High-Productivity Additive Manufacturing of Thermoplastic Composites through Fused Granulate Fabrication

L. Cummings-Jomphe, R. D. Farahani, M. Lévesque, and D. Therriault*

Department of Mechanical Engineering, Polytechnique Montréal, Montréal, Canada

**Corresponding author* (daniel.therriault@polymtl.ca)

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1. Abstract

Fused Granulate Fabrication (FGF) offers significantly higher material throughput than conventional Fused Filament Fabrication (FFF) through the direct extrusion of polymer pellets. While large-scale FGF systems have demonstrated extremely high deposition rates, relatively few studies have investigated medium-scale screw extruders (100–200 mm screw length) for the high-productivity manufacturing of thermoplastic composites. In this work, a medium-scale FGF platform based on a 135 mm screw extruder was developed and its capabilities were evaluated through three representative demonstrators. Fine-feature fabrication was first demonstrated through a 150 mm acoustic panel incorporating acoustic cells and microscaffold regions. High-throughput manufacturing was demonstrated through a near-meter-scale sandwich-structured longboard, for which a peak volumetric flow rate of 575 mm³/s was achieved, representing more than one order of magnitude increase over values typically reported for medium-scale FGF systems. Finally, an aircraft cabin interior cosmetic component was successfully fabricated using carbon fiber-reinforced polycarbonate (PC-CF), demonstrating the feasibility of processing engineering thermoplastic composites. Overall, the results demonstrate the ability of medium-scale FGF to bridge the gap between desktop pellet extrusion systems and large-format additive manufacturing platforms, enabling the rapid fabrication of near-meter-scale thermoplastic composite structures.

2. Introduction

Fused Filament Fabrication (FFF) is currently the most widely adopted extrusion-based additive manufacturing (AM) technology for thermoplastic composites. However, the productivity of filament-based systems remains fundamentally constrained by the use of continuous filament feedstock. In conventional FFF systems, volumetric flow rate is fundamentally limited by the combined constraints of the filament feeding mechanism and the thermal capacity of compact hot-end geometries [1]. As a result, filament-based systems are typically limited to volumetric flow rates below 100 mm³/s [2]. These limitations become increasingly significant when manufacturing near-meter-scale composite structures, where build times can extend to several days.

Fused Granulate Fabrication (FGF), also referred to as pellet extrusion additive manufacturing, addresses these limitations by directly processing polymer granules using a screw-driven extrusion system. Compared with filament-based processes, the extended melting zone and continuous conveying action of the screw enable substantially higher material throughput while also reducing feedstock costs through the use of commercially available polymer pellets. These advantages have driven the adoption of FGF for large-format additive manufacturing (LFAM), particularly for the fabrication of molds, tooling and marine structures [3,4]. In such systems, volumetric flow rates can reach several thousands to tens of thousands of mm³/s, enabling the production of multi-meter-scale components [3]. These performance levels are commonly achieved using screw extruders longer than 200 mm and nozzle diameters often exceeding 5 mm [5]. While well suited for very large structures, these LFAM architectures are not representative of the full spectrum of FGF systems currently being developed. In recent years, increasing attention has been directed toward more compact pellet extrusion platforms. To better distinguish these architectures, Curmi and Rochman classified FGF systems according to screw length as compact (<100 mm), medium-scale (100–200 mm), and large-scale (>200 mm) systems [5]. Of particular interest are medium-scale systems, which bridge the gap between compact pellet extruders and industrial LFAM platforms. Representative medium-scale FGF systems reported in the literature typically employ nozzle diameters between 0.4 and 1.5 mm and achieve volumetric flow rates below 50 mm³/s, while build volumes are generally below 0.5 m in at least one dimension [6–12]. For example, Tian et al. reported deposition rates of approximately 50 mm³/s using nozzle diameters between 0.5 and 1.5 mm [9], while Kumar et al. achieved approximately 25 mm³/s with a 0.8 mm nozzle [12]. Despite recent developments, relatively few studies have investigated medium-scale FGF systems for the high-productivity manufacturing of short fiber-reinforced thermoplastic composites, and reported deposition rates generally remain below 50 mm³/s across a limited part scale.

The objective of this work is therefore to develop and evaluate a high-productivity medium-scale FGF platform based on a 135 mm screw extruder for the additive manufacturing of thermoplastic composites. The platform was evaluated using neat and fiber-reinforced thermoplastics, including polylactic acid (PLA), carbon fiber-reinforced polylactic acid (PLA-CF), carbon fiber-reinforced polyethylene terephthalate glycol (PETG-CF), glass fiber-reinforced polyethylene terephthalate glycol (PETG-GF), and carbon fiber-reinforced polycarbonate (PC-CF). Its capabilities were demonstrated through three representative case studies spanning different geometric scales and manufacturing requirements: a cellular acoustic panel, a sandwich-structured longboard, and a large aircraft cabin interior cosmetic component. Particular attention was given to achievable volumetric flow rates, manufacturing productivity, and the ability to process composite materials using nozzle diameters ranging from 1.2 to 2.5 mm.

3. Methodology

3.1. Infrastructure

Figure 1 presents the medium-scale FGF platform developed in this work. Figure 1a provides an overview of the system, consisting of a Pulsar™ Atom pellet extruder (Dyze Design, Canada) mounted on a custom gantry platform by Aerotech (Aerotech Inc., USA). Motion commands were executed through the Aerotech controller, while extrusion, temperature regulation, and auxiliary functions were controlled using a Duet 3 6HC main board controller (Duet3D, United Kingdom). The extruder is equipped with a 135 mm screw and a two-zone heating system capable of processing thermoplastics at temperatures up to 450 °C. The motion platform provides a build volume of 765 × 425 × 150 mm and maximum travel speeds of 150 mm/s. Figure 1b shows the printing envelope together with the gravity-fed pellet feeder and the custom heated build plate, which can reach temperatures up to 120 °C. Figure 1c presents the printhead assembly. A liquid-cooling system (Dyze Design, Canada) was integrated to prevent premature softening and agglomeration of pellets within the feeding section, while two part-cooling fans were used to improve shape retention following deposition. Interchangeable nozzle diameters ranging from 1.2 to 2.5 mm were employed depending on the target application and desired volumetric flow rate.

3.2. Demonstrator parts and processing conditions

Three demonstrator parts were selected to evaluate the capabilities of the developed platform across different geometric scales, deposition rates, and material systems. All parts were fabricated using the standard screw supplied with the Pulsar™ Atom extruder (Dyze Design, Canada), featuring a compression ratio of 1.5.

The first demonstrator consisted of an enlarged acoustic panel adapted from the geometry investigated by Pierre et al. [13]. The panel measured approximately 150 mm in length, corresponding to a 2:1 scale-up of the original geometry. The structure comprised four distinct regions, including bottom skins, acoustic cells, and microscaffold layers with infill densities of 30% and 74%. This demonstrator was selected to evaluate the ability of the developed FGF platform to reproduce relatively fine geometric features while maintaining consistent deposition quality. The panel was fabricated using PLA (NatureWorks 3D850, NatureWorks LLC, USA) and a 1.2 mm nozzle. Printing was performed at an extrusion temperature of 220 °C, a layer height of 1.2 mm, a line width of 1.4 mm, and travel speeds ranging from 48 to 70 mm/s. Bead geometry, dimensional accuracy, and feature resolution were assessed using optical microscopy (VHX-7000, Keyence Corporation, Japan).

The second demonstrator consisted of a sandwich-structured longboard measuring approximately 820 mm in length. The structure comprised top and bottom skins separated by a honeycomb core, providing a representative example of a large lightweight composite structure. This demonstrator was selected to evaluate the high-throughput manufacturing capabilities of the developed FGF platform. The longboard was fabricated using PETG-CF (Bambu Lab, China) and a 2.5 mm nozzle. Printing was performed at an extrusion temperature of 270 °C, a layer height of 2.0 mm, a line width of 3.6 mm, and a travel speed of 80 mm/s. Additional longboards were also fabricated using PLA (NatureWorks 3D850, NatureWorks LLC, USA) and PETG-GF (FybeCycle, Canada) to demonstrate the versatility of the developed platform across multiple material systems. The resulting deposition rates were compared with representative desktop and industrial FFF systems, namely the Bambu Lab X1E (Bambu Lab, China) and the AON3D Hylo™ (AON3D, Canada).

The third demonstrator consisted of an aircraft cabin interior cosmetic component measuring approximately 750 × 420 mm. The part was selected to evaluate the capability of the developed platform to manufacture near-meter-scale components using fiber-reinforced engineering thermoplastics. The component was fabricated using PC-CF (CarbonX™ PC+CF, 3DXTECH, USA) and a 1.8 mm nozzle. Printing was performed at an extrusion temperature of 290 °C, a layer height of 1.3 mm, a line width of 3.0 mm, and a travel speed of 90 mm/s. Additional aircraft cabin interior cosmetic components were also fabricated using PLA (NatureWorks 3D850, NatureWorks LLC, USA) and PLA-CF (ABC3D, Canada).

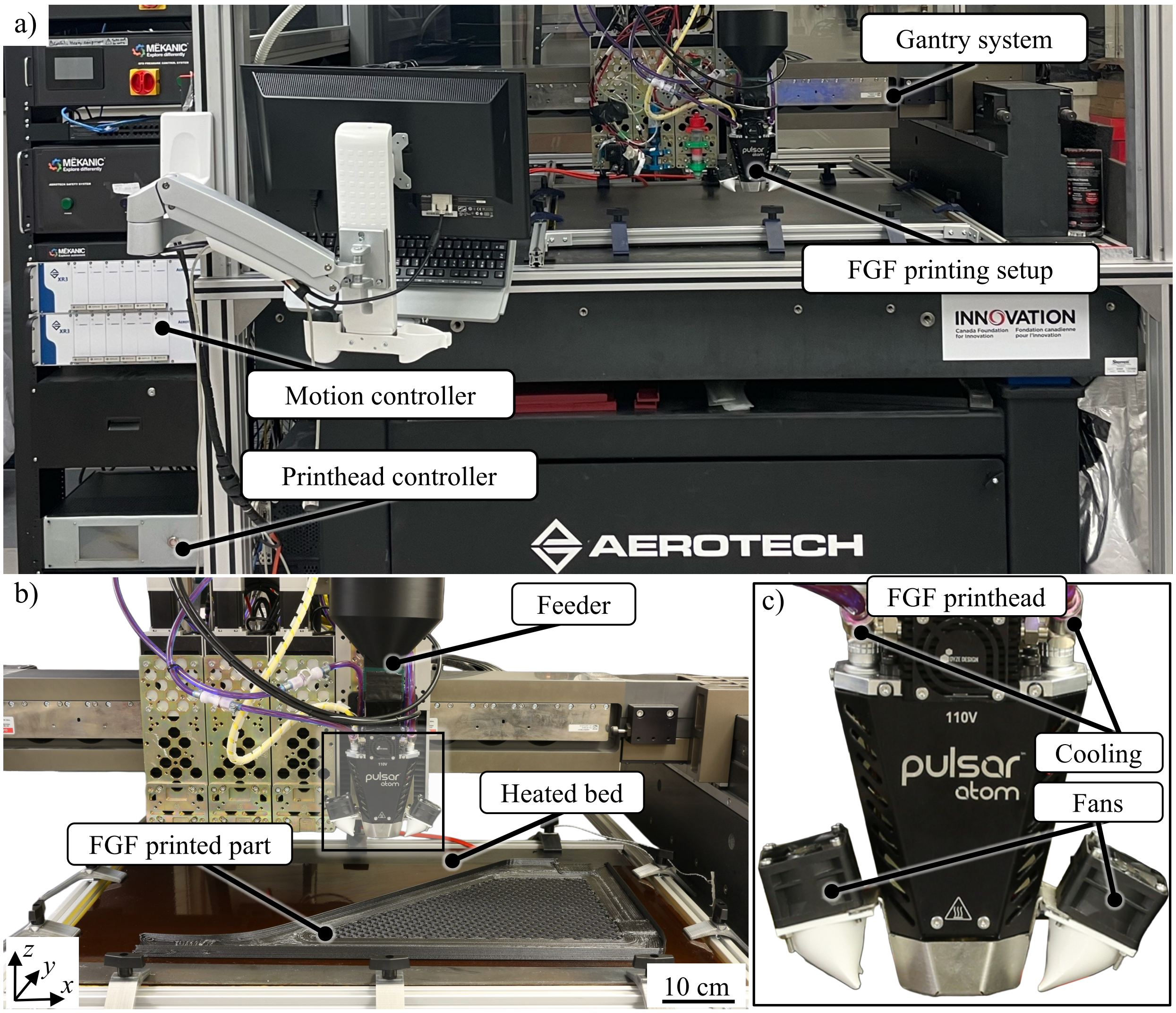

Figure 1. Developed medium-scale FGF platform: (a) overall system architecture; (b) printing envelope including the gravity-fed pellet feeder and heated build plate; and (c) printhead assembly showing the liquid-cooling system and part-cooling fans

4. Results and discussion

4.1. Fine-feature fabrication: acoustic panel

The PLA acoustic panel shown in Figure 2a was successfully fabricated using the developed medium-scale FGF platform, resulting in a component with a mass of 0.22 kg and a manufacturing time of approximately 100 min. Peak volumetric flow rates of up to 120 mm³/s were achieved during fabrication of the skin. Optical microscopy was used to assess bead geometry and deposition consistency within the different regions of the structure, with representative images presented in Figure 2b–d. In the acoustic cell region (Figure 2b), the travel speed was reduced from 70 mm/s to 48 mm/s, corresponding to a decrease in volumetric flow rate from approximately 120 mm³/s to 80 mm³/s. This reduction was implemented to improve deposition control in regions containing frequent changes in direction and short deposition paths. The deposited bead remained generally uniform and close to the target width of 1.4 mm. Localized under-extrusion was observed at extrusion restart following stop-and-go motion, while slight over-extrusion and material accumulation occurred at the end of the deposition paths. Aside from these transient effects, good dimensional agreement with the target geometry was achieved. In the 30% infill microscaffold region (Figure 2c), slight over-extrusion was observed at contact points with the underlying layer, while unsupported spans exhibited localized under-extrusion caused by extrudate sagging relative to the target bead width of 1.3 mm. Although part-cooling fans were integrated into the printhead to improve shape retention following deposition, some sagging remained visible over the unsupported distances. Improved deposition consistency and bead geometries closer to the target dimensions of 1.3 mm were obtained in the 74% infill microscaffold region (Figure 2d), where the shorter unsupported spans reduced sagging of the deposited material. Overall, the results demonstrate that the developed medium-scale FGF platform can successfully reproduce relatively fine geometric features using a 1.2 mm nozzle.

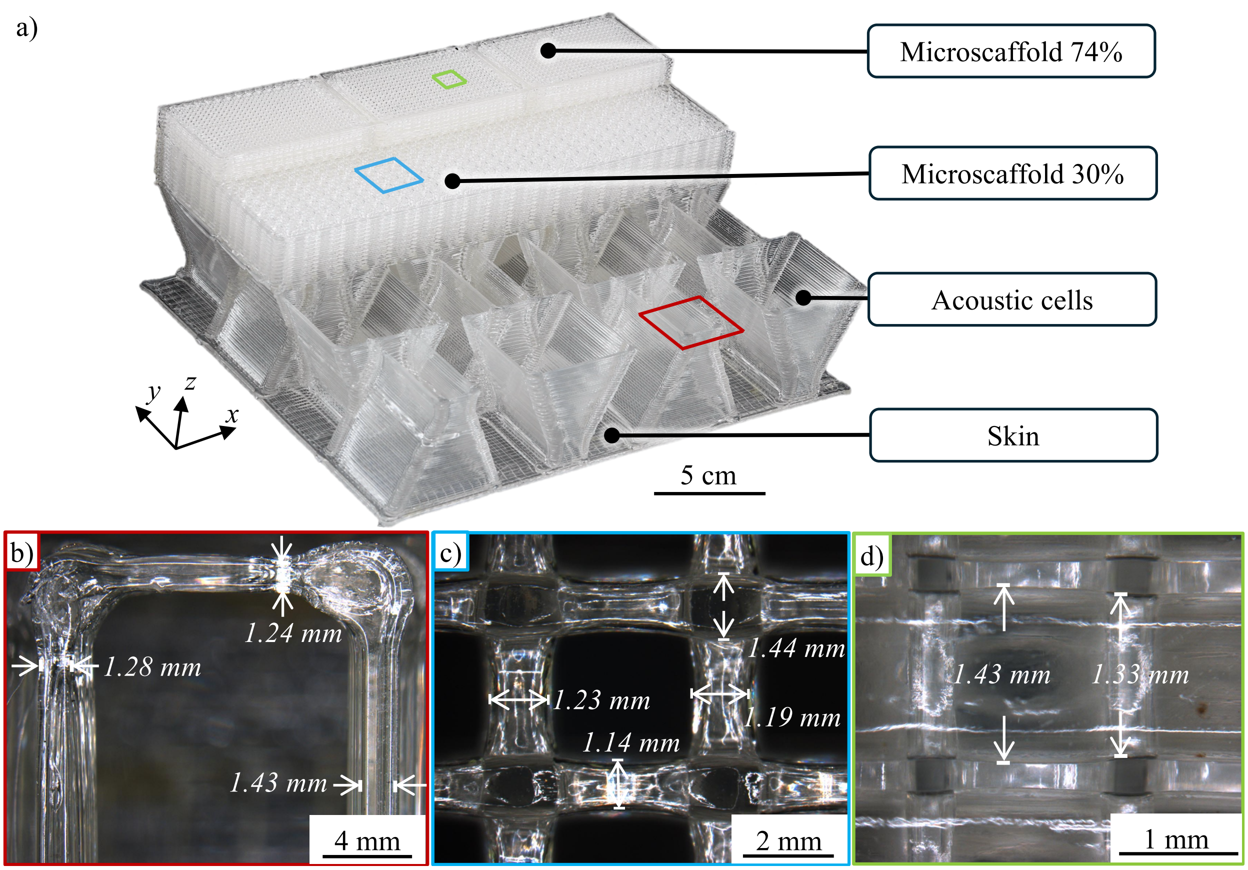

Figure 2. PLA acoustic panel printed in FGF: (a) printed panel; (b) acoustic cell region showing localized under-extrusion at extrusion restart and slight material accumulation at the end of deposition paths relative to the target bead width of 1.4 mm; (c) 30% infill microscaffold exhibiting local over-extrusion and sagging relative to the target bead width of 1.3 mm; and (d) 74% infill microscaffold showing improved deposition consistency and bead widths closer to the target value of 1.3 mm.

4.2. High-throughput manufacturing: sandwich-structured longboard

The manufacturing capabilities of the developed platform were evaluated through the fabrication of sandwich-structured longboards. Representative longboards fabricated using PLA and PETG-CF are shown in Figure 3a–b. The PLA longboard (Figure 3a) represented an earlier stage of process development and was manufactured at a peak volumetric flow rate of approximately 240 mm^3/s, resulting in a manufacturing time of 2 h 40 min. Following process adjustment, the PETG-CF longboard (Figure 3b) was successfully manufactured using a 2.5 mm nozzle, resulting in a part mass of approximately 1.7 kg and a manufacturing time of 75 min. A peak volumetric flow rate of 575 mm^3/s (2.5 kg/h) was achieved, substantially exceeding values typically reported for medium-scale FGF systems (generally below 50 mm^3/s). As shown in Figure 3c, this corresponds to deposition rates 23 times greater than those of the Bambu Lab X1E (desktop FFF system) and approximately six times greater than those of the AON3D Hylo™ (industrial FFF system). Achieving such deposition rates required careful thermal management of the extrusion process. The PETG-CF feedstock was processed at the supplier-recommended upper extrusion temperature of 270 °C to promote complete melting at high throughput. However, operating near this temperature limit increased the sensitivity of the process to residence time effects. Insufficient heating resulted in incomplete melting and inconsistent bead formation, whereas prolonged exposure at elevated temperature during process interruptions promoted premature softening of pellets within the feeding section and increased the risk of clogging. Consequently, continuous extrusion and liquid cooling of the feeding zone were important for maintaining stable material delivery under these operating conditions. An additional PETG-GF longboard was fabricated under processing conditions similar to those used for PETG-CF. A slight reduction in printing speed was required to maintain consistent material deposition and avoid under-extrusion. Improved shape retention was also observed during bridging operations, resulting in reduced sagging of unsupported regions compared with PETG-CF. These observations suggest differences in melt flow behavior between glass fiber- and carbon fiber-reinforced PETG systems, although additional characterization would be required to quantify these effects.

In addition to thermal management considerations, the longboard geometry introduced several manufacturing challenges. The discontinuous honeycomb core required frequent extrusion starts and stops, leading to localized gaps at the beginning of deposition segments. These defects were associated with the time required to rebuild melt pressure within the extruder after each restart. To mitigate this issue, a short 0.1 s dwell period was introduced before motion resumed, allowing pressure to recover and eliminating the gaps observed at the start of deposition segments. The honeycomb architecture also limited overall manufacturing productivity, as the generated toolpath was not optimized for thin-wall cellular structures. Rather than depositing adjacent walls sequentially, the toolpath frequently alternated between distant regions of the part, resulting in numerous non-productive travel motions. Consequently, although peak deposition rates of 575 mm^3/s were achieved during extrusion, overall manufacturing productivity remained strongly influenced by toolpath efficiency.

A second challenge was encountered during deposition of the top skin over the honeycomb core, which required bridging across long semi-supported spans associated with the 12% infill structure. These regions proved particularly challenging when using a 2.5 mm nozzle and high material flow rates. Significant sagging of the extrudate was observed when bridging directly across these unsupported spans. To improve shape retention, two intermediate bridging layers were introduced prior to deposition of the final skin, consisting of a 30% infill layer printed with a reduced layer height of 0.8 mm followed by a 100% infill layer printed at 1.0 mm. Part-cooling fans were also employed, while printing speed and extrusion temperature were reduced during bridging printing.

Overall, this demonstrator demonstrates that medium-scale FGF can manufacture near-meter-scale sandwich composite structures at deposition rates significantly exceeding those typically reported for comparable screw-based systems.

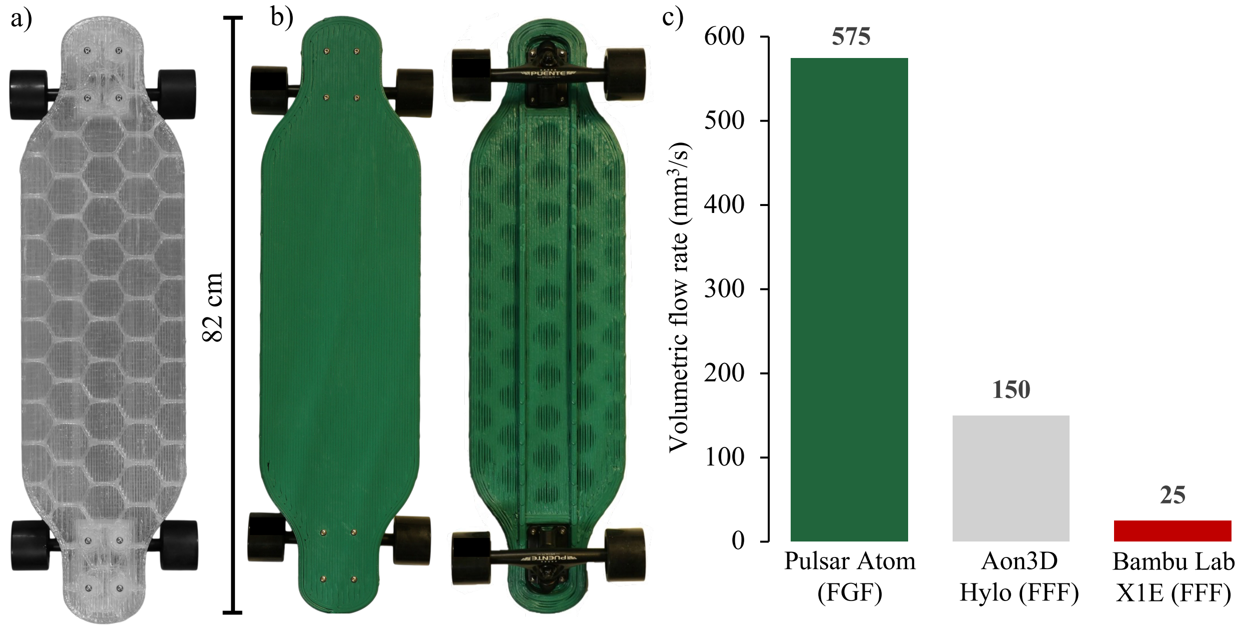

Figure 3. Longboard demonstrator used to evaluate high-throughput manufacturing capabilities: (a) PLA longboard fabricated during initial process development; (b) PETG-CF longboard fabricated with a peak volumetric flow rate of 575 mm³/s; (c) comparison of maximum deposition rates achieved using the developed FGF platform and representative FFF systems.

4.3. Engineering thermoplastic composite manufacturing: aircraft cabin interior component

The final demonstrator focused on the fabrication of large aerospace interior components using both standard and engineering thermoplastic composites. Representative parts fabricated using PLA, PLA-CF, and PC-CF are shown in Figure 4a–c. Initial trials were performed using PLA (Figure 4a), resulting in a component mass of approximately 769 g, a manufacturing time of 148 min, and a peak volumetric flow rate of 215 mm³/s. Similar to the longboard demonstrator, the initial honeycomb infill generated a large number of discontinuous deposition paths and non-productive travel motions, limiting overall manufacturing efficiency despite the relatively high extrusion rate. To improve productivity, a rectilinear infill strategy was subsequently adopted for the PLA-CF demonstrator (Figure 4b). This approach reduced the number of individual deposition segments and improved toolpath continuity, decreasing the manufacturing time to 108 min. The resulting component had a mass of approximately 860 g. The same printing strategy was then applied to PC-CF (Figure 4c) to evaluate the processing of a higher-temperature engineering thermoplastic composite. The component, with a mass of approximately 844 g, was successfully manufactured using a 1.8 mm nozzle, a printing speed of 90 mm/s, and a peak volumetric flow rate of 350 mm³/s, resulting in a manufacturing time of 50 min. No major print failure or severe warping was observed despite the large part dimensions and elevated processing temperature. The reduction in manufacturing time achieved across the PLA, PLA-CF, and PC-CF demonstrators highlighted the importance of toolpath continuity and infill strategy in fully exploiting the capabilities of the developed platform. More importantly, the successful fabrication of the PC-CF component confirms the feasibility of high-throughput medium-scale FGF for large engineering thermoplastic composite structures relevant to aerospace applications.

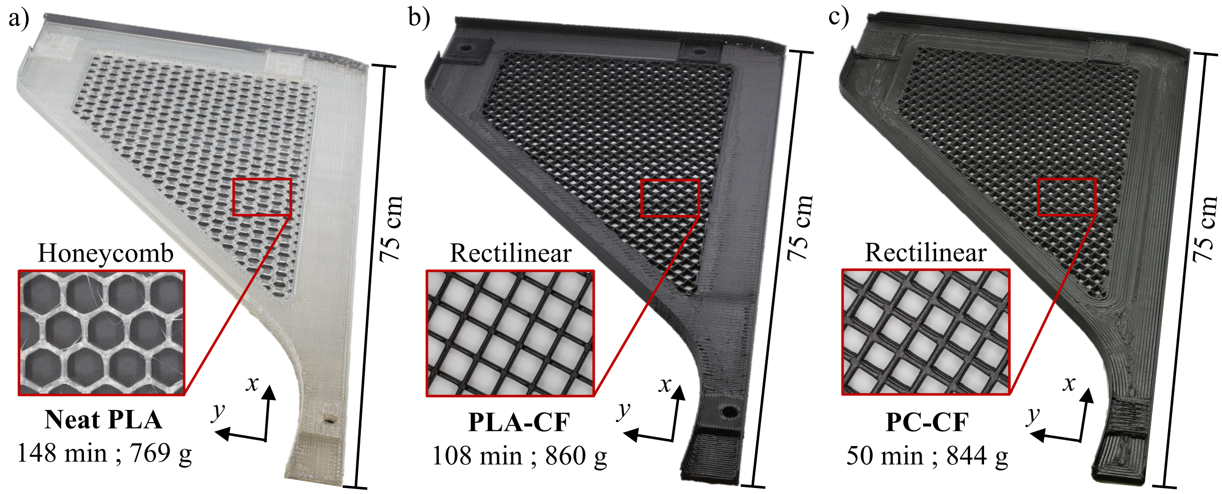

Figure 4. Aircraft cabin interior cosmetic component fabricated using different materials and infill strategies: (a) PLA component printed using a honeycomb infill; (b) PLA-CF component printed using a rectilinear infill; and (c) PC-CF component printed using a rectilinear infill at a peak volumetric flow rate of 350 mm³/s.

5. Conclusion

A medium-scale FGF platform based on a 135 mm screw extruder was developed and evaluated for the high-productivity additive manufacturing of thermoplastic composites. Fine-feature fabrication was successfully demonstrated through PLA acoustic panels incorporating acoustic cells and microscaffold regions. Although extrusion transients and unsupported spans posed challenges, relatively fine geometric features were successfully reproduced using a 1.2 mm nozzle. High-throughput manufacturing capabilities were demonstrated through near-meter-scale sandwich-structured longboards fabricated in PLA, PETG-CF, and PETG-GF. A peak volumetric flow rate of 575 mm³/s was achieved, exceeding values typically reported for comparable medium-scale systems by more than one order of magnitude. The results also highlighted the importance of thermal management and toolpath efficiency in fully exploiting high-throughput deposition conditions. Finally, large aircraft cabin interior cosmetic components were successfully manufactured using PLA, PLA-CF, and PC-CF. The successful processing of PC-CF without major print failure or severe warping demonstrated the feasibility of manufacturing large engineering thermoplastic composite structures using medium-scale FGF. Overall, the developed platform bridges the gap between desktop pellet extrusion systems and large-format additive manufacturing platforms, enabling the rapid fabrication of near-meter-scale thermoplastic composite structures while maintaining relatively fine geometric features and accommodating a broad range of material systems.

Future work should investigate the processing of high-performance thermoplastic composites, including carbon fiber-reinforced polyetherimide and carbon fiber-reinforced polyetherketoneketone, for semi-structural aerospace applications requiring elevated service temperatures and enhanced mechanical performance. Additional developments in high-temperature process infrastructure, including heated enclosures and thermal management strategies, will also be required to support the fabrication of near-meter-scale components.

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