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Continuous multi-filament 3D printing for tension-compression structure components

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Abstract:

In this research, we propose a Multi-Filament Fused Deposit Modelling (MFFMD) printer and a respective generator that can be used to produce structural parts with locally tailored functional properties. 3D-printed structural components can highly benefit from multi-material printing with tuneable functional properties. Currently, multi-material printing is mainly achieved using multiple separate nozzles, leading to discontinuous flow in switching materials. This limitation results in material interface delamination, minimal control in the continuous transition of material properties, and longer production time.To address this, we first design and build an MFFMD printer with a single customized nozzle allowing seamless switching between multiple filaments. We then develop a method that generates a continuous toolpath of a given geometry and differentiates materials based on various stress conditions at particular regions. To illustrate, we fabricate a Pratt truss as an example of a tension-compression structure as a case study. In one go, the MFFMD printer deposits resistant filament, respectively, at tension- or compression-concentrated regions based on local stress conditions. Comparative load tests are conducted to validate the performance enhancement of multi-filament prints against single-filament prints. Our proposed method is a prototypical study conducted on a small scale. While it mainly uses thermal plastic filaments, it can be expanded to other construction materials and scales in the future.

Keywords: additive manufacturing, multi-material printing, functionally graded material, structural performance, mechanics visualization

1. Introduction

This paper describes a novel method that uses cutting-edge multi-material additive manufacturing technology to continuously print tension-compression structures. The method allows the structure's material properties can be tailored locally based on its' stress patterns through numerical control of material deposition and composition regulation. The method results in the structure's mechanical performance enhancement.

3D printing offers considerable advantages in the design and fabrication of tension-compression structures, enabling greater design freedom, rapid prototyping, material and cost efficiency, and on-demand manufacturing. This technology facilitates the creation of complex geometries, custom components, and the integration of multiple functions while promoting sustainability through reduced material waste and optimized designs. Despite its benefits, when using 3D printing technology to produce structural components for construction purposes, limitations are explicit concerning material properties, printing resolution, and scalability must be considered to ensure its suitability for specific projects.

In the construction of tension-compression structures, taking truss as an example, the utilization of single and homogeneous materials presents numerous challenges, often resulting in suboptimal performance and structural inefficiencies. One such challenge arises from the limited material properties inherent in a single homogeneous material, which may lack the necessary combination of strength, stiffness, ductility, and fatigue resistance required for both tension and compression members [1]. This can lead to inefficient use of the material and compromise the overall structural integrity. Moreover, structures made from a single material are more susceptible to common modes of failure, such as corrosion or fatigue [2]. As a consequence, the entire structure is at an increased risk of degradation, whereas a combination of materials could help diversify the failure modes and enhance the structure's resilience. Additionally, using a single material may result in a heavier structure than necessary, impeding its efficiency and practicality. For example, a truss structure composed entirely of steel could be excessively heavy, whereas a combination of steel and aluminum could provide an optimal balance of strength and weight [3]. Therefore, employing a combination of materials can mitigate these challenges and lead to more effective tension-compression truss structures.

In recent years, various innovative methods have been developed to improve the fabrication and assembly of truss structures. Liu et al. (2018) [4] proposed a continuous carbon fiber reinforced thermoplastic lattice truss, which offers enhanced mechanical properties and manufacturing flexibility. This approach leverages the benefits of carbon fiber reinforcement to create lightweight and high-performance trusses. Another significant development in the field is the large-scale 3D printing of metal structure components, as demonstrated by Assunção et al. (2018) [5]. This technique enables the fabrication of complex geometries and rapid production, making it a promising solution for the construction of truss structures. Furthermore, Foster+Partners [6] explored the potential of 3D printing steel trusses, showing the feasibility of employing advanced manufacturing methods to create robust structural elements. Lastly, Kovacs et al. (2017) [7] introduced a method for 3D printing truss joints, facilitating rapid truss assembly and reducing the overall construction time. These advancements collectively showcase the potential of modern fabrication techniques in revolutionizing the design and manufacturing of truss structures.

Current research on 3D-printed truss structures primarily focuses on utilizing a single homogeneous material for the fabrication of components, neglecting the impact of local load conditions and material properties on overall structural performance. Although some studies [8] have considered local stress lines in the design of 3D printing toolpaths, the primary material employed remains homogeneous. Single homogeneous materials are inefficient in addressing the complex internal load distribution within tension-compression truss structures, especially in slender truss members prone to buckling under compressive forces, compromising structural integrity[9]. We propose the use of multi-material 3D printing to construct truss structures with different materials tailored to specific load requirements, thereby enhancing overall performance and stability. However, current studies on the subject of multi-material additive manufacturing focus less on construction purposes [10], [11], [12].

To tackle the aforementioned challenges, a viable methodology must be developed, enabling the additive manufacturing of tension-compression structures in an integrated manner. This strategy should involve the application of locally tailored material properties, contingent upon the stress distribution and loading conditions of the designed structure.

As a pilot study, this paper is situated from the fabrication perspective and discusses the multi-material printing technique and methodology. We select classic 2d truss structures as a trial to validate the performance enhancement through the proposed method.

In this paper, our primary objectives are twofold: First, we aim to integrate the design-make process of multi-material 3D printed tension-compression structures, leveraging the advantages of additive manufacturing technology to create a seamless workflow from design to fabrication. Second, we strive to enhance the mechanical properties of the resulting structures, enabling more robust and efficient performance compared to traditional single-material approaches. By achieving these objectives, we hope to demonstrate the potential of multi-material 3D printing in revolutionizing the construction of tension-compression structures and addressing the limitations of existing methodologies.

2. Methodology

In truss structures, members predominantly experience axial loads, manifesting as either tensile or compressive forces acting along their longitudinal axes. To ensure stability and load-bearing capacity, the materials employed in these members must exhibit adequate resistance to deformation, specifically elongation or shortening, under the influence of the applied forces. Utilizing fiber-reinforced materials with fibers aligned in the longitudinal direction can enhance the tensile strength and stiffness of the members, making them well-suited for withstanding tensile loads. Conversely, non-fiber-reinforced materials demonstrate fine compressive strength when oriented along their short axial direction, rendering them more appropriate for resisting compressive forces in truss members.

The fabrication of a truss structure as holistic through multi-material additive manufacturing necessitates several critical steps. Firstly, tensile and compressive members within the structure must be identified. Subsequently, the local segment orientation is determined based on the stress distribution. Utilizing the stress condition, a toolpath is designed, and appropriate materials are assigned for each member. The material data is then integrated into the toolpath and converted into G-code, which guides the 3D printer during the manufacturing process. The 3D printer employed, whether a commercial or customized system, must possess the capability to process and deposit multiple materials simultaneously, ensuring accurate and efficient fabrication of the truss structure.

We here use the classic Pratt truss as a case study to demonstrate our approach.

2.1. Identify stress situation for truss member

The Pratt truss is situated in a three-point bending scenario (Figure 1a). The load condition primarily involves vertical loads distributed across the structure through tension in diagonal members, compression in vertical members, and in addition, compression and tension, respectively, in the top and bottom chords. While the two outermost vertical members do not receive force in the three-point bending load case, they are treated as tension members in a typical Pratt truss setup where the bottom points receive a live load. Figure 1b shows a simulation run by Karamba3D.

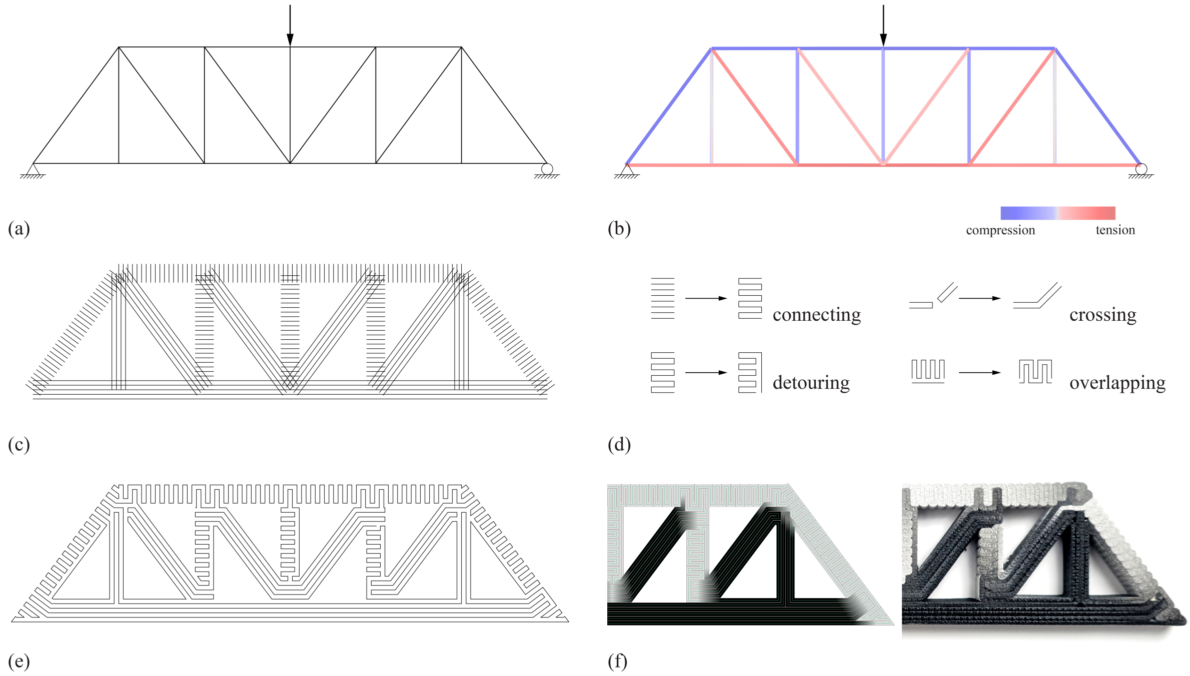

Figure 1: Multi-material printed truss toolpath generation process: (a) Input curves; (b) axial force conditions solved by Karamba3D; (c) raw curves according to the axial forces; (d) post-processing methods to form a continuous toolpath; (e) the final toolpath; (f) left: multi-material visualization of the print, right: multi-material printing

2.2. Translating stress pattern into continuous toolpath design

The mechanical property of a parallel print is similar to that of wood lumbers: the longitudinal direction takes more tensile forces while the tangential direction takes more compression. To utilize such knowledge, the local orientation of the toolpaths is determined by the stress situation (tension or compression). When the rod takes tensile forces its toolpaths are parallel to the rod direction; when it takes compressive forces its toolpaths are vertical. Figure 1c shows this step of generating raw toolpaths as discontinuous lines.

A continuous toolpath for 3D printing significantly saves production time and avoids underfilling and overfilling to enhance the bound [13]. In our case, post-processing (Figure 1d) is introduced to make the toolpath continuous. The curves are connected, primarily in a zig-zag fashion to form several loops. The loops are then merged by crossing and detouring. Finally, at the joints, we modify the toolpaths to create overlapping for better bounding.

The continuous planar toolpath is shown in Figure 1e. Multi-material information is then embedded to print the tensile part using carbon fiber filament and the compressive part using regular PLA filament. Figure 1f shows the visualization of the material-coded toolpath with the printed object.

2.3. Hardware modification

Improving the mechanical performance of structural components through multi-material additive manufacturing involves not only designing toolpaths based on local stress conditions but also utilizing specialized equipment for multi-material printing. In this regard, we made minor modifications to a conventional Fused Deposition Modeling (FDM) 3D printer to meet our demands.

Firstly, in terms of hardware, considering the challenges associated with material transition and bonding, we abandoned the use of a multi-nozzle, multi-filament mechanical system for multi-material printing. Although multi-nozzle systems are the most common approach for multi-material 3D printing and can fully facilitate multi-material printing, material transitions mainly rely on nozzle switching. This results in explicit interfaces between materials, which under load conditions, especially tensile forces, can lead to relatively weak bonding adhesion between materials and potentially compromise the overall structural strength.

To address this issue, we developed a detachable single-nozzle multi-filament extruder (Figure 2) to composite the proposed Multi-Filament Fused Deposit Modelling (MFFMD) printer. This extruder comprises a brass 3-in-1-out nozzle connected to three E3D V6 heatsink/heat throat kits. Each kit is connected to a corresponding stepper motor via an individual teflon hose. The brass nozzle is specially designed with three input chambers and one output chamber. The three input chambers merge at the nozzle's center and then connect to the output chamber. We set the output chamber's diameter at 1 millimeter, and the length at 5 millimeters, and the nozzle was fabricated using selective laser sintering. The three stepper motors are responsible for feeding the three filaments, which are then sent through the hoses into the three E3D V6 heatsink/heat throat kits for melting before being extruded through the output.

Meanwhile, the 3-in-1-out nozzle necessitates the addition of two extra stepper motors to the machine's stock configuration. Consequently, it is essential to replace the original printer motherboard, which conventionally supports only four axes (X, Y, Z, and E0). The new motherboard must support the aforementioned four axis as well as two additional feeding stepper motors (E1 and E2). In this study, we employed the BTT Octopus series multi-axis motherboard. This motherboard not only accommodates the standard three linear axes but also provides support for an additional five axes on the extruder, with the potential to integrate three more axes in future developments. At the firmware level, we adopted Marlin 2.1.2 and overwrote certain contents to enable the mixing extruder functionality. This allows for simultaneous adjustments of multiple feeding motor rotational speeds during the printing process.

2.4. Multi-material deposition

The firmware modification facilitates multi-material deposition using a single-nozzle, multi-filament configuration. However, conventional slicing software lacks comprehensive support for multi-material printing with this setup. To address this limitation, we developed a Rhino/Grasshopper-based G-code generator that enables users to input the designed toolpath of the target structure, along with material indications, and generate G-code compatible with the modified single-nozzle, multi-filament printer.

In general, the key steps for generating G-code for single-nozzle multi-material 3D printing involve using M163 and M164 commands to set up and store the configurations for each filament used and then printing the desired toolpaths with the corresponding filaments. Initially, each filament is activated for extrusion, while the others are deactivated, and the setup is stored. This process is repeated for all filaments involved in the printing process. Next, the pre-defined filament setups are called up using the T command sequentially. The corresponding toolpaths are printed by moving the extruder to the specified coordinates while extruding the appropriate amount of the selected filament at a predetermined speed. These steps enable a single-nozzle 3D printer to successfully perform multi-material printing

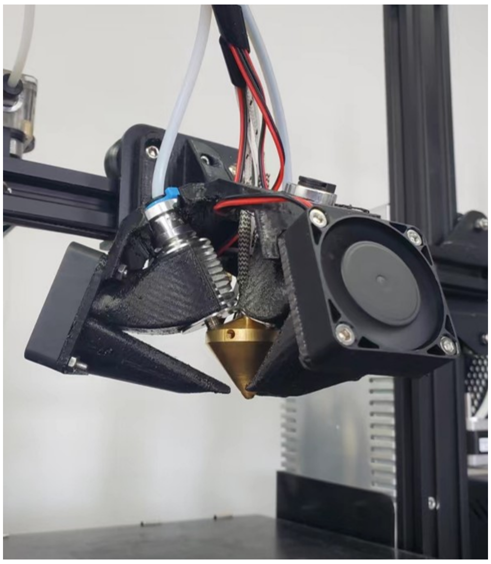

Figure 2: 3-in-1-out nozzle designed for Multi-material (filament) printing

by switching between different filaments during the printing process. Listing 1 is a short G-code for printing one continuous line with three different filaments. Table 1 explains the G-code commands and their meanings when printing multi-material.

Listing 1: G-code for printing one continuous line with three filaments.

```
M163 S0 P1
M163 S1 P0
M163 S2 P0
M164 S0

M163 S0 P0
M163 S1 P1
M163 S2 P0
M164 S1

M163 S0 P0
M163 S1 P0
M163 S2 P1
M164 S2

...

T0
G1 X0 Y0 Z1 E0
G1 X10 Y0 Z1 E10
T1
G1 X20 Y0 Z1 E20
T2
G1 X30 Y0 Z1 E30
```

Due to the extrusion of different filaments is proceed through the same nozzle, in addition to the identical

Table 1: Description of G-code commands, lowercase letters are values to fill in.

Command	Description
`M163 Ss Pp`	Set the weight for extruder motor *s* to *p*
`M164 Ss`	Store the current mix as tool index *s*
`Tx`	Select the previously stored tool index *x*
`G1 Xx Yy Zz Ee`	Move to (x,y,z) and extrude to *e*

or similar matrices of filament, the extruded materials exhibit a highly cohesive bonding. This bonding is essential for achieving reliable, robust, multi-material 3D printing with a single nozzle system. The following pseudocode describes the composition procedure of the G-code used for single-nozzle multi-material printing.

To ensure the overall strength of the printed structural components, we opted to connect all the force-informed toolpaths into a single continuous polyline instead of multiple line segments. This approach ensures the continuity of the printer's extruder movement to result in a continuous extruded filament through a single nozzle. However, this toolpath is mathematically a curve that is composed of multiple segments sharing endpoints. Each segment is assigned a corresponding resistant filament based on the local stress conditions of the structure using the T command in G-code.

In addition, to switch between different filaments, the new material will push out residual material once the new material's corresponding stepper motor begins feeding. Hence, the advancement of material switching is necessary, meaning that the endpoint of each segment needs to move forward for a certain length on the continuous toolpath. For our setup, we use the volume of the output chamber of the nozzle to determine the advancement length.

By using the above method to generate force-informed and multi-material-embedded toolpaths, we successfully 3D printed a three-material Pratt truss (Figure 3) to demonstrate our printability, in where the color distribution is based on the Finite Element Analysis result of a three-point bending simulation. The blue color indicates the stress-concentrated area, and the green color indicates where it withstands less stress.

3. Results

3.1. Experimental Setup and Test Procedure

To validate the improvement in the mechanical performance of the components fabricated using our proposed method, we prepared two truss samples (Figure 4) to conduct a three-point bending test. Each sample was printed with a layer height of 0.8 mm and an extrusion bandwidth of 2mm. The dimensions of all samples were 250mm in length, 65mm in height, and 16 mm in thickness. The printing time for each sample was approximately one hours. For the experimental specimen, we utilized HATCHBOX white PLA as the compressive material, which was deposited at the compressive members. In contrast, OVERTURE Carbon Fiber reinforced PLA filament was used as the tension-resistant material deposited at the tensile members. For the single material control group specimen, HATCHBOX white PLA was employed as the primary material. All test specimens were printed at a temperature of 200°C and a speed of 30mm/sec. Calculated from toolpath length, the multi-material experimental specimen contains 52.5% of the toolpath that withstands tensional stress while another 47.5% of the toolpath is bearing compression stress. The multi-material experimental specimen is weighted as 166g, while the single-material control group specimen is weighted as 179g.

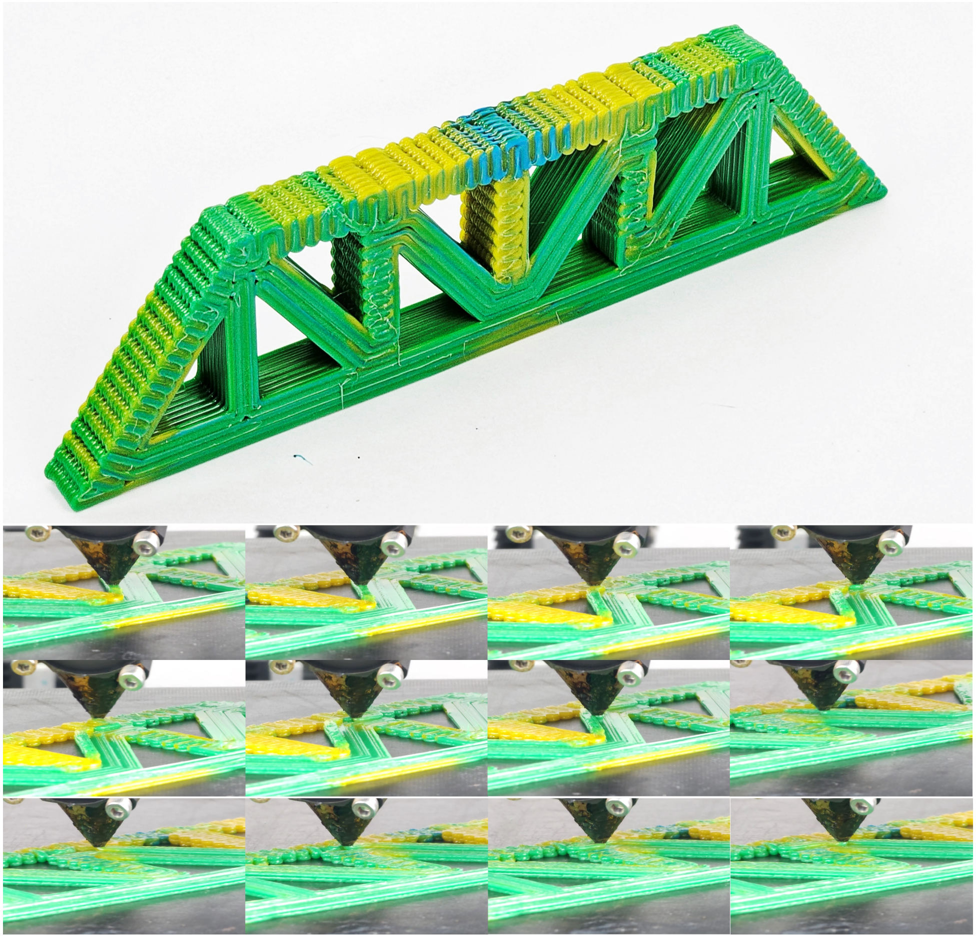

Figure 3: Upper: Printed Pratt truss with three different filaments: yellow PLA Filament, green PLA Filament and blue PLA Filament. Lower: the three-filament continuous printing process.

We utilized an Instron 4206 testing machine to perform the three-point bending tests. Each sample was positioned on the two lower supports of the fixture, and the loading nose was aligned to the center of the top chord of the truss specimen. The span length for the test was set at 220mm.

We first ensured that the loading nose was correctly aligned and centered. We then set the loading rate at 10 mm/min and initiated the test by applying force to the center of the truss using the upper loading nose. Throughout the test, the testing machine continuously recorded the applied force and the resulting displacement of the truss. We continued to apply force until the truss either fractured or yielded and repeated the test for both specimens.

3.2. Results and Observations

The three-point bending test as shown in Figure 6 determines the maximum load both specimens can withstand. As shown in Figure 5, the single-material control specimen yielded under a load of 0.83 kN. In contrast, the multi-material experimental specimen reaches the yield point at 1.16 kN, and one of the compressive members begins to buckle, causing overall plastic deformation in the truss. As expected, the multi-material experimental specimen exhibits a higher stiffness than the single-material specimen.

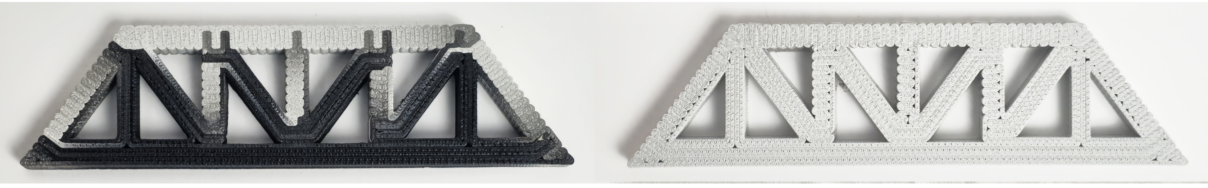

Figure 4: Two samples for three-point bending test. Left: multi-material experimental specimen printed with HATCHBOX white PLA and OVERTURE Carbon Fiber reinforced PLA. Right: single material control group specimen printed with HATCHBOX white PLA only.

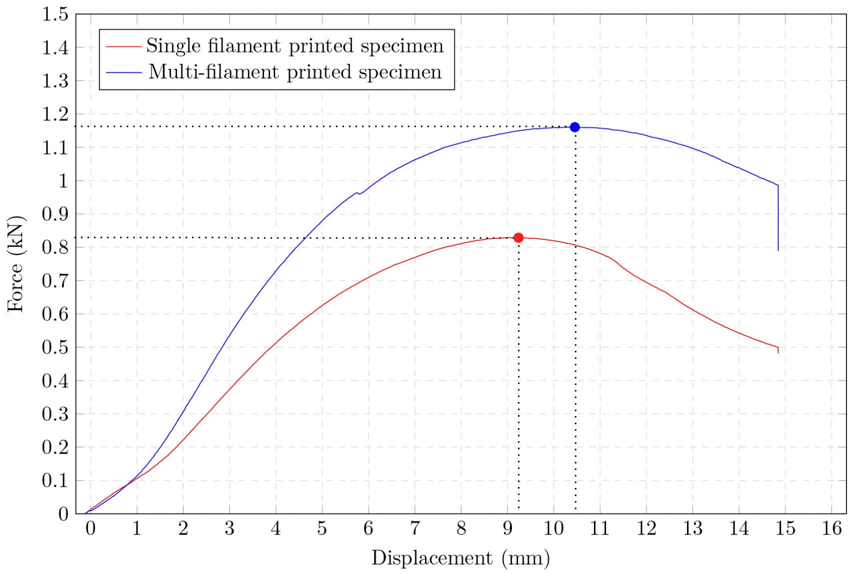

Figure 5: Result of three-point bending test

Figure 5 also presents the load-displacement curves obtained from the three-point bending tests for the different specimens. The load-displacement curves demonstrate that the multi-material specimen possesses substantially higher toughness compared to its single-material counterpart. The toughness is measured by the area under the stress-strain curve up to the fracture point. In our three-point bending test, we employ the trapezoidal rule for numerical integration to calculate this area:

$$\text{Area} \approx \frac{1}{2}\sum_{i=1}^{n-1}(\varepsilon_{i+1}-\varepsilon_i)(\sigma_{i+1}+\sigma_i) \tag{1}$$

where ε_i and σ_i represent the displacement and force values, respectively, for the i-th data point, and n is the total number of data points.

The numerical analysis revealed that the multi-material sample exhibits approximately 67% higher toughness compared to the single-material counterpart.

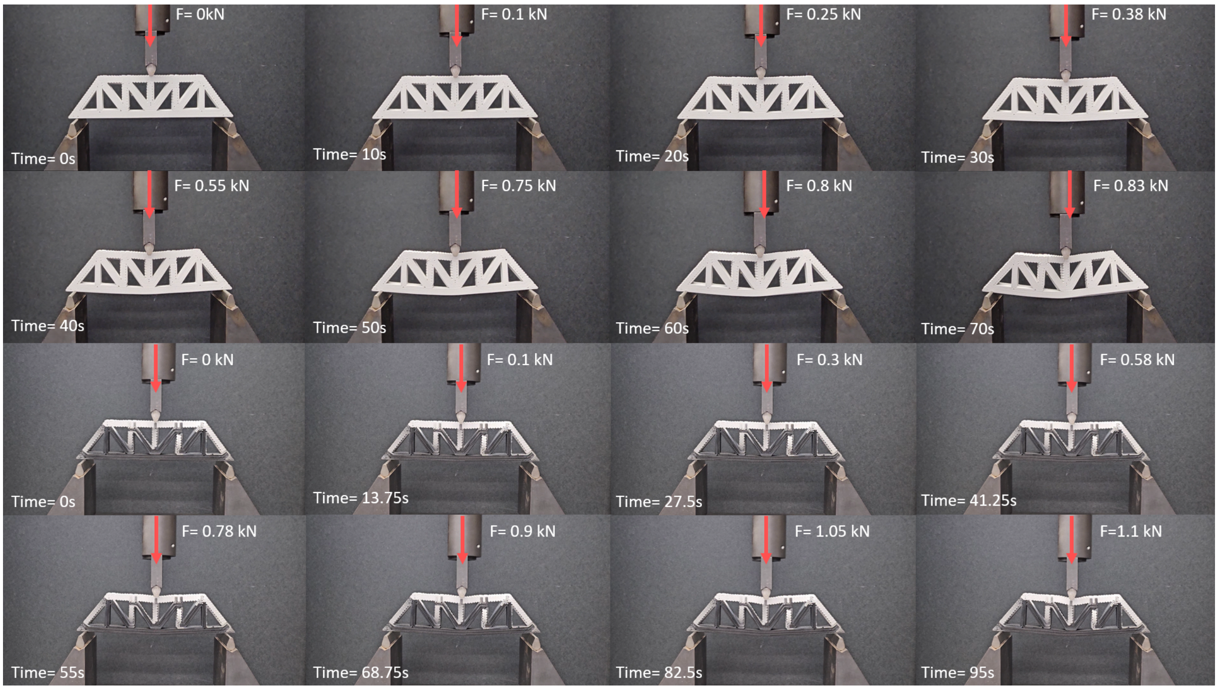

Figure 6: Three-point bending test of two PLA truss specimens. Upper two rows: single material (Regular white PLA) printed controlled sample. Lower two rows: Multi-material (Regular white PLA and carbon fiber enforced black PLA) printed experimental sample.

Due to the high elastic deformation capacity of PLA filament, we did not observe the behavior of two specimens under fracture conditions after the structure yielded under applied external loads. We conducted another test using PETG to examine the fracture behavior of multi-material printed structures when the load was applied. In Figure 7, A subsequent three-point bending test was performed, applying continuous load until fracture to investigate the specimen responses beyond material yield points. The control specimen was fabricated using standard white PETG, while the experimental specimen was composed of carbon-fiber-reinforced black PETG and standard white PETG. The examination of the fractured specimens post-testing revealed no initiation of cracks at the material transition regions, suggesting that the single nozzle configuration effectively mitigates delamination under tensile loading. A comparison between the post-test multi-material and single-material samples demonstrated that one tensile member in the single-material sample experienced failure and disintegration. In contrast, the corresponding tensile element in the multi-material sample remained undamaged. The primary cause of fracture in the multi-material sample can be attributed to the buckling of the adjacent compressive members.

4. Conclusion

This paper presented a groundbreaking method that harnesses the potential of state-of-the-art multi-material additive manufacturing technology to print tension-compression structures in a continuous manner. This innovative technique paves the way for unique opportunities in the development of structures that possess enhanced mechanical properties. The proposed method enables local customization of the structure's material properties based on stress patterns by accurately controlling material deposition and composition regulation. As a result, this approach not only improves the mechanical performance of the

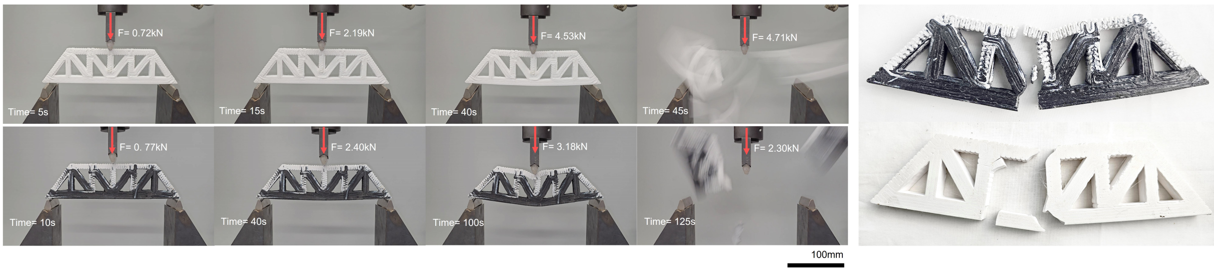

Figure 7: Left: three-point bending test for examing structure's fracture behavior. Upper left row: single material (Regular white PETG) printed controlled sample. Lower left row: Multi-material (Regular white PETG and carbon fiber enforced black PETG)printed experimental sample. Right: A comparison between the post-test multi-material and single-material samples. Upper right image:multi-material specimen, Lower right image:single-material specimen

structure but also optimizes material usage and reduces overall material waste. Distinguished from traditional manufacturing techniques and in collaboration with stress-informed toolpath design, the proposed method capitalizes on the versatility of heterogeneous materials to fabricate high-performance tension-compression structures with unprecedented capabilities. The current methodology is constrained by the build volume of the 3D printers, limiting the dimensions of fabricable structures. Additionally, the technique presently accommodates only 2D extrusion, potentially restricting the development of intricate and complex geometries. Furthermore, the existing setup is incompatible with the utilization of construction materials, such as concrete, for additive manufacturing purposes.

Future work should focus on adapting the multi-material extruder for compatibility with robotic systems, thereby enhancing fabrication freedom and scalability. Extending the method to accommodate 3D extrusion is crucial for enabling the creation of more complex structures and designs. Moreover, exploring the integration of construction materials, such as concrete, into the printing process is essential to broaden the range of potential applications in the construction industry.

The wider implications of the proposed multi-material printing system have far-reaching effects that extend well beyond the realm of additive manufacturing. By facilitating local tailoring of components, this pioneering method enables the development of high-performance structures with potential applications in diverse industries, such as aerospace, automotive, and civil engineering.

The system allows for the fabrication of objects with multiple material properties in a singular process, streamlining production workflows, reducing the need for subsequent assembly, and considerably mitigating inefficiencies in manufacturing and construction sectors. Furthermore, the establishment of this groundbreaking technology will offer invaluable insights for researchers across diverse disciplines to construct the single-nozzle multi-cartridge (SNMC) printer for multi-material applications at varying scales.

As a result, the comprehensive ramifications of this innovative system will not only promote the progression of interdisciplinary research but also contribute to a new era of efficient, sustainable, and advanced manufacturing solutions. By embracing the possibilities offered by multi-material additive manufacturing, we move closer to a future where design and functionality are seamlessly integrated, creating structures and components that redefine our understanding of efficiency and performance.

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