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BUILT ENVIRONMENT

ADDITIVE MANUFACTURING

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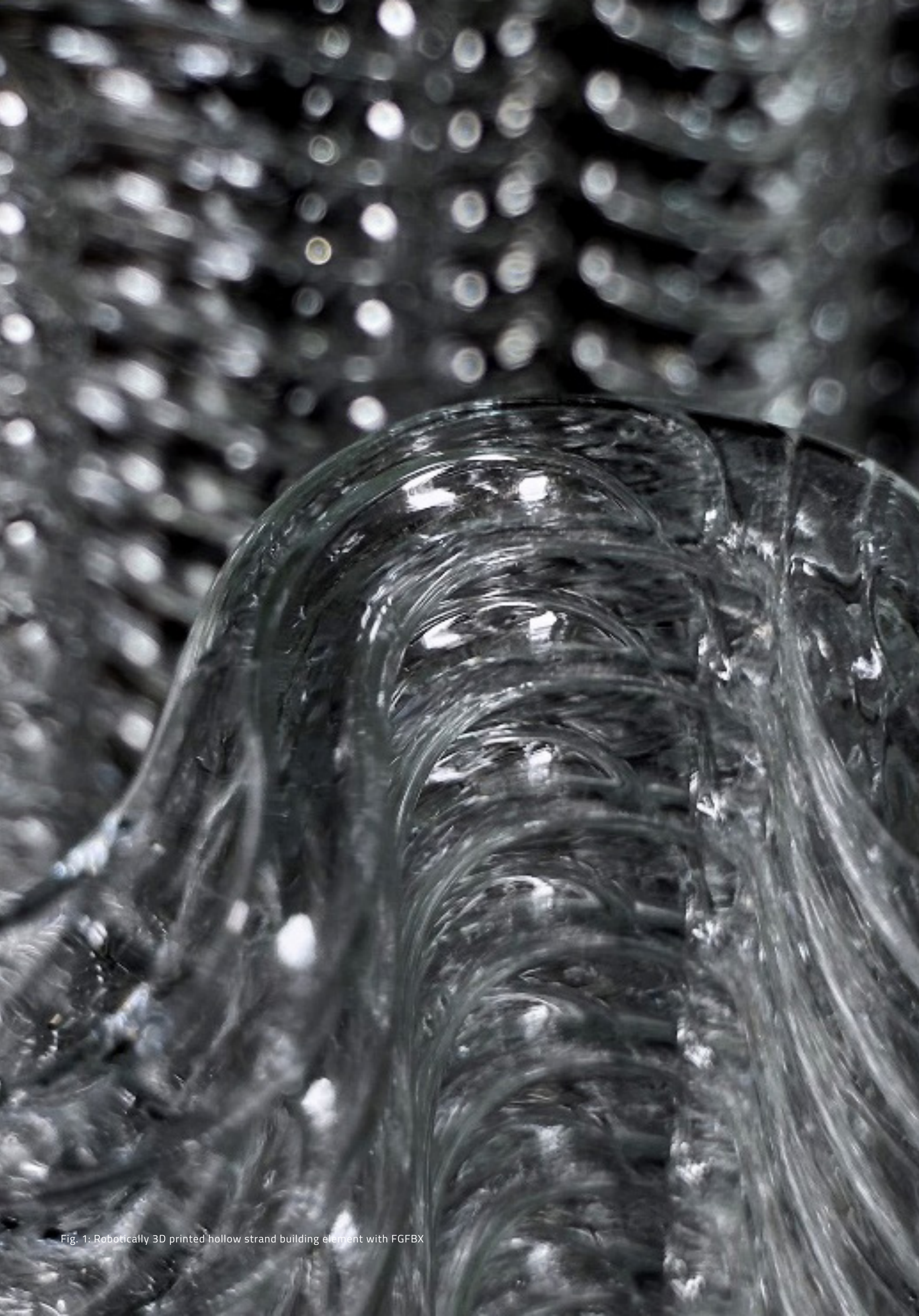

Fig. 1: Robotically 3D printed hollow strand building element with FGFBX

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

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Abstract

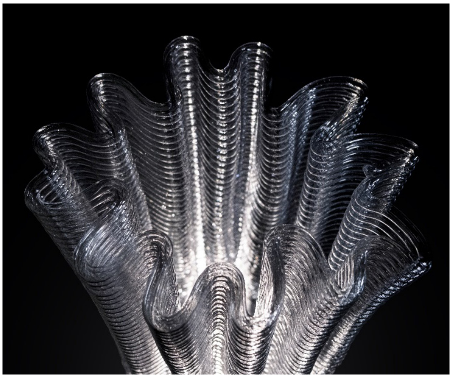
Blow Extrusion (BX) 3D Printing is an advanced additive manufacturing (AM) technique that allows 3D fabrication with hollow strands. We present BX using Fused Granular Fabrication (FGF) and Fused Filament Fabrication (FFF) which combines multi-material 3D printing, blow extrusion, robotic fabrication,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

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

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

Introduction

The construction industry is responsible for approximately 20 percent of plastic consumption in Europe [2]. Thermoplastics cover a large part of used plastics that allow for recycling and reuse [7], which makes it a suitable material for construction industry [4]. Additive manufacturing and large-scale robotic 3D printing have become a constantly expanding, well-developed research field in the AEC industries with a great market capacity [8, 9]. Our proposed method allows for significant material reduction in large-scale 3D printing with thermoplastics through the extrusion of hollow strands instead of solid material.



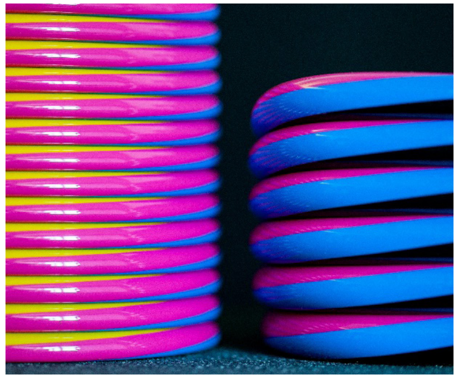


Fig. 2: left: BX 3D Printing with Fused Granular Fabrication (FGF), right: BX 3D printing with four colors Fused filament fabrication (FFF). Both specimens were manufactured using the same nozzle but different parameters for air flow.

Background

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

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

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

Methodology

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

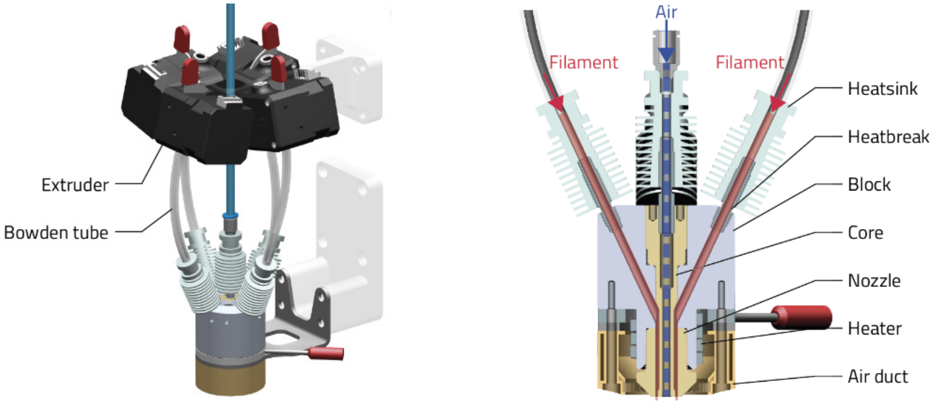


Fig. 3: FFFBX mechanical setup and printhead assembly

Mechanical challenges

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

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

(b) Independent of the feedstock, the nozzles require a design that allows air to be introduced through the center of the molten material. We achieve this by using a coaxial nozzle with a modular design. For FFFBX the four channels in the heated block (Fig. 03) hit a core and are fed into the nozzle. The tube diameter at the outlet is 8 mm on the outside and 6.5 mm on the inside in a non-expanded state. For FGFBX, the nozzle is installed on the existing pellet extruder and is characterized by a three-piece design consisting of block, core and barrel (see Fig. 04). In this case, the extrudate diameter is 10 mm on the outside and 8 mm on the inside in a non-expanded state.

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

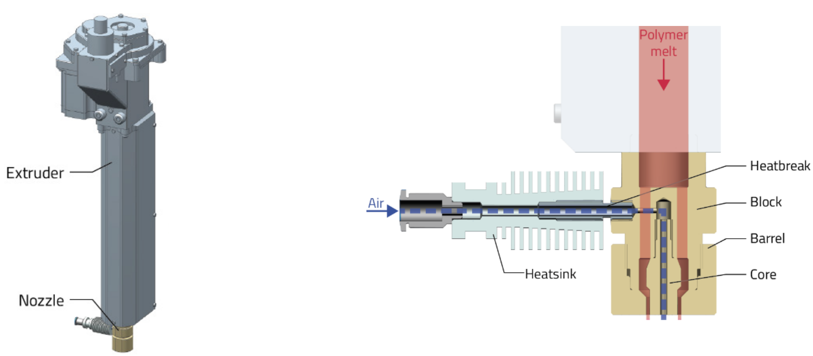


Fig. 4: FGFBX mechanical setup and printhead assembly

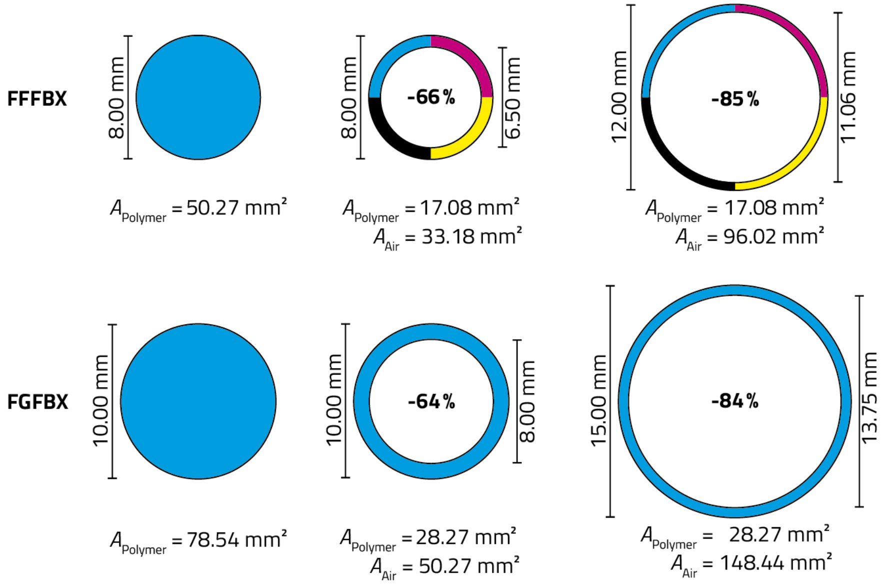


Fig. 5: Material reduction in percent compared to the full cross-section (left) for hollow strands produced using FFFBX and FGFBX without inflation (center) and with an increase in size by a factor of 1.5 (right) by Blow Extrusion where A represents the area.

Digital to physical framework for robotic 3D printing

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

Prototyping and Results

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

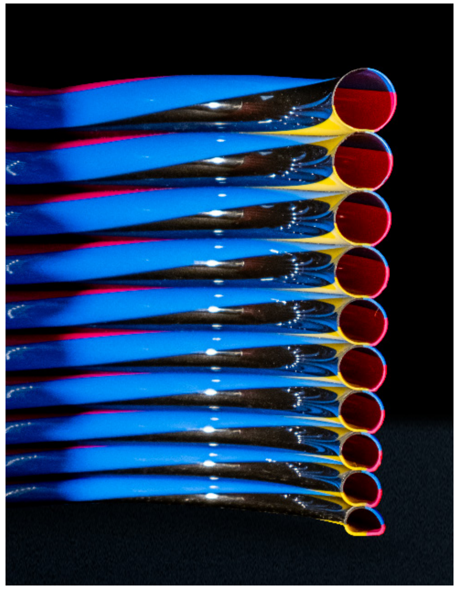



Fig. 6: left: BX 3D printed results with robotic arm FGFBX (segment of a Column prototype), right: varied the hollow strand cross sections with multi-material FFFBX

Conclusion and outlook

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

Acknowledgements

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