An Integrated Robotic 3D Printing System for Carbon Fiber Composite Building Elements

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ABSTRACT

This paper presents a novel method for fabricating lightweight composite building components by integrating possible strategies of fused filament fabrication (FFF) 3D printing (3DP).

Due to the versatility of the FFF molten material extrusion process, the fabrication method can vary in the deposition, spatial-extrusion, and multi-material add-on. For an efficient and effective FFF of large-scale freeform building elements, this research proposes to integrate these three strategies into a single 3DP process: the deposition of the surface shell for structurally-sound enclosed artifacts, spatial-extrusion infill for faster fabrication, and add-on continuous carbon fibers for structural reinforcement. This research includes the development of an integrated robotic fabrication system and the exploration of a material efficiency strategy by grading materials of plastic and carbon fiber.

Two prototypical large-scale elements, a beam and a sandwich panel, are fabricated. The prototypes show the potential of integrated FFF through features which include multi-material gradation, complex geometry, lightness, and structural integrity under rapid manufacturing.

BACKGROUND

Plastics are established materials with decades of successful use in architecture due to their excellent material properties: high-formability and lightness (Engelsmann, Spalding, and Peters 2012). Fiber-reinforced plastic composites, in particular, are well suited for lightweight building applications. Composites are defined as materials in which two or more elements are combined to form a new, useful material (Jones 1998). Notably, carbon fibers have a very efficient weight-to-strength ratio in comparison to other fiber materials, such as glass and aramid, and are 40% lighter and 10 times stronger than steel (Mallick 1997). Despite these beneficial properties, carbon fiber-reinforced plastics (CFRPs) have the limitation of often producing expensive molds, especially when the design of artifacts requires unique shapes (Kwon, Eichenhofer, Kyttas, and Dillenburger 2018).

Recent innovation in fabrication through 3D printing (3DP) has the potential to eliminate the need for a mold, which has been the main cost driver of conventional

CFRP manufacturing. At the same time, 3DP technologies boost up the formability of plastics further, allowing the fabrication of unprecedented freeform shapes and highly complex geometries with ease (Ryder et al. 2002). Moreover, 3DP also allows the single-process fabrication of multiple materials, enabling the efficient creation of composite building components with highly detailed and accurate placement of materials.

The interest of this research lies in plastic 3DP technological processes that can directly build up both polymer and continuous carbon fiber. Among the existing technologies, fused filament fabrication (FFF) satisfies this condition with numerous advantages. FFF is a widely available 3DP technology in which molten plastic material is extruded and hardens instantly after extrusion. FFF can use a wide variety of thermoplastics with fibers, and its hardware setup is simple and accessible. Furthermore, due to the nature of the versatile extrusion process, FFF is unique among the different plastic 3DP technologies for its ability to broaden the methods of the fabrication process, namely through layer deposition, spatial extrusion and add-on.

In architecture, this ability could allow not only the fabrication of complex shapes but also the integration of different structural types, such as spatial or porous structures and double-shell structures, to be fabricated at once in an uninterrupted procedure.

Furthermore, FFF 3DP can enable material gradations, i.e., different plastic material densities and varying carbon-fiber orientations. By placing the plastic and carbon fibers only where needed, the 3D-printed components can be efficiently adapted for specific load cases, achieving smaller dead-loads, and the amount of required material can be reduced, enabling efficient use of resources.

In this context, the paper reviews state-of-the-art methods of FFF 3DP in architecture, highlighting the specific advantages and challenges of each, and describes the development of an optimal and integrated strategy of 3DP for the efficient fabrication of composite building components.

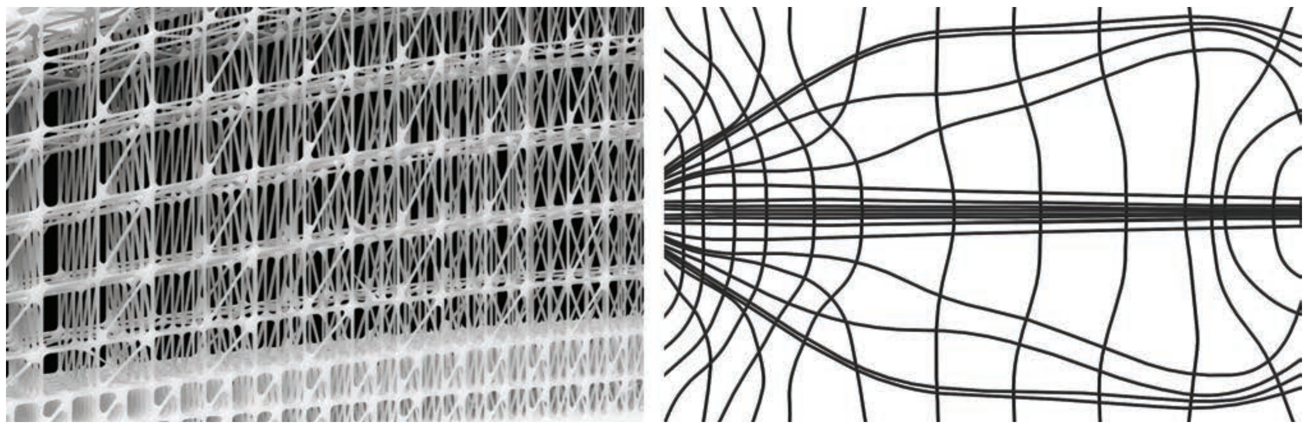


Figure 1: (Left) Example of varying the density of porous structures for the spatial-extrusion plastics; (right) exemplary stresslines for the add-on of CFRP.

STATE OF THE ART

This section presents an overview of recent developments in FFF 3DP for architecture.

Fused Deposition Modeling

FFF 3DP in contours, also known under the term fused deposition modeling (FDM), is the most popular method of plastic 3DP. FDM works by laying down material in layers; a continuous raw filament is fed through a heated extruder head and is deposited on the growing work.

FDM can produce artifacts to large scales (~26 m³) with fabrication speeds of up to 50 kg/h and flexible resolution (0.1 mm to 9 mm in extrusion diameters) (Duty et al. 2017). However, a reasonable speed for the fabrication of architectural components can only be achieved when the resolution is relatively low.

In architecture, the KamerMaker, developed by DUS Architects, uses a thick diameter extrusion nozzle (6 mm) with a 17 m³ print volume. This 3D printer has been used to build a Dutch canal house out of large-scale prefabricated components (Holloway 2013). This method showcases how a faster process can be achieved while improving the structural capacity by having thick wall features.

Spatial Extrusion

Due to the versatility of the molten plastic extrusion process, FFF can also work spatially by drawing molten plastics in the air and cooling them down instantly. In addition to the fast fabrication achieved through thick extrusion, spatial extrusion can also extend rapid fabrication further.

Spatial extrusion has been investigated in architecture by two groups, Gramazio Kohler Research at ETH Zurich and Branch Technology (Hack and Lauer 2014; Molitch-Hou 2015). Their processes have been specifically developed to achieve lightweight engineering and fast fabrication for the manufacturing of molds for concrete and/or foam casting.

However, the spatially extruded structure alone has a considerably low structural capacity due to its low-density characteristics. To improve the structural integrity of the spatially extruded plastic structures, the CurVoxels group at Research Cluster 4 at The Bartlett School of Architecture UCL explored computational design methods. The methods show how a computational tool allows the gradation of the material density of porous structures. These processes can achieve both the rigidity of the structure and a reasonable fabrication time (Kaleel, Kwon, and Li 2018).

Furthermore, by filling the internal geometry with light, low-dense spatial structures, spatial extrusion can act as an efficient infill structure for contour FFF 3DP (Ai Build 2016). These minimal tension connections allow faster 3DP while maintaining the stability of the building components.

Add-On

Nevertheless, most FFF 3D-printed artifacts can hardly be used alone for any applications in architecture due to their limited bending strength resulting from the weak bond between plastic layers. Due to the nature of the stacking procedure of FFF, the adhesion along the vertical axis of every layer is weak (Peters 2016). However, building components require strength in various directions.

As a possible solution to address this limitation, multi-directional FFF 3DP, otherwise known as add-on fabrication, has been investigated. By using multi-axis robotic arms, the add-on process works by applying additional material onto the previously FDM 3D-printed artifacts in a direction that is opposite to the vertical axis of layers. This method has noteworthy implications for improving the bonding strength of 3D-printed components, achieving equivalent structural behavior (Petch 2016; Tam et al. 2016).

Furthermore, the add-on method can also be used to apply carbon fibers allowing the reinforcement of 3D-printed artifacts, resulting in CFRP structures.

This section presented the state of the art of freeform FFF 3DP strategies. These three methods, with complementary characteristics, need to be combined for the efficient fabrication of composite building components in regard to fabrication time, material use, and structural integrity. Therefore, this research investigates the integration of all three strategies into a single 3DP process for the efficient FFF of large-scale freeform plastic elements: the FDM shell for the structural integrity, achieved through a relatively thick material deposition; the spatial-extrusion infill for the reasonable and efficient speed of fabrication; and the add-on to provide the necessary structural reinforcement through multi-directional material extrusion.

APPROACH: AN INTEGRATED FFF SYSTEM

In order to 3D print CFRP components with structural integrity in a time- and cost-effective manner, this research investigates: 1) an integrated fabrication strategy combining these three methods of FFF, and 2) an efficient strategy of locally differentiating material compositions of plastic and carbon fiber. Specifically, the following approach is conducted:

- *Fabrication process development.* Integration of successive planar layer deposition and spatial extrusion; integrated subsequent add-on process with strands of continuous high-performance CFRP material.
- *Computational design.* Path planning: Generating the uninterrupted path for deposition, spatial extrusion, and add-on processes. Plastic material gradation with the data from finite element analysis (FEA): By applying specific load cases, the amount of stress is calculated in the voxel field, and each voxel is then deformed and/or subdivided according to the stress-value, allowing only structurally weak areas to be densified (fig. 1, left). Carbon fiber material gradation with the data from FEA: The system allows the accurate placement of the CFRP in a structurally informed manner, generating stress lines as the tool path of the CFRP add-on, reinforcing along the stress vector fields, and discretizing multiple materials according to their functionality (form and structure) efficiently and accurately, hence reducing the amount of carbon fiber (fig. 1, right).

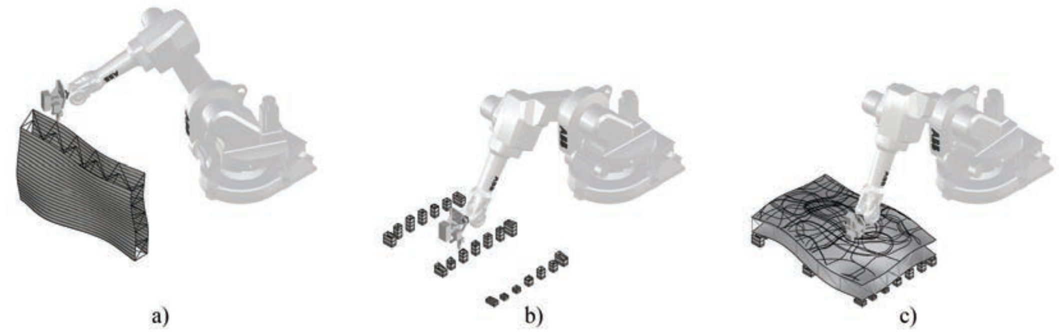
The approach is implemented in two applications, the beam and double-shell sandwich components, to explore design potentials. Specific areas of focus are identified for each full-scale demonstrator:

- *Beam.* This experiment focuses on investigating material gradation of plastic; as a possible option of integrating FFF fabrication processes—FDM, spatial extrusion, and add-on—fabrication steps follow 1) spatial extrusion, 2) deposition onto the spatial structure, and 3) add-on of CFRP (fig. 2).
- *Sandwich panel.* This experiment focuses on the design and fabrication of an efficient CFRP layout, allowing accurate placement of the CFRP in a structurally-informed manner; as a second possible option of integrating the FFF fabrication processes, fabrication steps are as follows: a) simultaneous 3DP of spatial structure and surfaces, b) FDM 3DP of temporary support rests, and c) manual repositioning (90° rotation) of the initially 3D-printed base structure onto the support rests for local reinforcement with add-on CFRP 3DP.

With two prototypes, this research develops path generation methods of integrating spatial extrusion, deposition, and add-on, with special consideration to avoid the geometrical limitations of each of the FFF methods and to allow wide applicability to various shapes and architectural components.

Figure 2: Fabrication steps of the beam component.

Figure 3: Fabrication steps of the sandwich component.



RESULTS

The research demonstrates the approach above through the 3DP of two full-scale building elements: the beam (1.8 m x 0.35 m x 0.15 m; ~30 hours; ø 4 mm nozzle) and sandwich panel (0.9 m x 0.6 m x 0.25 m; ~15 hours; ø 2.5 mm nozzle).

Beam

Spatially extruded structures were sandwiched vertically between a pair of surfaces, allowing the fabrication of the plastic object to be conducted by first 3DP the lower flat surface, then the spatial extrusion, and lastly the upper freeform surface. Consequently, the CFRP material could be directly added onto the top surface of the beam in an uninterrupted manner (fig. 4).

By demonstrating the 3DP of spatial structures with varying density based on the FEA (fig. 5, left), it was observed that the lightweight beam (~15 kg) could be self-supporting and bear approximately 60 kg of the center load (fig. 5, right).

However, the plastic deposition of the upper surface onto the spatially extruded structure reduces the quality of the surface, critically leading to the add-on CFRP being difficult. Immediately following the top surface deposition, these local errors influence the following step of CFRP add-on (fig. 6).

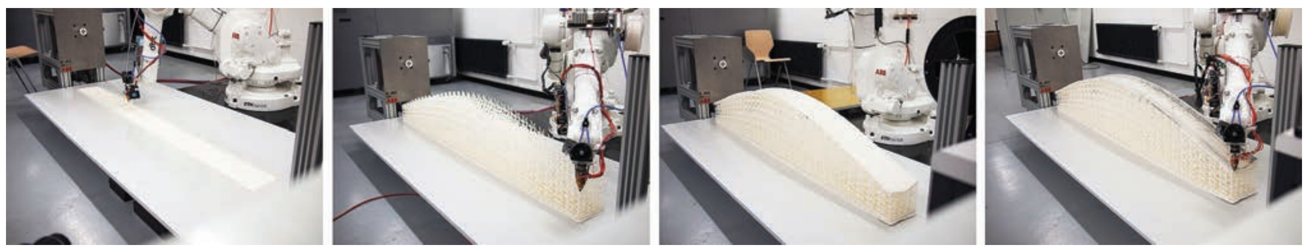
Consequently, precision represents one of the largest challenges, since any significant deviation between the precisely designed base surface and the fabricated one can interrupt the continuity of the add-on paths and affect the functionality of the CFRP.

Sandwich Panel

A pair of outer surface shells was 3D-printed with multi-directional, spatially extruded, minimal infill structures in between (fig. 8, top). Subsequently, the CFRP material was added onto the prefabricated outer surfaces of the panel after manually repositioning the panel on temporary support rests. By demonstrating the CFRP add-on along the calculated stress lines, the minimal carbon fiber materials could effectively reinforce the structure. It was observed that the bonding strength of the 3D-printed plastic was improved, allowing the creation of a self-supporting, double-curvature sandwich-panel element (fig. 7).

Moreover, the double-shell sandwich panel was proven to be fabricated in a single, uninterrupted

Figure 4: The 3DP sequence of the beam (left to right): deposition of the lower flat surface; spatial extrusion of inner structures; deposition of the upper surface; and CFRP add-on.



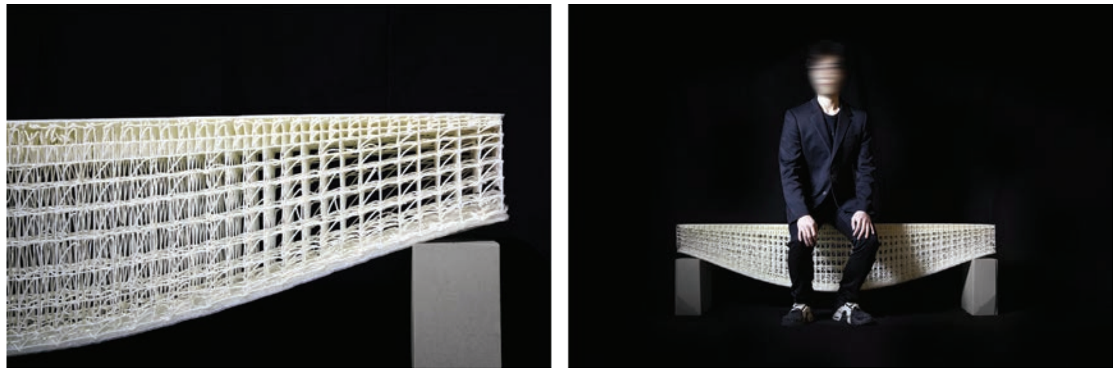


Figure 5: (Left) Graded material density of the spatially extruded structures; (right) sitting experiment on the beam.

fabrication process (fig. 8, top). The simultaneous fabrication of deposition and spatial extrusion enable a high surface quality without substantial deviation, allowing add-on processes (fig. 8, bottom).

However, uneven material shrinkage during the manufacturing process can lead to additive errors on the panel object, which requires the use of distance measuring and add-on path revision processes (Kwon et al. 2018). In addition to this challenge, manual repositioning also causes imprecision resulting in the inaccurate placement of the specific structurally informed CFRP layout.

Furthermore, the current hardware setup limits the thickness of the double-shell structure to no less than 10 cm due to the physical dimension of the custom extruder used. Also, manufacturable complex shapes are limited because of the current setup of nozzle position that is always fixed to the z-axis, while the CFRP add-on was realized multi-directionally, perpendicular to the freeform base surfaces.

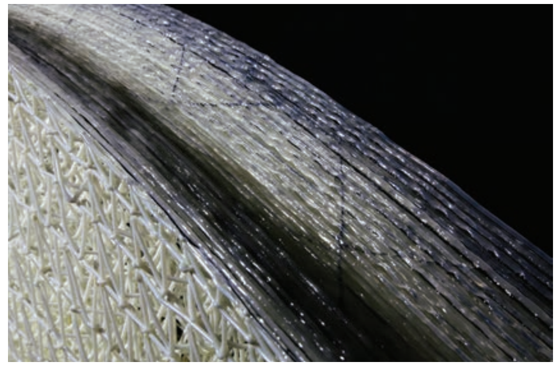


Figure 6: The uneven quality of the upper freeform surface, causing complications of CFRP add-on.

DISCUSSION AND OUTLOOK

From an architectural point of view, the proposed app-roach can be applied to several cases of building components where lightness and geometric- or material-based differentiation with reasonable fabrication speed is required. In order to further broaden architectural applicability, larger-scale applications should be tested.

Whereas thick extrusion methods decrease the fabrication time, they contribute to the loss of precision in geometrically complex artifacts. This dilemma of inverse proportional benefits remains one of the largest challenges. To address this, using multiple diameters of nozzles in a single 3DP process is considered in order to create surface shells with a high-resolution of extrusion (smallest feature 0.1 mm) and infill structures with a thick extrusion. The fundamental limitation of low bonding strength from FFF 3DP appears to be improved by the local CFRP add-on 3DP. Future research will quantify the structural benefits of CFRP through structural assessment methods such as three-point bending and compression tests. Moreover, taking into account the limitations observed from the results, one can consider further investigating:

- *Extrusion tool-head*. The design of the extruder should consider dimensional flexibility in order to minimally interrupt the fabrication process, resulting in building component designs that can achieve higher geometric freedom.
- *Multi-axis deposition and spatial extrusion*. Due to the fixed z-axis of the nozzle during the plastic 3DP, possible geometric features are limited. The ability to freely rotate the extrusion head, which is a unique benefit of using the six-axis robotic arm, can enable the realization of building components with unprecedented geometric freedom and support-free FFF 3DP.
- *Automated vertical repositioning*. Automation for the repositioning of prefabricated plastic structures is considered not only to improve the precision of the add-on process but also to further save the plastic material, which is currently used for the temporary support rests.

CONCLUSION

This paper describes a method of integrating three FFF 3DP strategies—deposition, spatial extrusion, and add-on—to materialize lightweight freeform building components. The presented

Figure 7: 3D-printed sandwich panel with stress line based CFRP add-on.

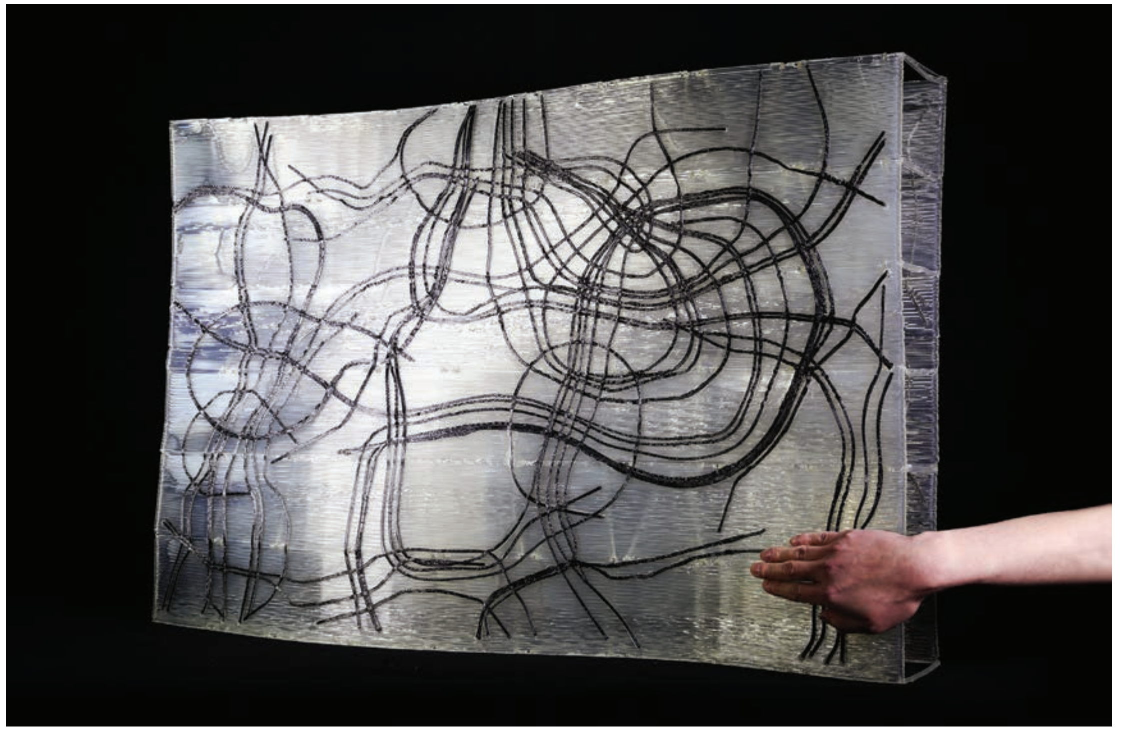
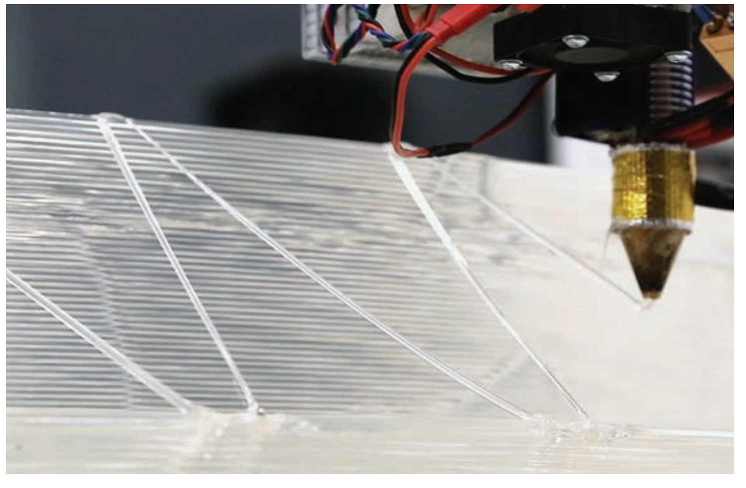
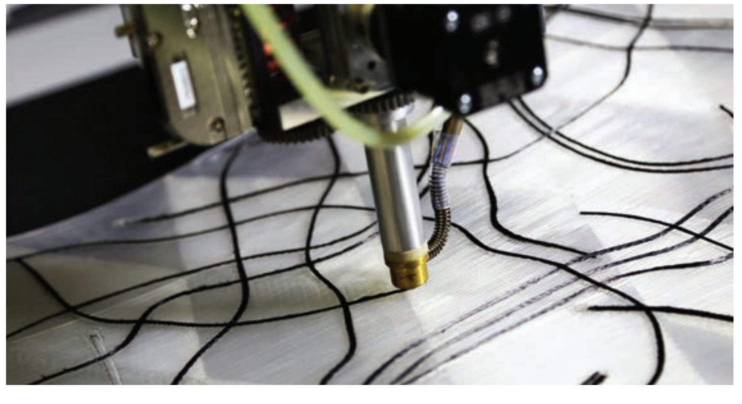


Figure 8: (right) Spatial extrusion processing; (below) CFRP add-on processing.





experiments, the beam and the sandwich panel, have shown the possibility of fabricating complex geometries combining surface and porous structures with features of efficient material gradation and structural multi-material use.

With further improvement of the fabrication process and assessment of structural capacity, the proposed strategy could be used for the prefabrication of double-shell building components, promising a more efficient and sustainable construction process through achieving the lightness of structures, elimination of waste material, and greater design freedom.

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IMAGE CREDITS

ACKNOWLEDGMENTS

The authors would like to thank many partners and collaborators whose dedication helped us fulfill the research described in this paper:

- Thodoris Kyttas, Demetris Shammas, Andrei Jipa, Mathias Bernhard, Pietro Odaglia, Dr. Mania Aghaei Meibodi, Angela Yoo, and the rest of the DBT personnel at ETH Zurich
- Professor Dr. Paolo Ermanni and Martin Eichenhofer (Composite Materials and Adaptive Structures, ETH Zurich)
- Michael Lyrenmann and Philippe Fleischmann (technical support, ETH Zurich)
- David Jenny (Gramazio Kohler Research, ETH Zurich)
- Ma Xijie, Philippe Steiner, Michael Thoma, and Katharina Wepler (student assistants, ETH Zurich)
- 9T Labs, Extrudr (industry partners), and HAL Robotics (software support).

This research is supported by the National Centre of Competence in Research (NCCR) Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement #51NF40-141853).