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Additive Manufacturing of Structural Prototypes for Conceptual Design

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Abstract

Additive manufacturing, also known as 3D printing, is a powerful technique for quickly fabricating complex geometrical models. This paper investigates the potential of using this technique for producing structural prototypes, or models that can be used in conceptual design to understand and compare the structural behavior of design alternatives. The main challenge is the anisotropy of the printed parts, which exhibit significant reductions in tensile capacity when loaded across printed layers. This paper characterizes this challenge through experimental results, and proposes and tests several new techniques to address anisotropy limitations.

Keywords: conceptual structural design, additive manufacturing, rapid prototyping, structural load testing

1. Introduction

This paper proposes and tests new ways of using additive manufacturing techniques, such as fused deposition modeling (FDM), to rapidly prototype physical models to study performance in the conceptual structural design of axial structures such as trusses. This work is important because it aims to give designers ways to quickly create physical models that are structurally accurate enough for comparative evaluation of design alternatives.

1.1. Conceptual structural design

In the design of buildings and bridges, conceptual design is a critical step in which key typological and morphological decisions, such as structural system and overall geometry, are made by architects and engineers. It is therefore important for designers at this stage to choose a design concept that performs well both architecturally and technically, including structural behavior. However, incorporating structural behavior in conceptual design is a challenge. The tasks of conceptual design mostly deal with synthesis, but the tools and methodologies designers use to study performance are based on analysis. Successful conceptual design aids must therefore link the synthetic generation of design ideas with the analytical capacity for performance evaluation. In the realm of computation, the research areas of design space exploration and optimization are able to achieve this to varying degrees. Examples that prioritize the generation of many design alternatives and that incorporate qualitative designer input, such as those based on interactive evolutionary algorithms (von Buelow [1], Mueller and Ochsendorf [2]), are promising.

1.2. Structural prototypes

While computational tools for conceptual design are valuable, working exclusively in the computational realm limits performance evaluation to structural theory. Physical models offer the ability to simulate the final built structure in ways that are different, and in some ways more accurate, than computational models. They can reveal issues related to both constructability, including connections, tolerances, and assembly sequences, as well as structural behavior that is hard to computationally model, including stability, nonlinear effects, and sensitivity to imperfections. Throughout the history of structural design, physical models have been used to develop, evaluate, and compare design concepts, often in parallel with calculations.

Since the advent of computational design and analysis, physical models have played less of a role in evaluating structural behavior. This is because computers are capable of increasingly sophisticated structural simulation, and because they enable increasingly complex geometry that is time-consuming and difficult to physically model using conventional means. However, structural prototyping is still a valuable technique that can provide unique feedback in conceptual design, and it is important that the design community be able to maintain this tradition. The aim of the research presented here is to develop new ways to do so, using modern digital fabrication techniques that can link with computational design software and tools.

2. Background on additive manufacturing

Digital fabrication involves the use of Computer Numerically Controlled (CNC) tools for prototyping and manufacturing. This includes laser cutting and milling (subtractive; material is removed from a larger block) and various type of additive manufacturing (material is used for near net shaping). The latter, additive manufacturing (sometimes called 3D printing) has the potential to build parts directly from digital files, which is an advantage for material efficiency and geometric complexity. Dozens of additive manufacturing methods exist; a detailed overview of these methods is given in Gibson et al. [3]. As noted in this source, these methods all share a layer-based approach, in which material is added in a series of layers parallel to the print bed, and can be differentiated through their primary manufacturing variables: materials, layer creation method, and type of inter-layer bond. This section gives an overview of existing uses of additive manufacturing for prototyping in architectural and structural design.

2.1. Additive manufacturing for prototyping in architectural design

Additive manufacturing methods, especially thermoplastic-based fused deposition modeling (FDM) and bonded powder, are widely used for prototyping architectural design models. The relatively low cost of consumer-grade and commercial-grade 3D printers and accompanying materials makes the process accessible to designers both in the university setting and in practice. Additive manufacturing is a very attractive option for architectural prototyping because of its capacity for achieving geometric complexity, its speed, and its automatic nature, especially compared to building architectural models by hand. Design ideas that were difficult to physically model in the past, such as doubly curved surface structures and intricate lattice patterns, can now be materialized quickly and with ease.

Architectural prototypes provide designers with valuable feedback about geometry and form. However, there is also the potential for models to convey and test physical behavior and performance, as structural prototypes. With the exception of the examples in the following section, this potential generally remains unmet.

2.2. Examples of use in structural studies

One important example of the use of additive manufacturing to study structural behavior is in the field of unreinforced masonry. Collapse mechanisms, load capacity, and related behavior have been studied through the use of precise blocks printed using bonded powder by the MIT Masonry research group and the BLOCK Research Group at ETH Zurich (Quinonez *et al.* [4], Block *et al.* [5]). This approach works well under the assumptions of masonry mechanics, where there is no tension or bending and elastic behavior is not of interest.

There are fewer cases of additive manufacturing used to prototype structures that are more commonly used today, which generally carry loads through a combination of tension, compression, and bending. One near-example is the Nervi Project [6], which used additive manufacturing to produce several large models of projects by the Italian architect-engineer Pier Luigi Nervi (1891-1979) in collaboration with Materialise, a Belgian rapid prototyping company. The physical models of Nervi's impressive structures were produced with precise detail, but they have not been used to study structural behavior, conveying geometry only.

2.3. Anisotropy limitations

The paucity of prototypes for structural design produced by additive manufacturing can primarily be attributed to the inconsistent mechanical properties of 3D-printed parts. Because the process adds material in horizontal layers, the strength and stiffness of printed specimens varies significantly, depending on whether forces are applied parallel to the layers or at an angle across them. This means that the fabrication process leads to anisotropic structural elements with variations in performance that do not accurately model structural behavior of final built structures. This is a significant problem for structural prototyping.

The exact degree of anisotropy depends on the additive manufacturing method used; anisotropy is especially pronounced for parts fabricated using FDM, which is nevertheless an attractive candidate for making structural prototypes because it is inexpensive and widely available. Existing research on the mechanical properties of FDM-produced ULTEM-9085 plastic specimens show that tensile capacity perpendicular to the printed layers is only 64% of the capacity parallel to the printed layers (Bagsik *et al.* [7]). Testing conducted by the authors confirms that this differential is even greater for FDM-produced specimens made with ABS plastic (mean failure stress of 25.7 MPa for parallel print orientation, 14.0 MPa or 54% for perpendicular, from Mueller [8]). Stress-strain results given in Fig. 1a also show that the failure mode for perpendicular prints is brittle, while parallel prints have ductile failure modes. This behavior occurs because the fusion between layers in the FDM process is not complete, creating a natural weak point for breakage, as shown in the diagram in Fig. 1b. This anisotropy presents a significant challenge in using FDM to fabricate structural prototypes, since the print-orientation-dependent properties do not correctly simulate the behavior of the real, full-scale structures.

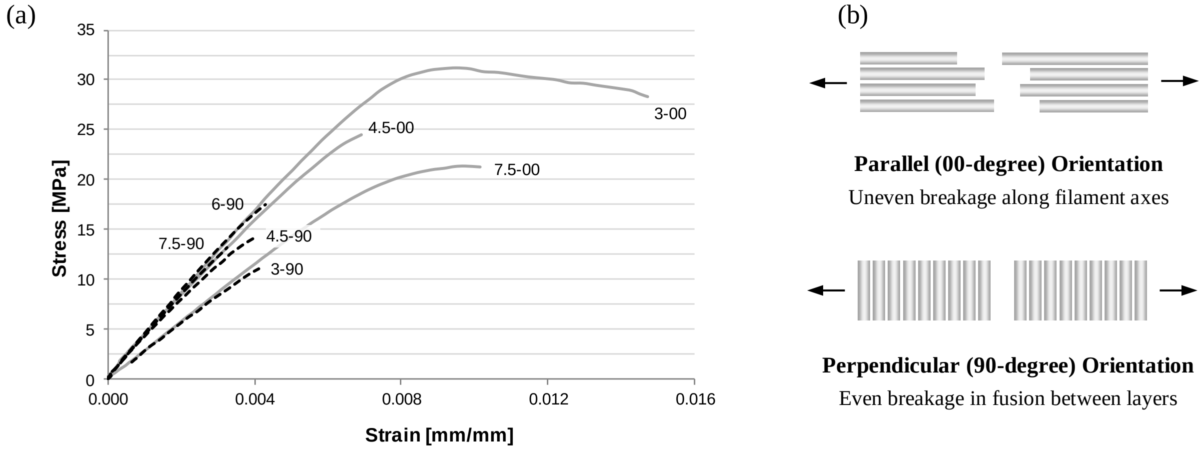


Figure 1: (a) Cylindrical ABS specimens loaded in direct tension; *x*-## notation indicates specimen diameter (*x*, in mm) and print orientation (##); (b) Illustration of breakage behavior based on print orientation.

2.4. Problem statement

The research presented in this paper characterizes and addresses this challenge by proposing and testing several new methods for using FDM for structural prototyping, with the goal of minimizing the effect of print orientation. The proposed prototyping methods are intended to be used for comparative testing of structural alternatives in conceptual design. Therefore, scale effects and differences in material properties between the model and the full-scale structure are not considered. The paper specifically focuses on prototyping truss-like structures consisting of discrete, axial-force elements that take both tension and compression.

3. Methodology

The methodology used in this research involves three steps. First, a conceptual design for a truss is generated using interactive optimization software. The second step develops and implements a range of FDM strategies to create models of the truss design. Third, the resulting prototypes are load tested to failure, and are compared in terms of structural behavior, fabrication ease, and related metrics. More details are given below.

3.1. Conceptual truss design

The truss design used in this experiment is generated using structureFIT, an interactive evolutionary structural optimization tool (Mueller and Ochsendorf [2]). The goal of this approach is to select an efficient, interesting truss design that resists the given loading with a small amount of material. The final selected design is shown in Fig. 2, with dimensions and loading corresponding to the model scale. As illustrated, the planar truss is simply supported and loaded with five downward point loads of 50 N each along the bottom chord. The structure measures 250 mm in length and its total height is approximately 50 mm. To calculate the required dimension for each round member, an approximate ultimate stress capacity for printed ABS plastic (22 MPa, estimated from test results given in Section 2) is used. Fig. 2 also shows relative member sizing and direction of internal member forces, with compression in red and tension in blue.

3.2. Fabrication strategies

In total, six different fabrication strategies are used to prototype the truss design described above. The first three strategies all employ a conventional monolithic print; in other words, the entire structure is fabricated as a single part in the 3D printer. The intention for the first three strategies is to understand the effects of anisotropy in a more complex and realistic structural configuration, compared to the direct tension results. The three strategies correspond to three print orientations, illustrated in Fig. 3, which have layers parallel to the truss plane (XY), parallel to the long dimension of the truss (XZ), and parallel to the short dimension (YZ). The Monolithic-XY prototype serves as a control, since its layers are oriented parallel to the structural action in each member, eliminating anisotropy.

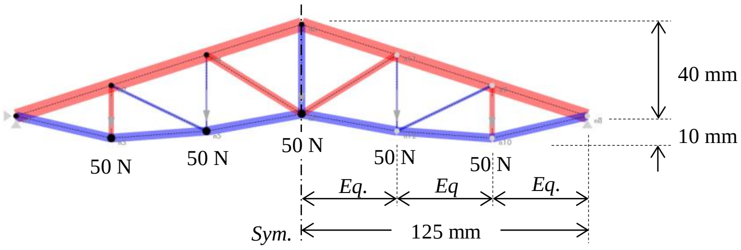


Figure 2: Diagram of truss design, with member sizes shown to scale and tension and compression shown (blue and red, respectively).

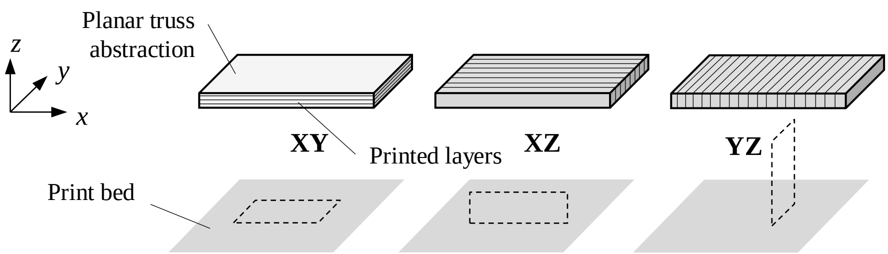


Figure 3: Three orientations for printing the planar truss (abstracted as a rectangle) prototype monolithically.

The second three strategies explore the concept of separately printing (or otherwise creating) members and joints, and assembling them by hand after printing. This concept aims to address anisotropy by ensuring that each member is printed with layers parallel to its axis of structural action. However, this creates the challenge of connecting the members at the joints. Three new strategies are proposed and implemented: adhesive connections between printed joints and printed members (Adhesive-Custom), adhesive connections between printed joints and members cut from standard ABS round stock (Adhesive-Standard), and interlocking snap-in mechanical connections. The adhesive connections use DevCon Plastic Welder, which achieves a bond of 9 MPa in shear with ABS. The connections are dimensioned according to both structural calculations and constructability considerations. All six strategies are summarized in Fig. 4.

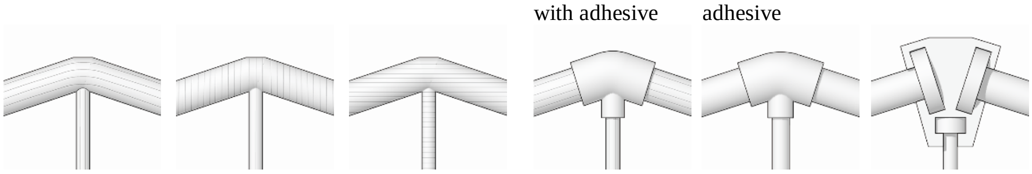
Fabrication Technique	Monolithic-XY	Monolithic-XZ	Monolithic- YZ	Adhesive-Custom	Adhesive-Standard	Mechanical
Description	Single print, with truss plane aligned flat with the print bed	Single print, with truss plane aligned vertically (landscape orientation)	Single print, with truss plane aligned vertically (portrait orientation)	Individual truss members and joints printed independently and assembled with adhesive	Individual joints printed, members cut from standard stock, and assembled with adhesive	Individual truss members and interlocking joints printed independently and assembled
Schematic Image						

Figure 4: Summary of six fabrication strategies used to make structural prototypes for the design in Fig. 2.

The specimens are produced in ABS plastic with a Stratasys Dimension sst 1200es 3D printer at the "Solid" interior setting, which controls the print density. The support material, the equivalent of removable formwork for additive manufacturing, is generally laid out according to the "SMART" setting (an algorithm assigns support material to only the most critical locations). However, some of the fabrication strategies call for the "Full" support material setting to account for irregularities in geometry and difficult orientations. The trusses are printed with six rectangular tabs on the top chord to receive a plate for testing, and five holes on the bottom to receive load for testing. Each prototype uses the exact same member sizing, except for the Adhesive-Standard technique, which uses the smallest stock bar size that performs within stress limits (diameters of 3.18 mm, 4.76 mm, and 6.35 mm are used).

3.3. Comparative load testing

Two truss prototypes for each fabrication technique are manufactured for testing. The two trusses are aligned in parallel and braced for buckling in the compressive chords using acrylic sheets fitted onto the printed tabs. To distribute the load between the five nodes on the bottom chords of the two trusses, a system of springs connected to an aluminum plate is employed. Load is applied through a load cell at the center of the aluminum plate, and the springs distributed the load equally between ten springs. Displacement is measured at the central apex of the trusses using a string potentiometer. The truss system is tested upside-down due to testing constraints, as shown in Fig. 5. For each fabrication technique, this testing setup is used to observe load-displacement behavior and failure load.

Figure 5: Load test setup, showing two parallel truss models, acrylic bracing plates, spring load-spreading system, and aluminum plates for loading and supports.

4. Results

This section presents the results from the fabrication and load testing processes described in Section 3. The results for both steps are summarized in Fig. 6, and explained in more detail below.

4.1. Fabrication and assembly

The table in Fig. 6 shows that as expected, the monolithic prototypes are easiest to fabricate, since no post-printing assembly is required. However, the Monolithic-XZ and Monolithic-YZ versions are considerably slower to print compared to the Monolithic-XY, due to their tall orientations in the print bed. In the case of the Monolithic-YZ, the accuracy and resolution of the print degrades significantly toward the top of the part, and several extra attempts were needed to fabricate complete versions of this part.

The prototypes requiring post-assembly are quick to print, but require time and effort afterwards. Both adhesive prototypes have issues with tolerance, where some of the members do not fit into the open sleeves of the printed joints, even though extra space is incorporated in the digital models. In these cases, the ends of the members are shaved down using a utility knife, which is slow and imprecise. Beyond this issue, the assembly sequence presents some kinematic challenges, since the sleeve-based joints do not always allow for easy member insertion. The Adhesive-Standard prototype is also difficult to assemble because the members are cut from stock in an analog fashion (using a band saw), and are therefore not completely precise in length. This leads to distorted geometry in the final assembled prototype.

The Mechanical prototype also has tolerance-related issues, in that some of the joints require a large force (applied with pliers) to snap together, but the assembly sequence is easier. Two versions of the Mechanical prototype were fabricated and tested, I and II; prototype II has bulkier joints intended to improve the structural performance, but the fabricated version exhibited greater tolerance issues, with overly tight interfaces between members and joints that led to mild deformations prior to loading.

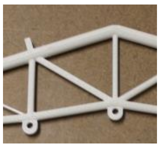
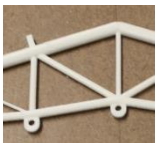
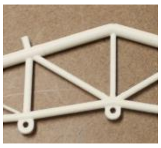
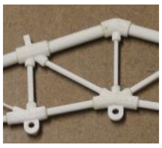
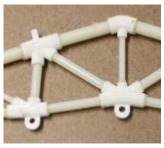
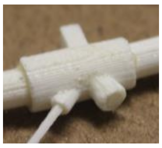
Fabrication Technique	Monolithic-XY	Monolithic-XZ	Monolithic- YZ	Adhesive-Custom	Adhesive-Standard	Mechanical
Printing Speed	Fast	Medium	Slow	Fast	Fast	Fast
Assembly Speed	Fast	Fast	Fast	Medium	Slow	Medium
Assembly Ease	Easy	Easy	Easy	Medium	Difficult	Difficult
Mass [g]	13.0, 13.1	13.1, 13.2	13.4, 13.1	16.6, 16.3	27.6, 27.7	23.3, 23.3 (I) 31.1, 31.0 (II)
Fabrication Images						
						
Failure Load [N]	715	367	191	279	723	316 (I) 235 (II)
Normalized Failure Load [N/N]	2792	1424	735	864	1587	584 (I) 386 (II)
Failure Mode	Gross section (tension), multiple locations	Delamination between layers (tension), multiple locations	Delamination between layers (tension), multiple locations	Adhesive bond and gross section (tension), multiple locations	Adhesive bond and connector (tension), multiple locations	Tear-out at connector (I), Pull-out at connector (II), multiple locations
Failure Profile	Brittle	Brittle	Brittle	Brittle	Slightly ductile	Ductile
Failure Images						

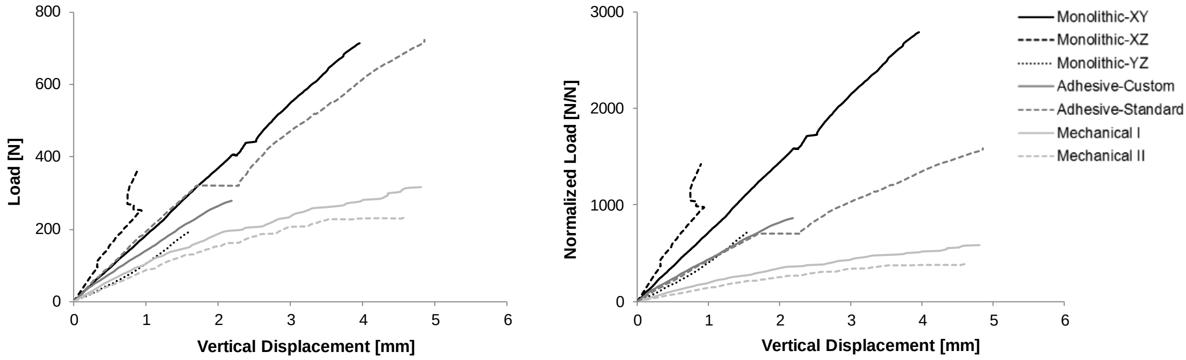
Figure 6: Fabrication and load testing results for each of the six fabrication techniques (for the Mechanical technique, two versions were created and tested).

4.2. Load capacity

The expected load capacity for each version of the prototyped structural system is 500 N (twice the applied value in Fig. 2 to account for two trusses). As shown in Fig. 6, only the Monolithic-XY and Adhesive-Standard techniques reach, and in fact, exceed, this value. In the case of the Monolithic-XY, this is likely because the stress value used to size the members is lower than the peak values observed for ABS with parallel print orientation (22 MPa vs. 30 MPa), suggesting that the Monolithic-XY reaches the full capacity possible with ABS and FDM. The other two monolithic prototypes reach loads of only about half and a quarter of this capacity, showing the significant impact of print orientation. The failure modes also confirm this interpretation: Monolithic-XY exhibits many simultaneous, jagged tension failures in individual fibers. In contrast, the other two monolithic prototypes fail in tension along fusion lines between layers.

The three prototypes made from independently printed members and connections do not perform as well as Monolithic-XY. The Adhesive-Standard model has a higher total failure load, but when normalized by weight, it performs only about half as well (this model is very heavy due to the larger-sized stock members). The

Adhesive-Custom model out-performs Monolithic-YZ, the worst of the monolithic prints, but does not perform as well as the two others. For both adhesive models, the failure mode is a combination of bond failure in shear and gross section failure in tension in the printed parts. The members made from stock ABS do not exhibit internal failures. This indicates that the adhesive performance is good enough to be comparable to the capacity of the printed parts themselves. Both versions of the Mechanical model perform relatively poorly, exhibiting flexible behavior and low failure loads. This result occurs because the joints deform considerably prior to failure, softening the structure. This is especially apparent in the case of Mechanical II, which had overly tight connections that were deformed even before load was applied. For this reason, the failure load is lower than Mechanical I, despite the addition of extra material in the joints. The load-displacement plots for all seven tested prototypes are shown in Fig. 7.



(a) (b)

Figure 7: (a) Load-displacement plots for six fabrication techniques (seven prototypes). (b) The same plots with the load for each prototype normalized by weight

5. Discussion and conclusions

This paper has focused on the problem of anisotropy in structural prototypes fabricated via additive manufacturing. This section includes a brief discussion of the experimental results, insights into important future directions for work in this area, and a summary of contributions.

5.1. Discussion of results

This work is motivated by the possibility of gaining more from additive manufacturing than just a materialization of geometry. If the anisotropy limitations of attractive methods, such as FDM, can be overcome, models created using this process can be used as structural prototypes, which can convey important information about physical behavior as well as form. The results from the experimental work presented in this paper suggest that these limitations present a significant challenge that is yet to be completely resolved.

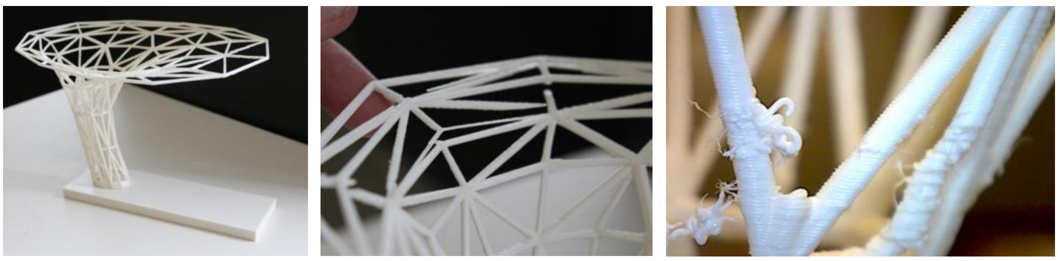


Figure 8: Three-dimensional grid shell model made in ABS with FDM with print-orientation issues.

The structural prototypes created through monolithic printing represent the conventional approach to additive manufacturing. The significant variability in their load capacity indicates that print orientation has a critical impact on structural behavior. While the models used in this paper are planar, and therefore able to avoid this problem in the case of the Monolithic-XY print, more general three-dimensional models will be greatly affected.

This means that the conventional, monolithic printing method cannot be used to produce three-dimensional prototypes that accurately model the structural behavior of the final forms, as illustrated in Fig. 8.

This paper experimented with several methods to address this problem, by strategically aligning print orientation with structural action of individual members and using post-print assembly methods. Unfortunately, neither the adhesive nor mechanical methods successfully matched the capacity of the Monolithic-XY control case, but they did perform better than the worst of the monolithically printed models (Monolithic-YZ). Furthermore, several issues with these assembly methods were discovered, most significantly inconsistent print tolerances. Further research is therefore needed to improve these assembly methods, discussed in the following section.

5.2. Future work

There are several important directions for future work in this area. First, the connection methods proposed here should continue to be developed until they perform as well as the control monolithic model, printed flat. The methods should also be adapted to apply to more complicated, three-dimensional geometry, such as that shown in Fig. 8. This may involve coarser discretization for individual printed parts, so that relatively flat panels are printed instead of individual members, to ease assembly. Computational work is also needed to discretize and design connections for models automatically, with designer-provided geometry as an input and print-ready connecting parts as an output. This should be integrated with existing software, such as Rhino and Grasshopper. Further research should also consider alternative ways to overcome anisotropy due to horizontal layers by eliminating layers entirely, and instead, adding materials along three-dimensional paths related to stress trajectories in structures. Finally, while this paper focuses on the prototype scale, these techniques could also be expanded to fabrication of full-scale, end-use products, such as buildings and bridges, where anisotropy becomes even more significant due to scaling issues.

5.3. Conclusions

The main contributions of this paper focus on characterizing and addressing the challenges of anisotropy in structural prototypes fabricated using FDM. Specifically, this paper has provided new experimental results about tensile anisotropy due to print orientation in FDM-produced ABS specimens, showing a 46% reduction in capacity in parts loaded perpendicular to printed layers. This paper also illustrates the impact of anisotropy in planar truss structures, with results that show load capacity decreased by up to 73% due to print orientation. Several new fabrication techniques are proposed, based on the idea of individually printed parts assembled via connection strategies. While none of the techniques reached the capacity of the monolithic control, models produced via adhesive connections exhibited the most promising behavior, and merit further research and development.

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