LARGE-SCALE 3D PRINTING FOR FUNCTIONALLY-GRADED FACADE

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Abstract. Additive manufacturing (AM) technologies such as fused deposition modeling (FDM) have been gaining ground in architecture due to their potential to fabricate geometrically complex building components with integrated functionality. With that in mind, this paper showcases a novel design and fabrication strategy for the production of functionally graded façade elements. Three functional integrations are investigated: gradient infill structures (Figure 1), a non-orthogonal discretization approach for 3D-printed façade elements, and an integrated snapping panel-to-panel connection system. The presented process is then incorporated into a large-scale demonstrator consisting of eight individual façade-panel elements. This paper first presents a prototypical approach for a large-scale, graded 3D-printed facade system with non-standard discretization and then opens the discussion to further related challenges.

Keywords. Large-scale 3D Printing; Freeform Façade; Functional Integration; Complex 3D Assembly Connection.

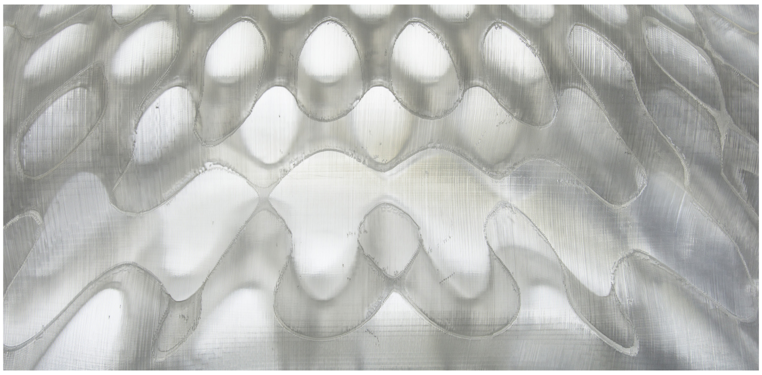


Figure 1. Graded infill microsurface.

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 1, 183-192. © 2020 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

1. Introduction

1.1. BACKGROUND

The primary function of a façade is to serve as an interface between the interior and exterior environments of a building while sheltering its occupants (Zaera-Polo 2014). Thus, façade design needs to be site-specific in order to address particular climate challenges, such as inclement or arid weather (Zaera-Polo 2014). These design constraints, along with the fact that façades account for 70% of a building's energy performance (Yang and Choi 2015), make façade design vital for sustainable architecture. Furthermore, often the façade is the first and sometimes only impression of a building, being its most prominent component (Zaera-Polo 2014); and as such, it needs to meet certain architectural design criteria, in addition to the primary functional requirements.

While complex façade design requirements are currently addressed with conventional fabrication strategies, AM technologies are gaining ground in architecture and expanding the design space of façade elements. AM enables the fabrication of building components with high geometric complexity and holds the potential to materialize the unprecedented integration of multi-functionality (Aghaei-Meibodi et al. 2017; Kwon et al. 2019). 3D printing (3DP) can offer the opportunity to integrate functional geometric features of complex assembly details as well as functional layers such as insulation, internal channels for conduits and ventilation, and/or electric infrastructure in a single fabrication process. Moreover, the unique geometries of every façade element can accommodate views, shading, and other site-specific requirements due to the customizability of 3DP. Unlike internal building components such as slabs and walls, which are designed universally, often regardless of building location, façade elements are relevant for the investigation of site-specific adaptability. Achieving such functional integration and site-responsive designs is challenging, time-consuming, and expensive for conventional fabrication methods because it requires the use of unique, single-use molds (Strauss 2013). However, AM technologies can accommodate these complexities and functionalities without added time or cost.

Therefore, this research stems from the interest to integrate multiple functional and design aspects of a façade into a coherent computational design and fabrication process.

1.2. STATE-OF-THE-ART

In line with the increased application of AM in architecture, recently a few projects have been investigating 3D-printed façades (Strauss 2013), mostly by using FDM as a fabrication method (Snooks 2018). FDM is an AM fabrication method that creates three-dimensional objects from thermoplastic materials, by depositing material layer by layer. In contrast to other AM technologies, FDM offers the freedom to produce geometrically complex shapes at a faster rate of production and lower cost (Ryder et al. 2002).

Several research projects which used FDM 3DP are considered as precedents for this paper. SensiLab Studio (Snooks 2018) and Fluid Morphology (Mungenast 2017), both utilize large-scale FDM 3DP for full-scale building elements. Two other research projects combine the use of multiple materials for functionally graded performance of 3D-printed façade elements. In Digital Composites (Kwon et al. 2018), carbon fiber is 3D-printed laterally to the FDM layers of the façade panel along the stress lines to provide structural stability. Similarly, Electric Skin integrates the fabrication of electric infrastructure simultaneously with the building skin in a custom, multi-material 3DP process (Kwon et al. 2019).

2. Complex Snap-Fit Graded Façade

Although these precedents show the possibilities of FDM to innovate the design approach for façade elements, they also raise new questions. While the geometries presented by the projects are rather complex, the discretization systems remain orthogonal. The freedom offered by 3DP could enable an alternative and more integrated, non-orthogonal discretization procedure, specifically for complex geometries. Furthermore, while the exterior of these digitally designed elements has been investigated to a certain extent (Mungenast 2017; Snooks 2018), the internal geometries and their capacity for functional integration have not yet been widely explored.

A 3D-printed façade is not only defined by its inner and outer shell, but also by its internal geometries, or infill structures (Kwon and Dillenburger 2019). In contrast to conventional manufacturing, AM enables the creation of complex interior structures at no additional costs and has the capacity to create unprecedented functionally-graded inner cores. Therefore, the design space of inherent site-specific façade characteristics could benefit from the freedom gained through AM design and fabrication.

Accordingly, the research aims to develop these topics beyond the state-of-the-art of FDM 3D-printed façades by focusing on three main aspects of façade elements: gradient infill structures, a new discretization method and integrated snapping connection details between elements. In addition, two design aspects are explored: façade element topology and translucency.

3. Approach

FDM is used for this research and polylactic acid (PLA) is chosen as the 3DP material, due to its ubiquity, ease of 3DP, and interchangeability by other kinds of polymers. Functional and design criteria are investigated through a series of test prints. Initially, connection details and material properties are tested through small-scale prints, while infill patterns and an exterior shell design method are developed through medium-scale experiments. As a final step, full-scale elements are 3D-printed, achieving precise tolerances of assembly connections. The results, which are explained throughout the following sections, were applied on a one-to-one scale demonstrator.

3.1. FUNCTIONALLY GRADED INFILL STRUCTURES

The 3DP infill patterns investigated in this research create a gradient inner structure that varies the opacity and translucency of the facade panel, dependent on the size of the inner geometries. It is influenced by external inputs such as light directionality and its location on the building as well as the overall façade itself. The infill geometry is a minimal surface generated through volumetric modeling, a digital design process that utilizes distance functions to generate geometry (Bernhard et al. 2018). The size of these internal geometries is controlled by the function of the minimal surface through parameters such as wavelength and amplitude, and the gradient is generated through external control inputs, such as curves or points (Figure 2.a).

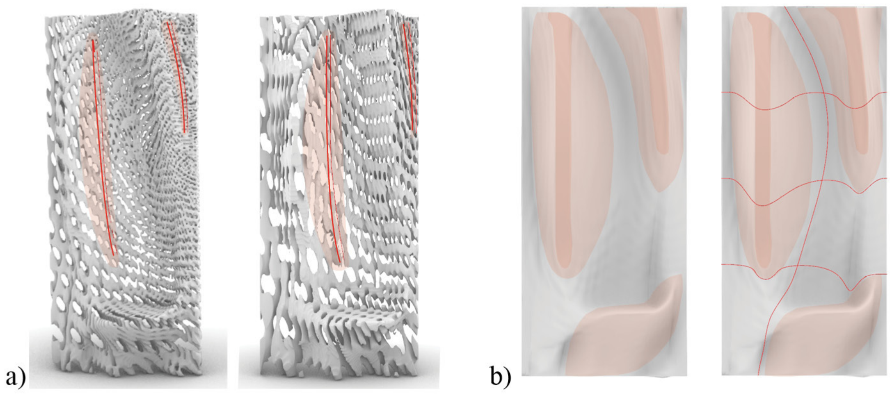


Figure 2. a) Investigated minimal surface internal gradient geometries with wavelengths of 10 and 5. b) Zones and lines of discretization.

3.2. DISCRETIZATION METHOD FOR NON-ORTHOGONAL FAÇADE ELEMENTS

In order to improve transportability and human-scale operability, a computational discretization method is implemented, improving time-effectiveness in on-site assembly. The overall facade can be subdivided through horizontal and vertical curved seams, creating efficiently discretized non-orthogonal panels (Figure 2.b). The vertical seam is located in the façade thinnest section area in order to achieve the lowest seam section variability and ease of assembly. This is calculated by conducting closest point analysis on curves obtained from slicing the exterior and interior surfaces. Horizontal seams are placed at equidistant heights, taking into consideration the maximum 3DP volume of the fabrication setups. These seam curves are used as a reference in generating the horizontal connection tabs (Figure 3.b). These two different strategies prioritize the vertical seams over the horizontal seams so as to establish a predefined assembly sequence. All pieces are oriented in such a way that all 3D-printed supports are minimized and their removal eased.

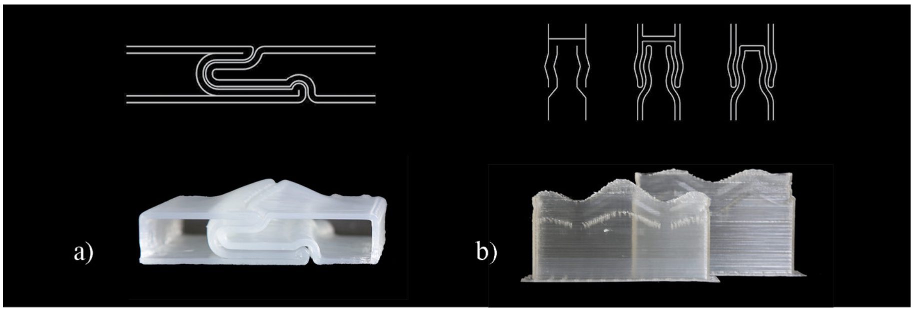


Figure 3. a) Vertical connection with a tolerance of 1mm. b) Horizontal connection with a tolerance of 2mm.

3.3. DESIGN METHOD FOR NON-ORTHOGONAL FAÇADE PANEL CONNECTIONS

Implementing AM techniques allows for more design flexibility and the fabrication of non-conventional complex façade designs. Standard connection systems need to be rethought by incorporating the benefits of 3DP. This will result in improved connection functionality and a new connection appearance.

In order to understand conventional connection systems, metal or foam-cored sandwich panel connection details are analyzed (Koschade 2011) and snap-fit connection strategies are studied (Bonenberger 2016). Snapping features are integrated into the connection design to take advantage of the bending properties of the PLA (Klahn et al. 2016).

3DP tolerances and offsets are an important factor in the design of the snapping connection and have to be calibrated for each snapping feature. Two lateral snapping tabs with a 2mm tolerance constitute the horizontal seams, whereas a snapping hook with 1mm tolerance locks the elements together in the vertical seams (Figure 3).

3.4. THREE DISTINCT FABRICATION SETUPS

For FDM 3DP to be applicable at an architectural scale with reasonable fabrication time, the 3DP process for the large-scale demonstrator is parallelized, and three different setups are used (Table 1). For all setups, a custom low-resolution tool head is implemented. In general, the layer height of a conventional desktop 3D printer is approx. 0.1mm-0.25mm, allowing high 3DP resolution. In this research, low-resolution/high-volume 3DP setups are used, with a layer height of 1mm and a layer width of 2.7mm, which delivers more robust prints at a much faster 3DP time.

Table 1. Comparison of three different setups.

Printing Setup	Build Volume	Print Speed	Benefits / Quality
BigRep One	100x100x100cm	20mm/s	The largest available 3DP volume.
Custom Multi-Head 3D Printer	95x65x100cm	25mm/s	The fastest available 3DP speed.
ABB IRB1600 With Custom FDM 3DP Tool	100x70x82cm	23mm/s	Robust control of 3DP parameters with the highest quality.

4. Results

The following experiments incorporate optimal parameters derived from early-stage 3DP tests. The highest PLA translucency is achieved by 3DP with a nozzle temperature of 230ºC and reducing print speed by 30%. 3DP time is reduced by limiting overhangs to 50º to eliminate the need for supports but maintain 3DP quality.

4.1. INITIAL TEST RESULTS

4.1.1. Infill Gradients

Medium-scale experiments are conducted to investigate certain infill inherent functionalities, such as light control, structural enhancement or graded transitions (Figure 4).

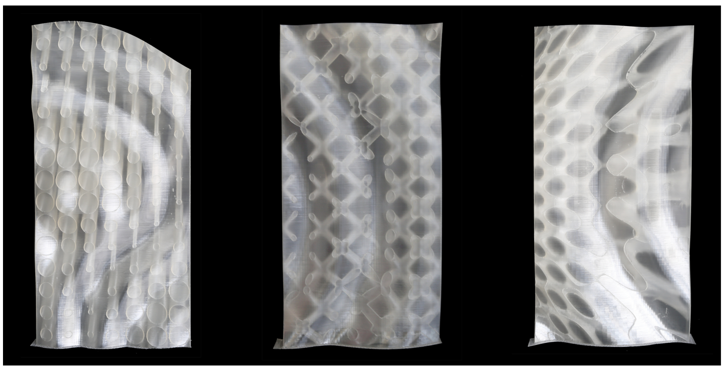
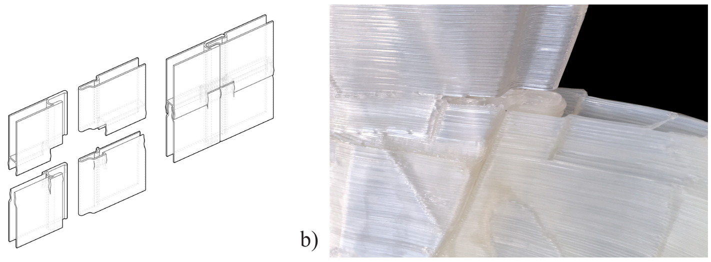


Figure 4. Investigated infill geometry types: circular gradient, truss-gradient, ShwartzP minimal surface gradient.

4.1.2. Connection Experiments

Different connection typologies such as compression, notches, and snapping are tested in small-scale. The connections that show the best performance horizontally and vertically are identified and subsequently, the cross-point between them is designed, introducing a hierarchy of vertical seam over the horizontal seams

(Figure 5).



a) b)

Figure 5. a) Assembly system connection crosspoint. b) Crosspoint in large-scale demonstrator.

4.2. LARGE-SCALE DEMONSTRATOR

The final demonstrator is a facade with a height of 3.0m and a width of 1.3m (Figure 6). In order to design it, a computational tool is developed with three main stages. As an initial step, daylighting studies inform the design of the overall façade geometry. The facade element has two major sections: the bottom, which incorporates an integrated functional seat, while the top is angled in such a way to receive direct light for most of the year. Attractor lines are used to apply sine wave functions that generate micro-patterns on the exterior and interior shell in order to improve surface rigidity (Jipa et al. 2019). As a second step, the infill geometries are generated, and finally, the full façade is discretized and smart connection details are applied.

Figure 6. Final 3DP façade demonstrator.

In order to allow for faster fabrication, the façade thickness varies between 2cm to 6cm and the volume of the seat is reduced, by incorporating an interior hollow pocket (Figure 7).

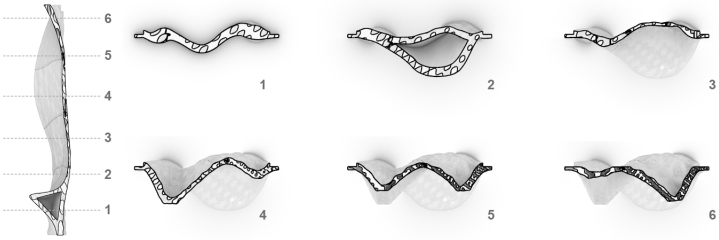


Figure 7. Façade vertical and horizontal sections.

Figure 8 shows the individual units discretized by one vertical seam and three horizontal through the above-mentioned computational method (see section 3.2). Each of the eight discretized panels is less than 10kg, except for the biggest piece (12kg). According to the size of pieces and each 3DP setup, pieces 1, 2, and 8 are 3D-printed on BigRep One; 4 and 5 with the ABB IRB1600; and 3,6 and,7 with the custom-built Multi-Head 3D Printer. The shortest 3DP time is 27 hours and the longest is 68 hours. The whole façade was simultaneously 3D-printed on these three setups in five days and post-processed (support removal, surface finish, etc.) in 4.5 hours, while the assembly was done within a few minutes only.

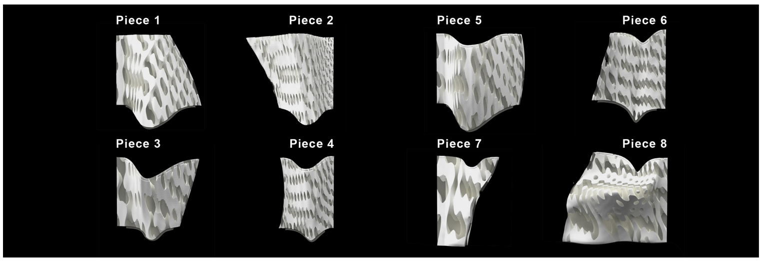


Figure 8. Volumetry of façade final pieces.

5. Discussion and Outlook

This research needs to be considered as a first prototypical approach to develop design and fabrication methods for bespoke façade elements. However, relevant aspects, such as insulation, wind loads, transparency, airtightness, and aging or deformation have not been evaluated yet, which is needed to make this façade system feasible to create an actual architectural component. As further topics of investigation, specialized testing facilities can be used providing the opportunity to simulate wind loads or heavy rain on a façade prototype allowing to study and to improve its behavior. Heat exposure and UV light overexposure experiments are considered to test material strength and to analyze PLA deterioration.

5.1. STRUCTURAL INTEGRATION: FOAMED COMPOSITES

Façade panels could be transformed easily into insulating composites, using the 3D-printed object as a mold for foam or other infill materials. There are several issues which should be considered: type of foam/material (particle-based, expansive, etc.); to what extent does this influence its recyclability; how to 3DP an airtight object in order to prevent leaks due to expansion forces of foam; effective material bonding between PLA and selected foam.

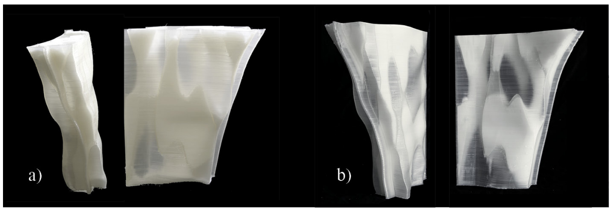


Figure 9. Initial tests of polyurethane foam infilled façade elements.

5.2. LOGIC OF DISCRETIZATION: FURTHER DEVELOPED

A more coherent design can be achieved with an improved discretization logic. Ideally, it should be programmed to not only follow the thinnest sections of the façade but also take into account the internal geometries. For the large-scale demonstrator, this is not taken into consideration, as seams and infill structures were not correlated. Prospectively, placing seams where there is less quantity of infill structures can create a more robust connection system and a consistent design.

5.3. CONNECTIONS FAÇADE-CEILING / FLOOR SLAB

The main focus of this research, regarding assembly strategies, is the panel-to-panel connections. For now, those connections are designed for fast 3DP and simple assembly. What still needs to be investigated is how water and airtight those connections are. Moreover, there are connections that have not been developed yet, such as panel-to-slab or panel-to-ceiling. These connections would have to hold the tributary weight of the façade applied linearly/punctually on the connection, plus wind loads.

6. Conclusion

This research demonstrates the potential of using 3DP to fabricate freeform customized façades elements where complexity can be added without increasing the cost of production. The developed assembly/connection system enables a non-orthogonal discretization approach, allowing for a more coherent overall design, which takes advantage of 3DP and its material properties. Currently, the developed gradient infill structure mainly serves visual and shading aspects, but additional functionalities can be imagined and integrated, such as inner channels to collect rainwater, and to heat and/or cool the façade, as well as insulation properties.

As AM holds the potential to customize façade elements adaptively, the authors strongly believe that 3D-printed façades can have a positive impact on the performance of buildings in the near future regarding integration, functionality, aesthetics, and sustainability.

Acknowledgments

The research was developed for a thesis of the 2018/19 MAS ETH DFAB. The MAS ETH DFAB is a one-year full-time educational program of the NCCR Digital Fabrication, jointly organized by Digital Building Technologies (DBT) and Gramazio Kohler Research. The authors would like to thank a number of partners and collaborators whose dedication helped fulfill the research described in this paper, including Mathias Bernhard, Andrei Jipa (DBT, ETH Zurich), FormFutura, Extrudr, Kaupo (industrial partners), Victoria Scoville and Loren Rapport.

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