Simulating 3D Printing Infill Structures for Potential Renewable Materials

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This paper evaluates the feasibility of using sustainable materials for agricultural drones in a proposed technical elective at the University of Illinois, Urbana-Champaign. By analyzing reference vehicles and their conventional material choices, it establishes a baseline for comparison. Different 3D-printed infill patterns will be assessed through finite element analysis to determine their structural viability compared to the aforementioned reference materials and structures. The findings will help determine whether sustainable materials can match conventional options, guiding material selection for the course.

I. Nomenclature

PLA = polylactic acid
SLS = selective laser sintering
FDM = fused deposition modeling
ABS = acrylonitrile butadiene styrene
PET = polyethylene terephthalate
ASTM = American Society for Testing and Materials
FEA = finite element analysis

II. Introduction

This research paper is part of a larger research project to determine the feasibility of and develop a new technical elective at the University of Illinois Urbana Champaign. The goal of this technical elective is to teach fourth year students to design and manufacture agricultural drones that serve to meet the needs of farms located near Champaign-Urbana, Illinois, with a focus on using sustainable materials and manufacturing techniques. This paper serves to help determine the feasibility of using sustainable materials. Other members of the materials sub team will identify possible materials to use. The main goal of this paper is to simulate tensile tests for different 3D printed infill patterns using the identified sustainable materials through finite element analysis and determine whether they can be used in the eventual technical elective. Overall, the research looks to answer the question: “Can the chosen sustainable materials be implemented in ways that are structurally comparable to conventional material choices?”

III. Theory

In order to determine whether the sustainable materials are suitable for use in the drones that will be created in the new class, we need to look at similar reference vehicles and their comparable

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materials. The book "Small Unmanned Fixed Wing Aircraft Design: A Practical Approach" discusses various design and manufacturing methods used to create fixed wing drones with masses between two and 150 kg [1]. This size range and construction is comparable to the range that our drone will likely fall into. The text discusses the use of 3D printing, and specifically the use of fused deposition modeling acrylonitrile butadiene styrene (FDM ABS) and selective laser sintering (SLS) nylon for many different aircraft components. They opt to use SLS nylon most often: using it for much of their fuselage, their fuel tanks, and their wing ribs. This widespread use of SLS nylon suggests it is a useful material to compare any sustainable 3D printed material to. It is thus useful to note that SLS nylon typically has a tensile strength of around 40-45 MPa, depending on the manufacturer [4].

For the potential use of the thermoplastic PET (polyethylene terephthalate) in the drone, it's important to look at different infill patterns used in conventional additive manufacturing. When creating a 3D printed part, different infill patterns can be used to reduce material use, weight, and manufacturing time while also giving different structural properties. These infill patterns are most commonly generated while using a slicer software to prepare the part for printing. A widely used slicer software is Ultimaker Cura, which is free and open source. This wide use of Cura makes its infill patterns ideal to use when conducting tensile and compressive tests. We will look at using tests defined by the American Society for Testing and Materials (ASTM) which sets the industry standard for materials testing, including tensile and compressive tests. In fact, these tests have already been done for samples printed from polylactic acid (PLA), one of the most common 3D printing materials (alongside ABS) [5]. Researchers from the Franco-German Institute for Technology and Business, and James Madison University have tested the fourteen standard infill patterns offered by Cura in compression by printing multiple samples of each pattern and performing "ASTM D695-15, the 'Standard Test Method for Compressive Properties of Rigid Plastics'" [2]. Following a similar process for obtaining the tensile strengths of different variants of PET that the materials team has selected will help identify which infill pattern most closely matches the material properties of conventional 3D printed materials used for similar projects.

IV. Methodology

The materials team is currently still investigating the feasibility of using available 3D printers at the University of Illinois to print PET. This poses an issue in that physical samples are unlikely to be created during the time allotted to write this paper. Due to this time constraint, preliminary stress vs. strain curves will be obtained by using finite element analysis in the CAD software SolidWorks to simulate tensile strength tests for each infill pattern. This concept is not new, as researchers from the Department of Manufacturing Engineering Management at De La Salle University in the Manila, Philippines, have already conducted simulated tensile tests for various infill patterns using PLA in the CAD program Fusion 360 [3]. In their research, they modeled a sample according to the ASTM type IV dimensions. They then used Fusion 360's built in finite element analysis to simulate the ASTM D638 plastic tensile strength test to produce stress-strain plots for several infill patterns. This research paper looks to follow the same general method, while opting to use SolidWorks 2024 instead of Fusion 360 due to its advanced simulation capabilities.

Typically, slicer software will allow the user to choose the infill density, which dictates the density of the infill volume (i.e. a higher density will correlate with smaller gaps in the infill pattern). In our study, we will model the ASTM D638 type I specimen in SolidWorks using grid, and triangular infill patterns at multiple infill densities (testing 3D infill patterns such as cubic, quarter cubic, or octet will most likely require physical tests). The CAD models representing the sliced models that Cura creates for grid and triangular infill patterns are shown below in Figure 1 and Figure 2 respectively. The outer walls are all 12 mm thick, the default parameter in Cura, and the infill lines are 4 mm thick, which is approximately the width of a single line of extruded material.

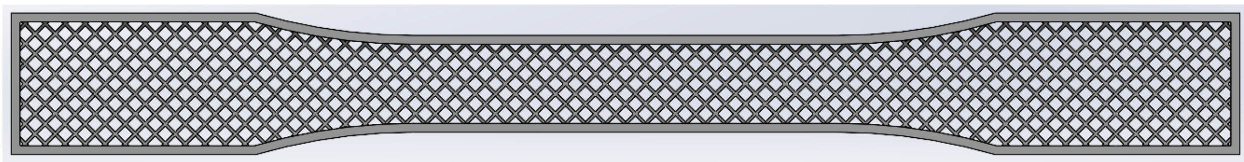

Figure 1: ASTM D638 Sample with Grid Infill

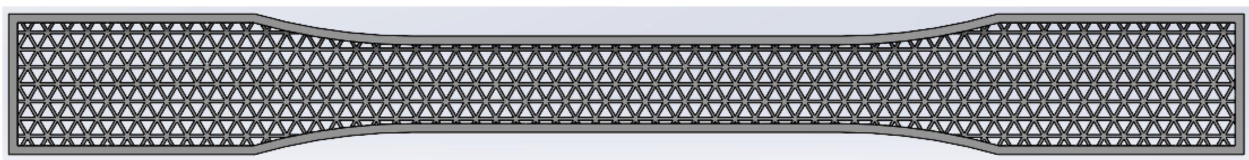

Figure 2: ASTM D638 Sample with Triangular Infill

The simulation uses a custom PET material in which linear elastic and non-linear plastic characteristics are defined. This is to allow for plastic deformation after the yield strength is reached. The tensile simulation is performed by using SolidWorks' non-linear analysis feature. Variable time steps are used, with the minimum and initial step sizes set at 0.005 seconds, the maximum step size set to 0.15 seconds, and the number of adjustments set to 10. One end of the specimen is fixed, and the other has a prescribed displacement of 10 millimeters applied to it.

V. Results

When each simulation is completed, the raw data is given as the displacement and the resultant force at each time step. Then, the stress is calculated at each time step as the resultant force divided by the gauge area (91 millimeters squared). The strain is calculated as the displacement of the sample divided by the length of the sample. SolidWorks automatically ends the simulation when the stress decreases over a time step, meaning that the last simulated datapoint should be close to the ultimate tensile strength. The stress versus strain data for 4 different infill configurations is show below in Figure 3, representing simulated tests for solid, grid, and triangular infill patterns.

The specific data for the four triangular infills is shown in Figure 4, and the data for the two grid infills is shown in Figure 5.

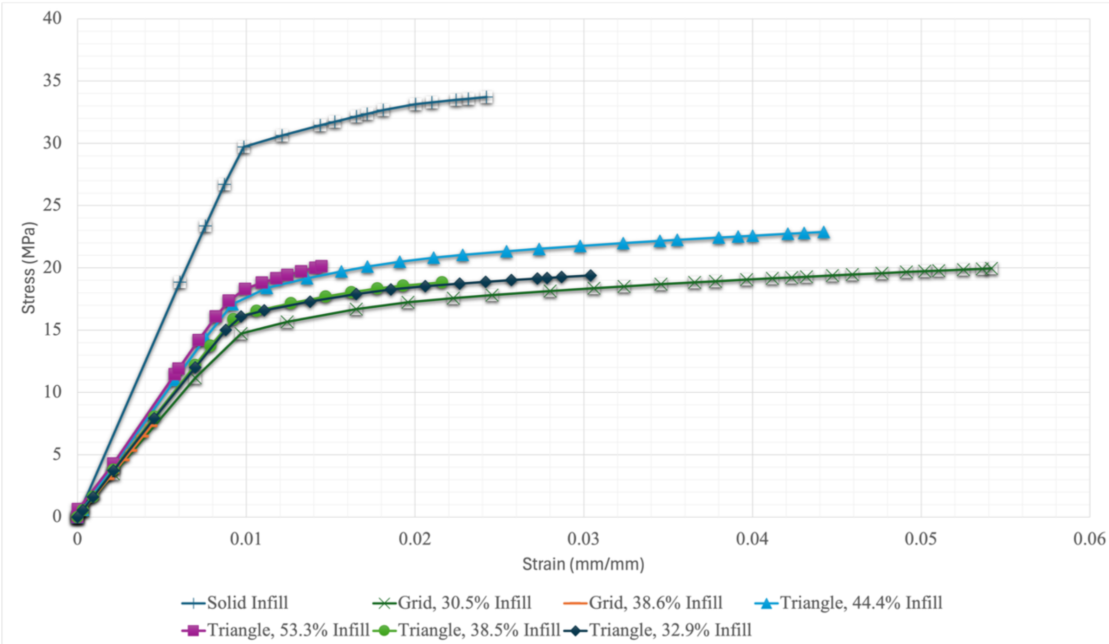

Figure 3: Simulated Stress vs Strain Data for PET using Solid, Grid, and Triangular Infills

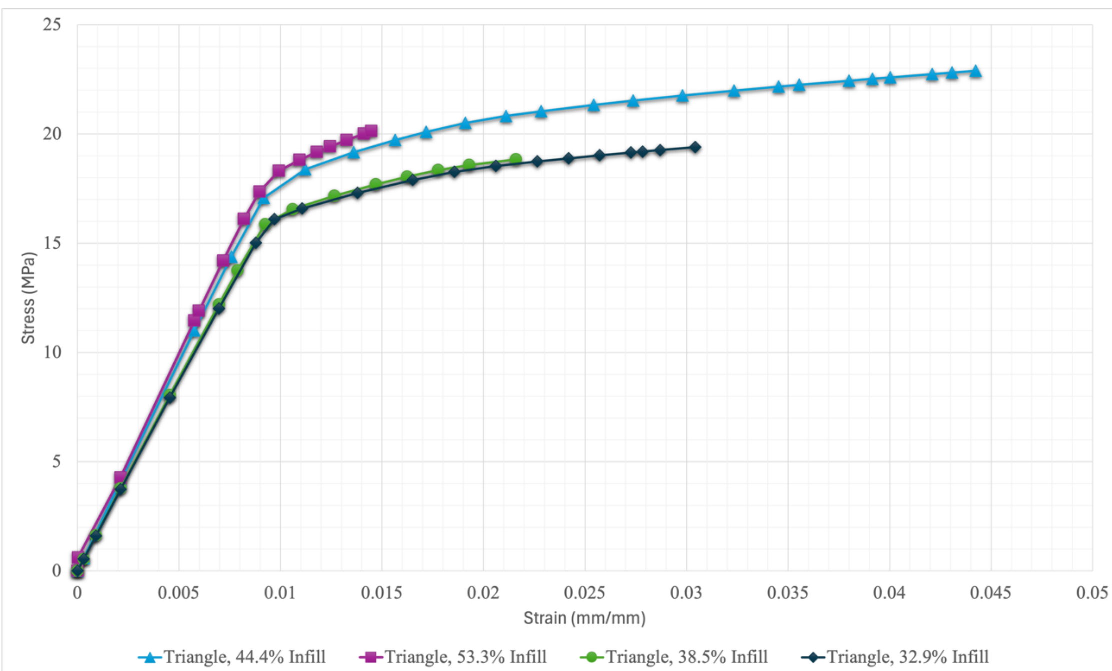

Figure 4: Simulated Stress vs Strain Data for PET using Triangular Infills

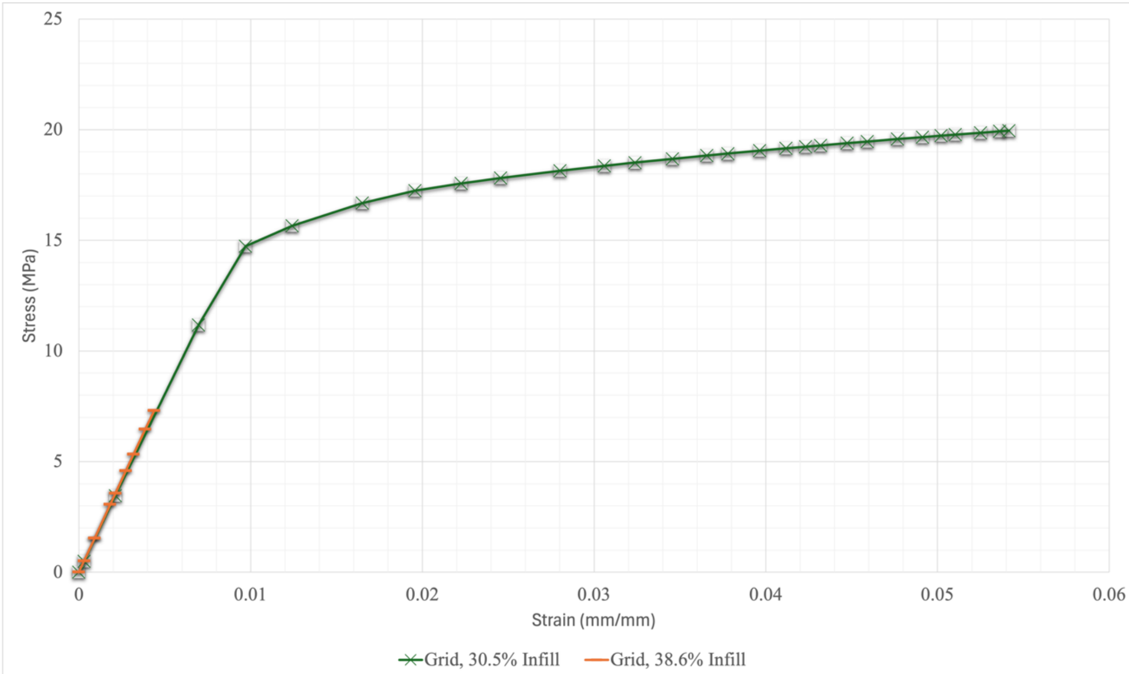

Figure 5: Simulated Stress vs Strain Data for PET using Grid Infills

The material properties calculated for each are shown below in Table 1, with the most notable value being the yield strength divided by mass. This value is very useful as we arguably want the highest value possible here to minimize weight while maximizing strength. The yield strength itself was found using the 0.2% offset rule [6]. The mass was found through Solidworks' mass properties tool. The infill density was calculated by dividing the volume of the infill structure by the volume of the internal cavity with no infill (both values being determined using Solidworks' mass properties tool) [7]. The Young's Modulus (also known as the elastic modulus) is calculated as the slope of the curve in the elastic regime.

Table 1: Simulated Material Properties

Infill Type	Infill Density	Yield Strength (MPa)	Mass (g)	Young's Modulus E (GPa)	Yield Strength / Mass (MPa / g)
Solid	100%	29.70	18.73	2.981	1.586
Grid	30.5%	14.74	16.16	1.642	0.912
Grid	38.6%	7.31	17.17	1.686	0.426
Triangle	32.9%	16.09	16.51	1.763	0.975
Triangle	38.5%	15.87	17.14	1.789	0.926
Triangle	44.4%	17.07	18.14	1.935	0.941
Triangle	53.3%	18.32	19.27	1.895	0.951

VI. Discussion

First, it's important to look at the calculated data for the solid sample and compare them to expected values to verify the accuracy of our simulation. From Table 1, we can see that our calculated yield strength for the solid infill is 29.70 MPa, which closely reflects the expected value of approximately 30 MPa. This helps verify the FEA method used for this paper gives reasonably accurate results.

Next, we look at how the infill pattern affects the material properties. Looking at the grid infill, we can see that its yield strength is much less than that of a solid infill, which is something that we will see for all non-solid patterns. It is then important to observe how the infill density affects the yield strength. With the grid pattern, we can see that increasing the infill density from approximately 31% to 39% very slightly increases its young's modulus from 1.642 GPa to 1.686 GPa. It is important to note that the simulation for a grid infill with an infill density of 38.6% seems to have stopped earlier relative to the other simulations. This simulation was run multiple times with finer meshes to try to get a different result, but the simulation still stopped early. With that said, the data for this infill configuration should be treated as an outlier, as this specific infill seems to create issues for the solver.

Looking at the triangular infill, we can see that it has a higher yield strength than the two grid infills. Which is reflected in the yield strength per mass property recorded in Table 1. We can see that all of the values in this column for triangular infills are 0.926 MPa/gram or higher, whereas the grid infills have a maximum value of 0.912 MPa/gram. This shows that a triangular infill will generally give a higher yield strength versus a grid infill of the same mass. It should be noted that the solver stopped early for the triangular infill with a density of 53.3%. With that said, it stopped after the yield strength was reached, so the yield strength for this simulation should be considered correct, but the elastic region may not be. This shouldn't affect the information that we want however, as our class will likely focus on designing for within the elastic regime.

One notable tradeoff that appears when increasing the density of the infill no matter the pattern is that higher densities lead to more rigid materials. This can be seen by observing the plots ending at lower strains as the infill density increases.

VII. Conclusions

The goal of this paper is to comment on whether 3D printed recycled PET could be used to construct an agricultural drone, and to determine which infill patterns are more beneficial to use in construction. First, while the yield strength of solid 3D printed PET (29.70 MPa) was found to be slightly lower than that of ABS plastic and SLS nylon (~45 MPa [8] and ~36 MPa respectively [9]), it is close enough to merit further research, especially using actual samples of recycled PET. Looking at infill specific results, this paper can advise that the class consider a higher density triangular infill for secondary structural applications. This is because the triangular infill has been shown to perform better than the grid infill, and a higher density is needed to prevent the material from slipping into the plastic regime, which we want to avoid for design purposes. These simulations show that a solid infill still has the best strength per mass, so solid PET would likely be the best choice for primary structural applications. This is only applicable for using 2D infill patterns though, as only 2D patterns were tested.

VIII. Further Research

It is important to note that physical tensile tests for any future developed material are extremely important. The simulations in this paper use averaged PET data for the custom material in SolidWorks. However, solid PET's material properties can vary widely and are dependent on how the PET is processed. Because we are planning on recycled PET from water bottles by creating

PET pellets, heating them up to create filament, possibly adding a chain extender, and then extruding them, the actual properties of our material may vary.

Additionally, physical testing would allow for data collection for various 3D infill patterns such as cubic and octet that are too complex to be modeled in SolidWorks but might prove to be better choices for our future drone components.

These physical tests would not only allow for a better understanding of our particular material, but the data obtained from them could then be used to create a custom material or materials in SolidWorks (or other CAD tools) that accurately reflect our real material. This would then allow for the use of CAD and the accompanying analysis tools (such as FEA) to create and analyze future 3D printed drone component designs in the class.

Acknowledgments

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