and computational design framework for specific materialization within the design-build system. Considering this theoretical framework, this article focuses on material systems in the field of additive manufacturing, which result in hollow objects.

RotoForm is a research trajectory at TU Darmstadt, targeting digital additive manufacturing of hollow lightweight building elements. The material system RotoForm exists through the behavior of mineral materials, sequential casting, and the phase-changing characteristics of mineral building materials from liquid to solid. This additive materialization technique allows the addition of continuous layers of material inside the formwork. Each layer results in a thicker outer shell and a smaller cavity inside the hollow object (Fig. 4).

The digital fabrication technique RotoForm operates through a specific machinery setup, a digital design-simulation framework, and the design of mineral material flew behavior and rheology (Mehdizadeh et al., 2022). The rotational casting machine continuously spins the formwork at a steady speed and in a designated direction. This movement ensures an even distribution of material across the a)



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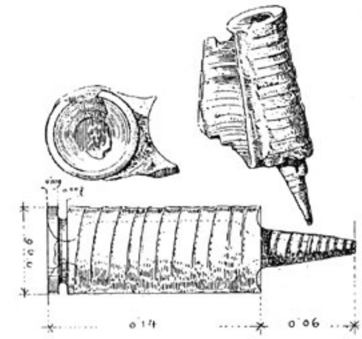

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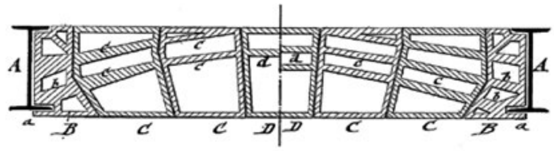

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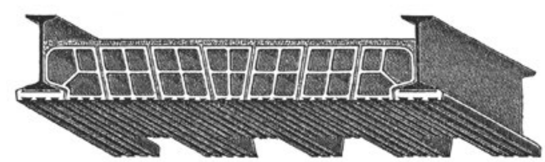
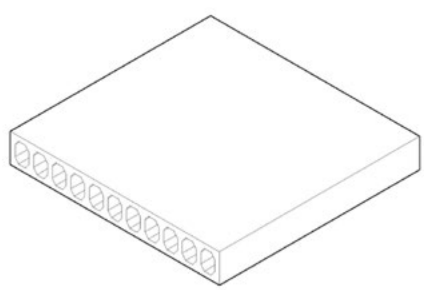


Figure 1: (a) barrel vault made of terracotta tubes. hollow stone conical/tubular vessels, with interlocking connections with no iron support system (b) a single hollow clay pipe vault element 500 B.C. Drawing from (Durm (1905), S.299; Storz (1994), S.10.) (c, d) a patented hollow stone ceiling by Austrian engineer Friedrich von Emperger, founder of the journal "Beton-und Stahlbetonbau," in the U.S. in the 1890s. The positioning of the material in this section is very similar to the compression force diagram in the structural elements. (Drawing: Sitzungsberichte der Bezirksvereine. In: ZdVDI 40 (1897), S.1008.)

a)



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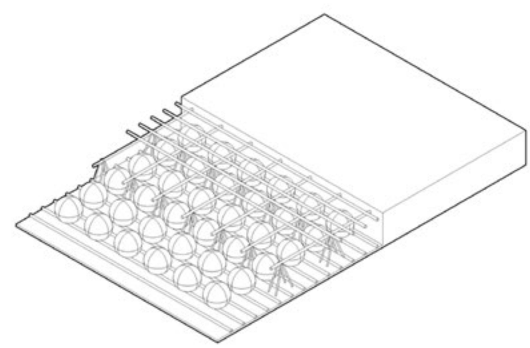
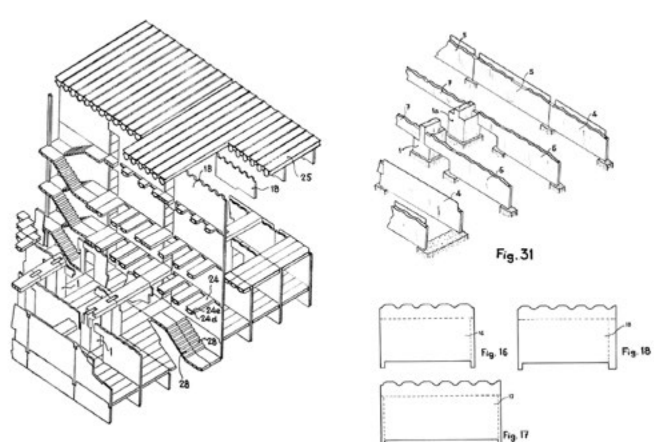


Figure 2: (a) Deep hollow-core floor unit section (b) Cobiax technologies hollow core system.



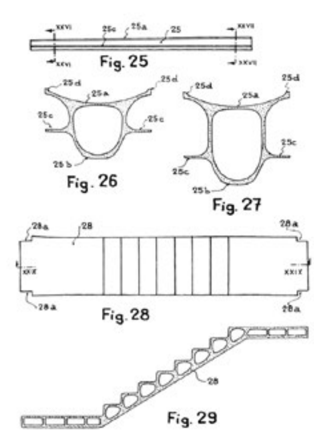


Figure 3: (a) The ceiling element, “Bones,” of Miguel Fisac and himself. (b) Housing prefabrication system 1965 drawings of Miguel Fisac (Photo credit: the Miguel Fisac Foundation, Image reprinted from AV Magazine monograph on Miguel Fisac, 2003, edited by Galiano Frampton, Mortazavi.)

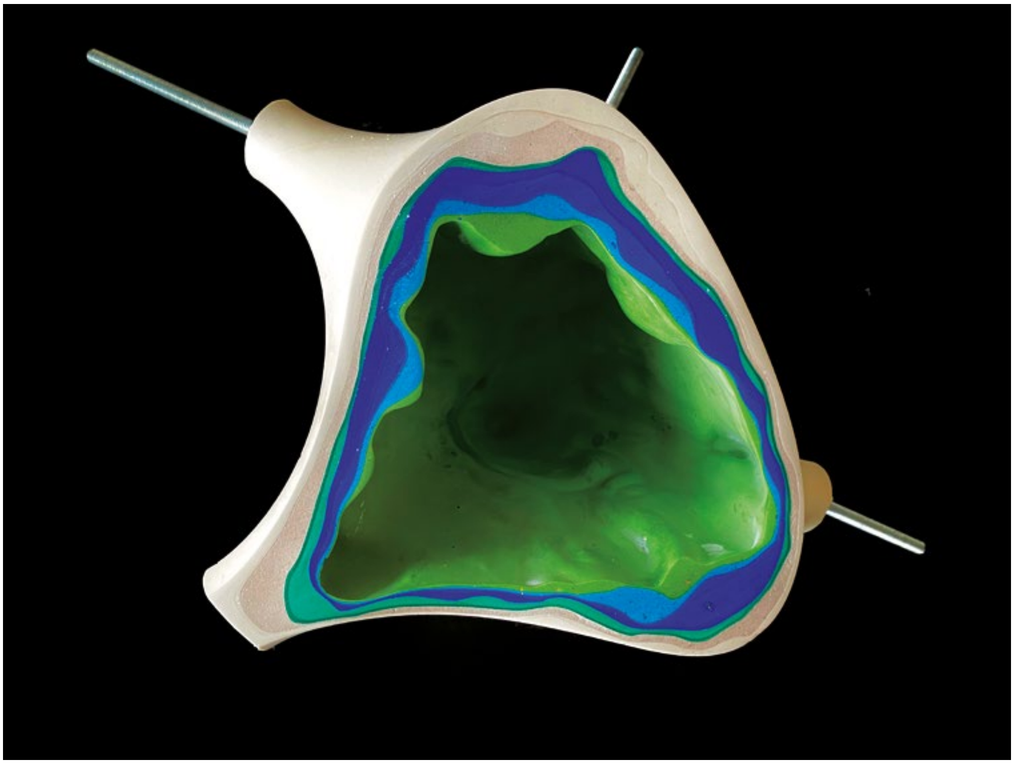


Figure 4: RotoForm node, rotationally cast within a closed, hyperplastic, pre-tensioned membrane in eight layers, using uneven rotation parameters and trajectories. The node materialized with a water-based polymer dispersion and mineral material. DDU (Photo: Samim Mehdizadeh, 2018)

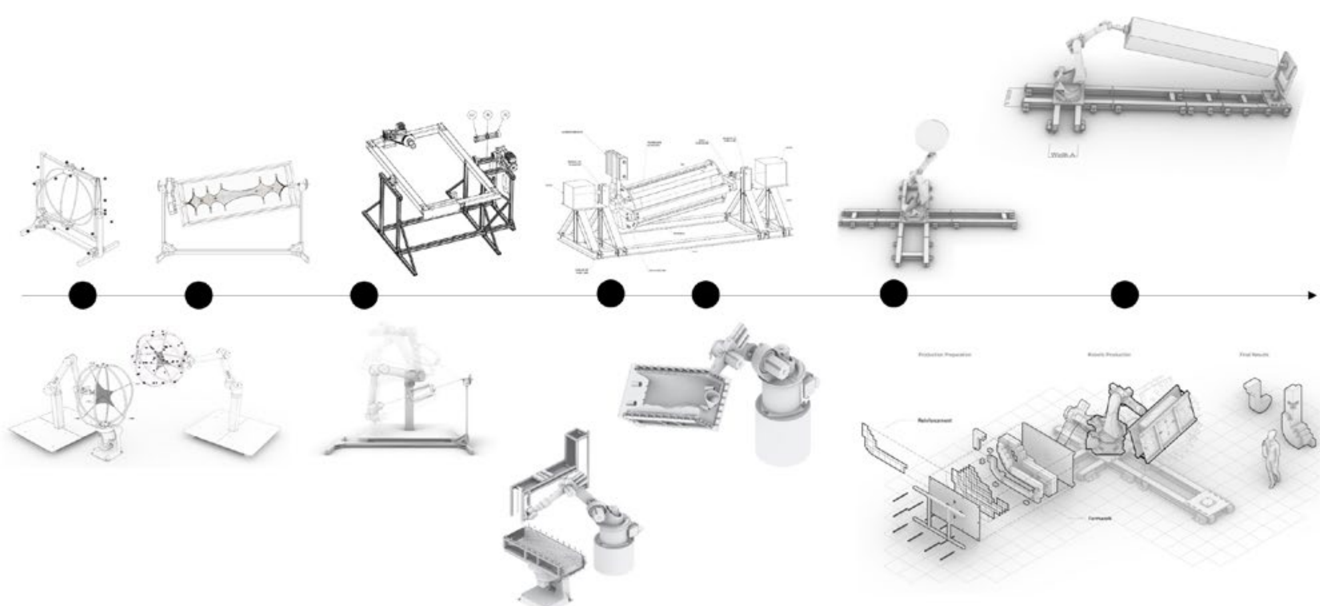


Figure 5: RotoForm machinery setups were developed, built, and tested at DDU, PMD of TU Darmstadt, and Spannverbund GmbH. Between 2018 and 2022, these setups were used to examine a diverse range of spin trajectories and machinery configurations concerning implementation, setup, and the fabrication of hollow, lightweight elements. (Drawings: Samim Mehdizadeh, Spannverbund GmbH. PMD TU Da. Joschua Schäfer)

entire formwork, preserving consistency in both sequence and duration. The three-dimensional motion results from two rotational axes, typically perpendicular to one another, operating at varying speed ratios.

Machinery setup, Robotic sequential Casting

Expanding the machinery setup is a crucial part of this research trajectory to explore the role of machinery configurations, rotational casting parameters, and the expanded capacities of this additive manufacturing method for hollow, lightweight elements. Robotic setups and specific rotational trajectories have been investigated using both small- and large-scale robotic systems, which have the potential for transition to large-scale machinery setups (Fig. 5).

HOLLOW LIGHTWEIGHT AND ADDITIVE MANUFACTURING; BLOW EXTRUSION (BX)

Blow Extrusion (BX) 3D printing is an innovative additive manufacturing (AM) method that enables the production of hollow strand structures (Tessmann et. al. 2022) (Fig. 6.). Our offered BX approach integrates Fused Granular Fabrication (FGF) and Fused Filament Fabrication (FFF), combining multi-material 3D printing, blow extrusion, robotic fabrication, and computational design. By utilizing hollow strands with adjustable cross-sectional diameters, our technique significantly reduces material and resource consumption.

The use of large-scale 3D printing with thermoplastics is rapidly expanding in technology-driven research within the architecture, engineering, and construction (AEC) industry. Real-world construction applications, such as interior walls (*Aectual | 3D Printed Architecture & Interiors, actueccessed 2024*), acoustic elements (Setaki et al., 2023), exterior façade elements (Sarakinioti et al., 2018), and concrete formwork (Jipa & Dillenburger, 2021), have been used in research and practice. BX 3D Printing decreases material consumption while creating lightweight and robust elements.

The additive manufacturing method BX significantly decreases material usage—by up to 85%—compared to printing with solid cross-sections, while also offering precise regulation of material flow. Additionally, this approach facilitates large-scale 3D printing of hollow strands with adaptable cross-sections by adjusting airflow during extrusion to control strand inflation (Fig. 7).

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

Technical Background

Large-scale additive manufacturing with thermoplastics presents several challenges. In the AEC industry, optimizing plastic usage and reducing printing time are critical concerns. From a mechanical standpoint, key issues include limited material throughput, thermal deformations, and the time required for solidification. This research addresses these challenges by improving both AEC applications and mechanical properties through the transition from conventional solid filament deposition to the extrusion of hollow strands.

The process utilizes ring-shaped hollow strand extrusion with a coaxial nozzle, allowing for controlled pressure adjustments within the extruded strands, resulting in variable cross-sections. This approach enables the production of hollow strands rather than solid plastic layers, significantly lowering material consumption per unit volume. Additionally, the encapsulated air enhances cooling efficiency, leading to increased throughput and faster printing speeds.

The introduction of 3D printing for hollow strands using filament feedstock was first proposed by Hopkins (Hopkins et al. 2020). More recently, (Leschok et al., 2024) from DBT at ETH Zürich explored an alternative approach utilizing pellets as feedstock for robotic 3D printing of hollow strands. Their method, based on Fused Granular Fabrication (FGF), achieves a material throughput of 50 kg/h, whereas Fused Filament Fabrication (FFF) is significantly lower, reaching only 0.5 kg/h. The stark 100-fold throughput difference highlights the practical limitations of filament-based methods for large-scale hollow strand fabrication.

Blow Extrusion Machinery; Thechnichal Development

The core development of this research involves a series of prototypes and process evaluations through continuous monitoring. Throughout our studies, we have explored and demonstrated the integration of this advanced extrusion method in two key directions: (a) FGFBX, which enables mono-material extrusion from pellets with variable cross-sections, and (b) FFFBX, which supports multi-material extrusion from filaments, also with adjustable cross-sections.

At this stage, prototyping has played a crucial role in assessing feasibility and determining the potential applications of both FGFBX and FFFBX. A significant aspect of the technical development has been addressing mechanical challenges to refine and optimize the extrusion process.

Mechanical Challenges

The mechanical design of the print heads presents several key challenges, including: (a) material throughput, (b) nozzle design, and (c) precise air control for inflation.

Digital to Physical Framework for Robotic 3D Printing

The digital workflow for these processes integrates a geometric slicer, robotic simulation, and real-time communication between the UR10 robotic arm and a custom-built extruder setup. This streamlined digital-to-physical transition begins with 3D modeling and parametric design in Rhinoceros and Grasshopper. Our custom slicer enables the programming and visualization of variable cross-sections, ensuring precise material deposition. Additionally, a dedicated client software facilitates real-time data transmission between the robotic arm and extruder system. For efficient synchronization, we utilize an open API framework (Moonraker/Klipper), enabling coordinated control over extruders, air pressure, and robotic movements (Fig. 8).

Prototyping and Results

By replacing polymer with air, we achieved a material reduction of approximately 65% without expanding the strand further, and up to 85% by increasing its diameter by a factor of 1.5 using our BX technology (Fig. 7). During the initial prototyping phase, we first explored the maximum printable dimensions and assessed the UR10 robotic arm's operational reach (Fig. 10). Next, we experimented with variations in the hollow strand's cross-section (Fig. 9). The demonstrator models were fabricated using transparent PETG for the FGFBX process, while the FFFBX method utilized four-color PETG (CMYK—cyan, magenta, yellow, and black).

Hollow lightweight Robotic Blow Extrusion

Using the robotic setup and FGF allowed us to explore the capacities of continuous large-scale prototyping with BX. The digital design-to-fabrication setup allows us to use both FGFBX and FFFBX extruder setups with any robotic arm machine, using the same digital framework. We have challenged the system's scaling in two setups for vertical and horizontal printing (Fig. 10).

The vertical printing setup with the UR10 robotic arm has been used to print 1100 mm long segments within the diameter of 40–60 cm in a variable shape. Our robotic setup, extruder, controlling system, and digital framework allowed us to vary the diameter of hollow strands systematically from 10 to 20 mm in this prototype. The Hight of the vertical prototypes are limited to the robotic arm and not the process. Within a larger robotic setup, the printing area limits can be eliminated.

These prototype segments demonstrate the significantly increased printing velocity in comparison to 3D printing with solid strands. Each segment has been built with approximately 5000 g of PETG granules, which showcases the lighweight elements through hollow additive manufacturing (Fig. 11. & 12).

Throughout a series of experiments using robotic setup and Blow extrusion for horizontal printing we explored the manipulation and tweaking the blow extrusion parameters. The results demonstrate great potential for varying and manipulating the Diameter of hollow strands immediately up to approximately 4 Times. (Fig. 13 &14).

TECHNICAL DISCUSSION

Using the robotic setup and FGF allowed us to explore the capacities of continuous large-scale prototyping with BX. The digital design-to-fabrication setup allows us to use both FGFBX and FFFBX extruder setups with any robotic arm machine, using the same digital framework. We have challenged the system's scaling in two setups for vertical and horizontal printing. The vertical printing setup with the UR10 robotic arm has been used to print 100 cm long segments within the diameter of 40–60 cm in a variable shape. Our robotic setup, extruder, controlling system, and digital framework allowed us to vary the diameter of hollow strands systematically from 10 to 20 mm in this prototype. These prototype segments demonstrate the significantly increased printing velocity in comparison to 3D printing with solid strands. Each segment has been built with approximately 5000 g of PETG granules, which showcases the extremely lightweight elements through hollow additive manufacturing.

CONCLUSION AND OUTLOOK

This paper emphasizes the crucial role of additive manufacturing in the materialization of hollow structures. Within the scope of this article, two additive manufacturing procedures are introduced, each utilizing specific machinery setups. Hollow structures in the construction industry hold enormous potential for significantly reducing material consumption.

Minimizing material use is a highly effective and straightforward strategy that contributes to sustainability goals in general and the AEC industry specifically. Material reduction is essential for building materials such as concrete and plastics, which constitute a large portion of materials used in construction and have a significant negative environmental impact.

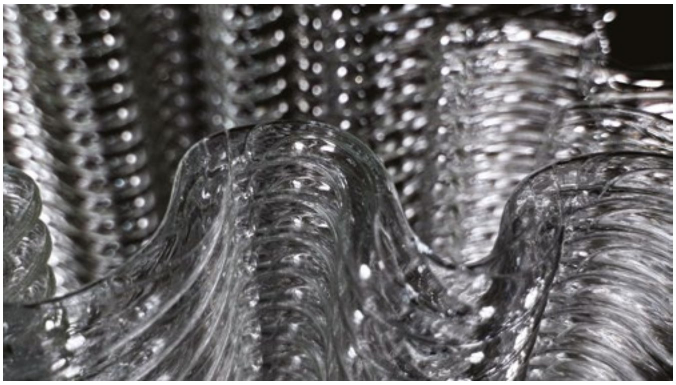


Figure 6: Hollow-strand 3D printed Prototype in vertical printing setup with FGF blow extrusion method .

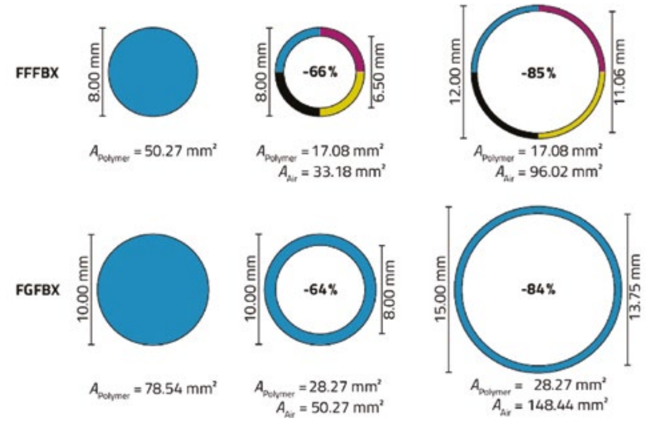


Figure 7: Material reduction in percentage compared to the full cross-section (left) for hollow strands produced using FFFBX and FGFBX without inflation (center) and with an increase in size by a factor of 1.5 (right) by Blow Extrusion (BX) where A represents the area.

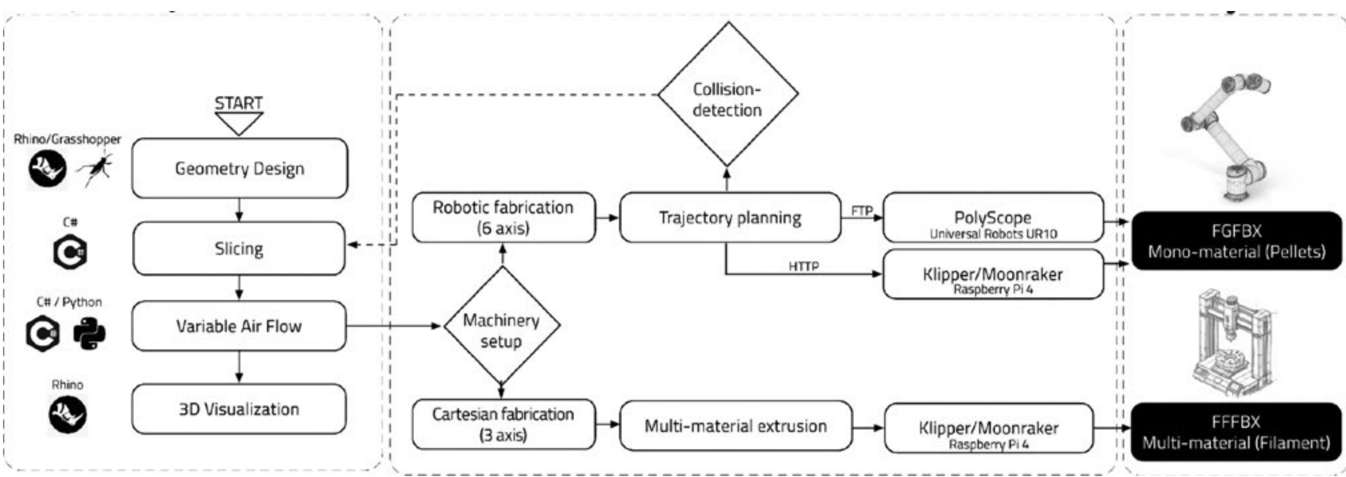


Figure 8: the Digital design to materialization framework. Made of costume made slicer and Data streamline between the machinery and several synchronize actuators.

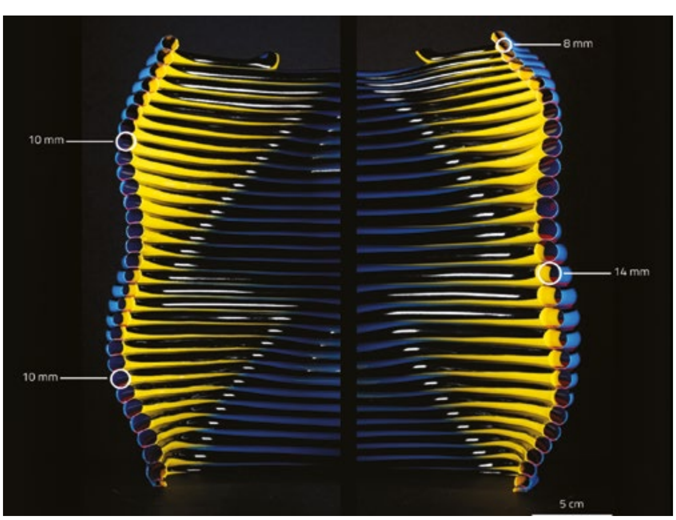


Figure. 9: FFFBX with four filaments in different colors. The two prototype sections compare the effects of constant and varied parameters for BX. On the right, the printing parameters are adjusted continuously, increasing the section size by up to 1.66 times. The hollow strand is printed with multi-material FFFBX. (Material: *Extruder* PETG (C, M, Y, K); Measurements: *Keyence* VR-5200, n=5, λc = 25 mm)

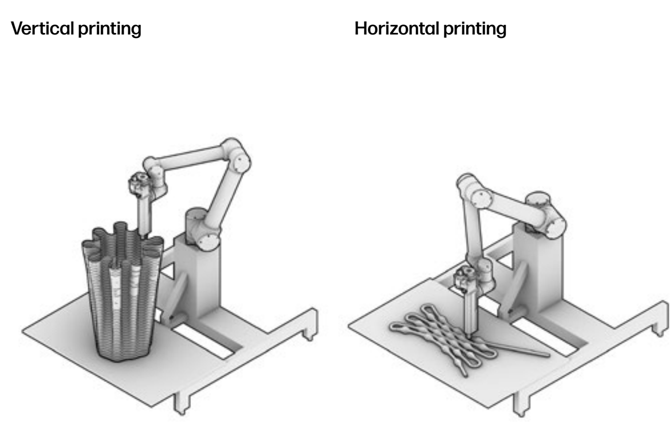


Figure 10: (a) vertical and horizontal printing setup plan.

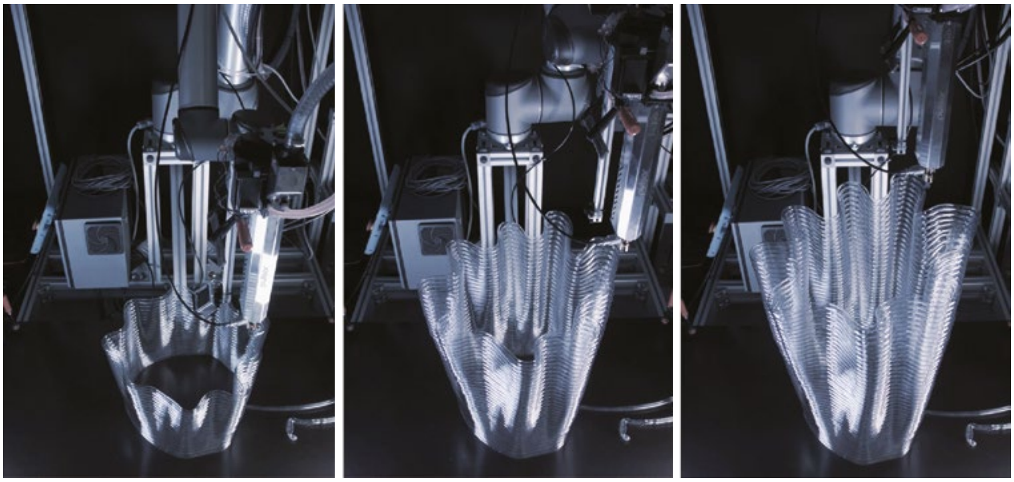


Figure 11: The actual robotic 3D printing is set up for large scale vertical 3D printing using the UR10 robotic arm and FGFBX extruder. From left to right the print progression. Time between images: approx. 60 minutes.

Figure 12: large scale Prototype Blow extrusion in two segments at maximum printing area of the robotic setup with UR10 robotic arm. Each segment of prototype is 1100 mm high and took about 300 minutes to print. Each segment only uses 5 Kg of PETG for print. (Photo Credit: Samim Mehdizadeh).

Figure 13: the results of blow extrusion in FGFBX procedure and PETG material varying the pipe diameter through variable material flew, air pressure. The hollow strands Diameter varies from 10mm to 45mm (Photo credit: Samim Mehdizadeh).

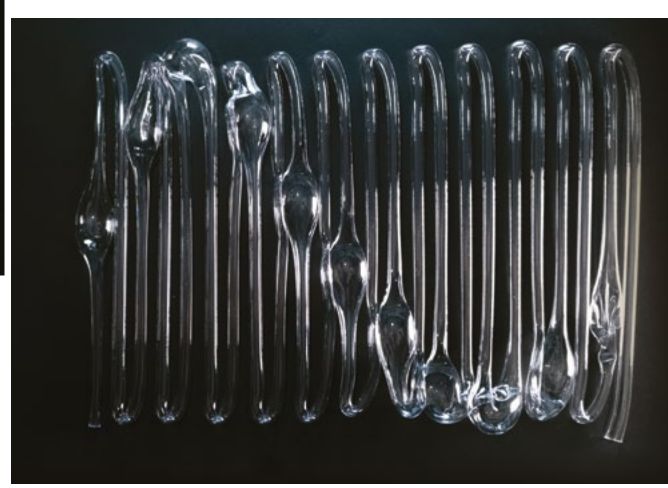


Figure 14: The results of blow extrusion in FGFBX procedure and PETG material varying the pipe diameter through variable material flew, air pressure. The hollow strands Diameter varies from 10mm to 45mm (Photo credit: Samim Mehdizadeh).

ACKNOWLEDGEMENTS

The presented scope of research on Blow extrusion is the result of interdisciplinary research at TU Darmstadt between the faculties of mechanical engineering and architecture, kindly funded by the "Forum for Interdisciplinary Research" (FiF) of TU Darmstadt under the project name "*Luft nach oben*" The research has been supported by Dr. Dieter spiel at Institute of Printing Science and Technology (IDD), Prof. Dr. Andreeas Blaeser at Institute for BioMedical Printing Technology (BMT), Department of Mechanical Engineering, TU Darmstadt. We would like to thank IDD's student assistants Moritz Birkner and Philip Gransow and DDU student Assistant David Bekesi for his support on large scale prototyping.

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