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An Undergraduate Research Project in Material Science for Improved Rapid Prototyping

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Stephen Wilkerson (swilkerson@ycp.edu) received his PhD from Johns Hopkins University in 1990 in Mechanical Engineering. His Thesis and initial work was on underwater explosion bubble dynamics and ship and submarine whipping. After graduation he took a position with the US Army where he has been ever since. For the first decade with the Army he worked on notable programs to include the M829A1 and A2 that were first of a kind composite saboted munition. His travels have taken him to Los Alamos where he worked on modeling the transient dynamic attributes of Kinetic Energy munitions during initial launch. Afterwards he was selected for the exchange scientist program and spent a summer working for DASA Aerospace in Wedel, Germany 1993. His initial research also made a major contribution to the M1A1 barrel reshape initiative that began in 1995. Shortly afterwards he was selected for a 1 year appointment to the United States Military Academy West Point where he taught Mathematics. Following these accomplishments he worked on the SADARM fire and forget projectile that was finally used in the second gulf war. Since that time, circa 2002, his studies have focused on unmanned systems both air and ground. His team deployed a bomb finding robot named the LynchBot to Iraq late in 2004 and then again in 2006 deployed about a dozen more improved LynchBots to Iraq. His team also assisted in the deployment of 84 TACMAV systems in 2005. Around that time he volunteered as a science advisor and worked at the Rapid Equipping Force during the summer of 2005 where he was exposed to a number of unmanned systems technologies. His initial group composed of about 6 S&T grew to nearly 30 between 2003 and 2010 as he transitioned from a Branch head to an acting Division Chief. In 2010-2012 he again was selected to teach Mathematics at the United States Military Academy West Point. Upon returning to ARL's Vehicle Technology Directorate from West Point he has continued his research on unmanned systems under ARL's Campaign for Maneuver as the Associate Director of Special Programs. Throughout his career he has continued to teach at a variety of colleges and universities. For the last 4 years he has been a part time instructor and collaborator with researchers at the University of Maryland Baltimore County (http://me.umbc.edu/directory/). He is currently an Assistant Professor at York College PA.

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An Undergraduate Research Project in Material Science for Improved Rapid Prototyping

by

Aidan McFall York College of Pennsylvania (Student)

Stephen Wilkerson and Stephen Kuchnicki York College of Pennsylvania

Fused Deposition Modeling (FDM) is one of the most widely used additive manufacturing techniques. Currently there are a multitude of FDM filaments available. FDM and several other additive techniques can now routinely be found at K-12 schools, colleges, and universities. Not surprisingly, numerous hands on manufacturing projects for higher education make use of Three Dimensional (3D) printers to produce models and working prototypes of designs developed by students. These are routinely used for robotics, mechatronics, control projects and many capstone design activities. Now, instead of expending excess time and money for a complicated first of a kind part; a 3D printed substitution can be created for a fraction of the cost, time, and resources of a machined part. More often than not, users will design a prototype using a CAD[1] package. Then a STL[2] file is created and sent to a slicer program to produce the part using well established FDM techniques. Initially, little concern to the orientations or filament choices (typically out of PLA[3]) is given. The resulting model or prototype in many cases is easily broken. Much is learned in the process and a new part or redesign is made taking into account the weaknesses and failure locations in the original. The new design might even be accompanied by a Finite Element Method (FEM) or other analyses to support the proposed changes. This process results in a spiral development that continually improves the functionality and survivability of the prototype.

This paper stems from an independent study project that was focused on layer orientation within a 3D printed FDM model. Since many models are created without any regard to their geometric infills, alignment, or the accompanying stress forces, some guidance in 3D model orientation seems warranted. To attempt to uncover the different properties in regard to layer orientation, four of the most commonly used materials were tensile tested. The results are summarized in order to determine their maximum strength, ductility, and modulus of elasticity. This invaluable knowledge will help with initial material decisions, design layups, and orientations. Some of the surprising results are given here. Furthermore, the results contained in this limited offering should prove invaluable for many projects requiring working prototypes. Results and a discussion of best practices are also provided as a measure of merit for this project.

In this paper's body we lay out the methodologies, in detail, used by the student during this single semester study so that others might duplicate the effort. As this was the third attempt at this particular material based independent study, we also added our observations of the

[1] Computer Aided Design (CAD): https://www.techtarget.com/whatis/definition/CAD-computer-aided-design
[2] Standard Triangle Language STL: https://all3dp.com/1/stl-file-format-3d-printing/
[3] Polylactic Acid, commonly known as PLA a common FDM printing material: https://all3dp.com/1/best-pla-filament/

effectiveness of this project's design and made assessments as to the effectiveness of our approach. A discussion of the figures of merit and why this testing ultimately improves rapid prototyping are included.

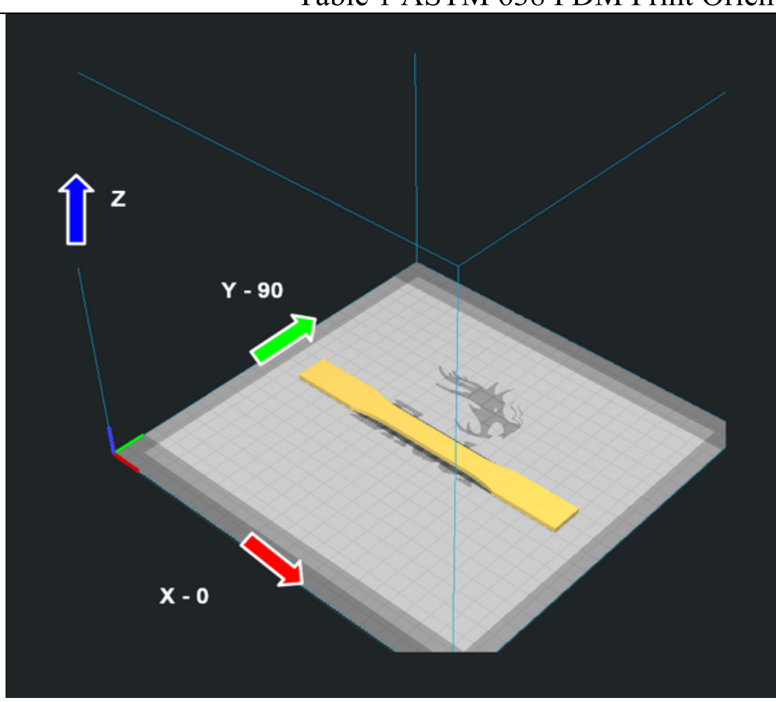
Background:

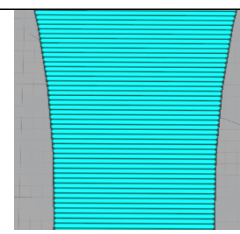
Popescu et.al. points out that the material attributes in FDM specimens like tensile and compression strength are paramount in designing and testing experimental prototypes [1]. Johnson and French further stipulate that consumer grade 3D printers have kept pace with their commercial counterparts. Moreover, 3D printers of all kinds have become a staple at many colleges. Nonetheless, FDM material characterization has lagged behind the widespread use of these new technologies [2]. ASTM international has developed test method and a standard dumbbell specimen D638 for testing the tensile properties of plastics [3]. Hill and Haghi developed a design methodology and approach for testing FDM materials used for the rapid prototyping process [4]. These studies and others form the foundation for the approach take in this limited study [5,6,7].

Testing Procedures:

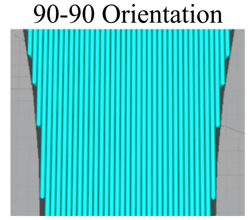
Prints were created without any walls or upper and lower layers, so as to only test the strength of the infill. Note that the print orientations listed below refer to the angle vectors given to the printer. For example, a 0-90 print consists of a vertical layer, then a horizontal layer, and it then repeats this pattern. A 0-0 print is simply repeated vertical layers, while a 90-90 print is repeated horizontal layers.

Table 1 ASTM 638 FDM Print Orientations

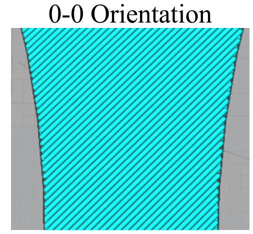




90-90 Orientation



0-0 Orientation



45-45 Orientation

Samples were loaded into a Tinius Olsen tensile tester. They were secured tightly, but otherwise no special actions were taken throughout the testing process. A Prusa I3 printer was used to create the specimens. The specific printer settings are detailed in the Appendix.

Test Results:

PET is notably the least affected by layer orientation, with the 0-0 and 90-90 layers differing by only 11.7% in terms of strength. It is also notable that the 0-90 printing method is not statistically significant from the 90-90-layer orientation, and that this is the only time a significance value greater than 0.05 appears in this study. Another example of PET's low variability is the difference in elongation between its 90-90- and 0-0-layer orientations. With a difference of 6.9%, PET has the lowest difference in ductility between its perpendicular layer orientations. Note that the 0-0 orientation is the stronger of the two, while the 90-90 is more ductile. This is shared with PLA, while the opposite behavior appears with the Carbon Fiber and ABS samples. Each PET sample failed in the horizontal direction. Figure 1 summarizes the maximum tensile strength results for the materials tested. Table 3 provides the plots from these tests.

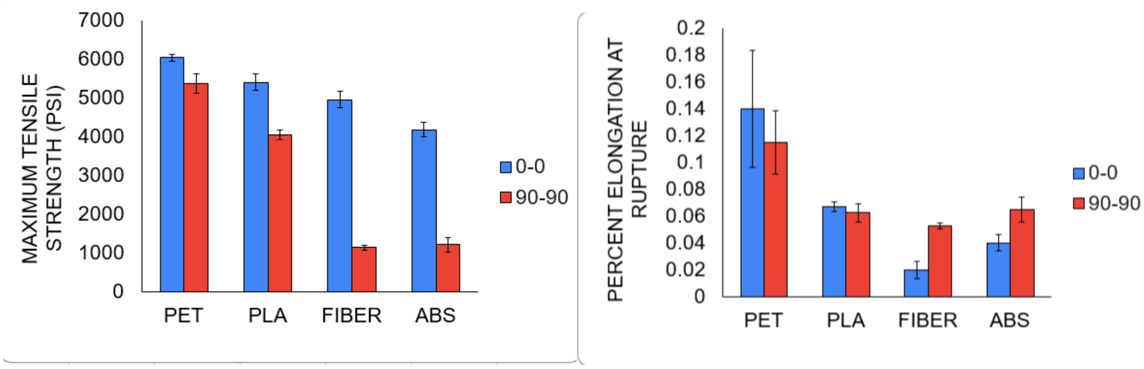
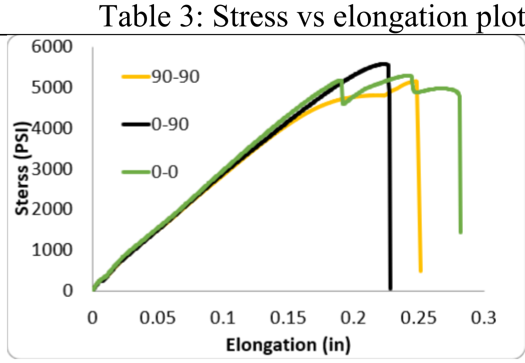
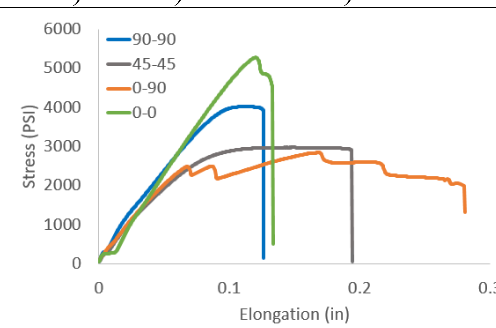


Figure 1: Summary of Material Maximum Strength and Elongation at Rupture

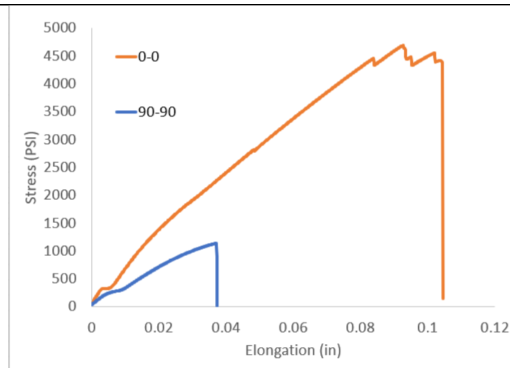
Table 3: Stress vs elongation plots for a) PET b) PLA c) Carbon & d) ABS



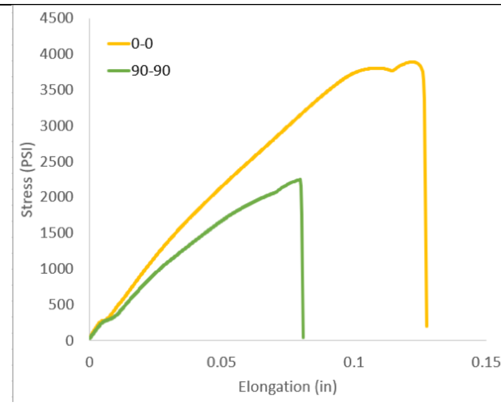
(a)



(b)



(c)



(d)

PLA has 28.7% difference between the strength of the 0-0- and 90-90-layer orientations. PLA has the second lowest difference between its perpendicular orientations, only being beaten out by PET. This is true on elongation as well, with PLA having a 19.6% difference between the 0-0- and 90-90-layer orientations. Note that the 0-0 orientation is the stronger of the two, while the 90-90 is more ductile. This is shared with PET, while the opposite behavior appears with the Carbon Fiber and ABS samples. The 0-0 sample failed at approximately a 30-degree angle relative to the horizontal directions, the 45-45 sample failed with a crack going halfway down the horizontal direction, before going up at a 45-degree angle. The 90-90 sample failed along the 90-degree angle, and the 0-90 sample failed with the filaments in the vertical direction stretching outwards. Some PLA failure are shown below in Figures 2-4.

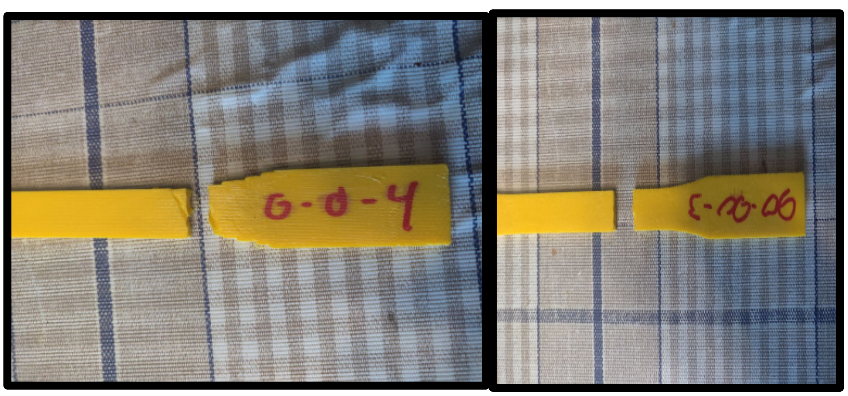


Figure 2. PLA failure Left 0-0 failure mode, Right 90-90 failure mode.

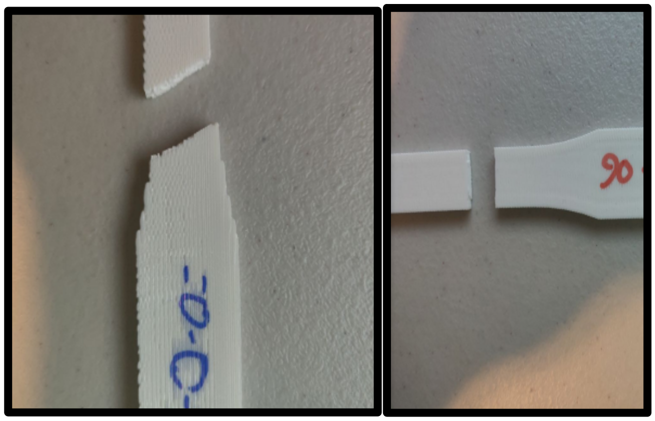


Figure 3. PLA failure Left 0-0 failure mode, Right 90-90 failure mode.

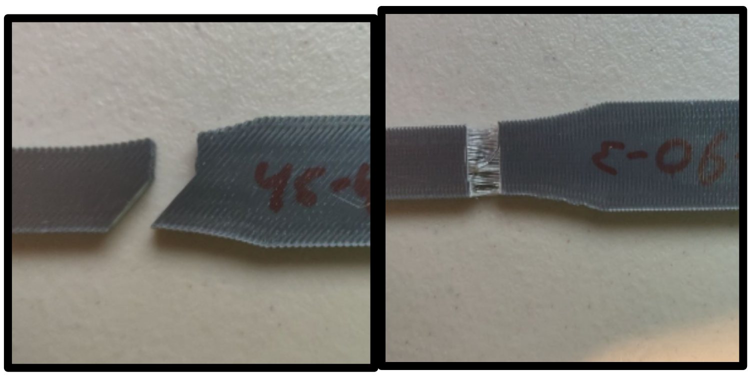


Figure 4. PLA failure Left 45-45 failure mode, Right 0-90 failure mode.

Carbon Fiber exhibits the greatest difference between the 0-0 and 90-90 orientations, 125.4% difference in strength. It also achieves the lowest strength of the group, with its 90-90 orientation measuring a value stress value of 1137 psi at rupture. This material has the largest %difference of any of the materials between its 0-0 and 90-90 elongation at 89.7%. Notably, carbon fiber shares a property with ABS plastic, as it is more ductile in the stronger orientation (0-0), unlike the properties of both PLA and PET, which are more ductile in their weaker layer orientation of 90-90. The 0-0 sample failed along the vertical direction. The 90-90 sample failed along the horizontal axis. Some carbon fiber failures are shown below in Figure 5.

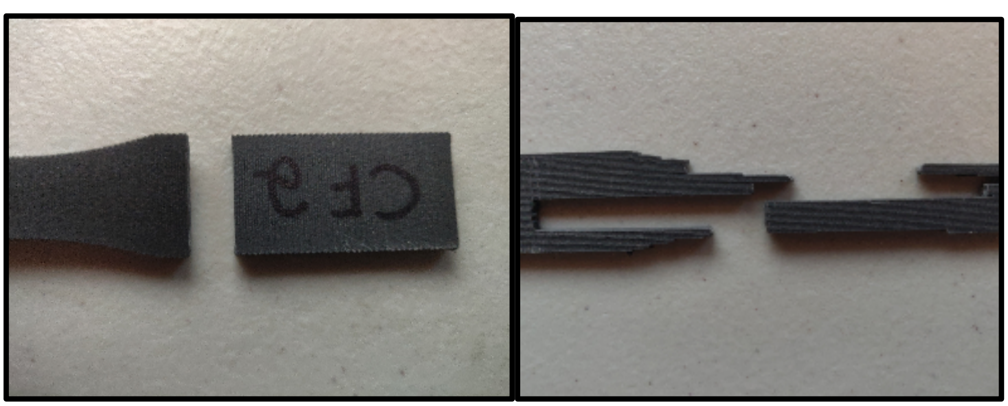


Figure 5. Carbon Fiber failure Left 0-0 failure mode, Right 90-90 failure mode.

ABS placed third in terms of differences between the orientations with respect to strength, with the difference between the 0-0 and 90-90 orientations being 110%. ABS difference between its two perpendicular orientations, are 47.6%. Note that like Carbon Fiber, the more ductile layer orientation happens to also be the strongest orientation, that being 0-0. Each ABS sample failed on the horizontal axis. Some ABS failures are shown below in Figure 6.

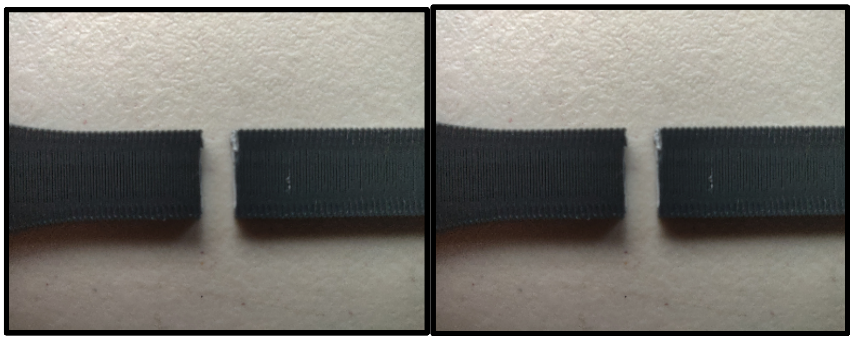


Figure 6. ABS failure Left 0-0 failure mode, Right 90-90 failure mode.

Discussion:

This testing reveals and reinforces important material properties present throughout the materials used. Some of the results are fairly intuitive, and thus our testing was useful in proving intuition. This is evident with the testing on the carbon fiber samples. The expectation is that any material reinforced with carbon fibers will be stronger along the direction the fibers have been in laden. In the case of a material printed with carbon fiber filament, this would correspond to the direction the filament is extruded along. Thus, it should come as no surprise that the samples printed from this filament were much stronger when the filament was aligned with the vertical direction than with that of the horizontal. Our assertion that the fibers only increase strength in the direction they are aligned with seems to have been proven, with the sample gaining over 125% strength when compared to the 90-90 orientation.

The 90-90 samples failed along the printed layers, with the layers separating from each other, where the "welds" of the printer layers being the first part of the structure to fail. This behavior appears to be typical. However, when the fibers are oriented vertically, or, when the 0-0 sample is tested, an entirely different failure mode occurs. The sample fails almost as if it is a puzzle piece, with cracks dispersed throughout the part. ABS, in some respects, was very similar to Carbon Fiber. As mentioned previously, this material had a similar magnitude of strength gain (110%) when printed in the 0-0 direction. However, unlike carbon fiber, both of the samples ruptured along the sample's horizontal axis. PLA samples had variable failure modes depending on the orientation of the layers. These were described previously, but it is worth noting that each orientation produced a unique failure mode. In particular, the failure of the 0-90 sample was interesting, with the vertical fibers elongating before rupture. Each PET sample failed along the horizontal axis of the sample. This behavior seems to be correlated with the low differences between PLA's elongation and strength, as it would be strange to see a completely different failure mode from samples that differ only by, at most, 11.7% maximum strength.

Using lines of best fit in the linear portion of the stress strain curve for each material, we can calculate their moduli of elasticity. It should be noted that each of the PET moduli are almost identical, which falls in line with our results. This can be visualized where each stress strain curve sits atop one another. In a similar fashion, the PLA curves align closely, but what is interesting is that the 45-45 and 0-90 samples are both lower than the 0-0 and 90-90 orientations. This behavior indicates that modulus of elasticity changes independently of orientation, with certain weaker orientations nevertheless holding more strongly in the elastic region of the material. Carbon Fiber and ABS both behaved as expected, with the weaker orientation of 90-90 having a lower modulus of elasticity for each material.

This study was conducted to determine the effects of layer infill orientation on a sample's maximum strength, its ductility, and its modulus of elasticity when it was subjected to a tensile force. Fortunately, valuable insight was gained into various material properties. One such discovery was PET's similar properties in both the 0-0 and 90-90 orientations. This seems to imply the bonds between filament strands are nearly as strong as the filament itself. On the other end of the orientation spectrum, carbon fiber was clearly very orientation dependent. Thus, if a part might be stressed in multiple directions, or if the creator is unsure of which direction will receive the greatest stress, PET would be a superior choice. On the other hand, if a 3D printed part is slated to receive more stress in predetermined directions, layers of ABS plastic could be oriented appropriately so as to maximize strength.

Because of the many parameters used in 3D printing, this study could be expanded in countless ways. For the sake of brevity, only a few will be suggested. First, more materials could be tested, most importantly on the 0-0 and 90-90 orientations, to determine how much their strength varies. It would be useful to create a kind of baseline for each material, seeing how much their strength varies depending on layer orientation. Additionally, similar testing could be performed, but with compressive strength being measured instead of tensile strength. This could provide valuable insight, especially since 3D printed parts can sometimes be load bearing and might be subjected to high compressive stresses. Another test that might be useful to perform is a fatigue test, as it is useful to see how different orientations hold up over a large magnitude of cycles.

Conclusion

The body of the report gives the details of the work that was done by the student and his findings. However, what is also interesting is the evolution of the independent materials research project over the past 3 years. When we started this project, we focused on the relevant details including test specimen type, layup, and various materials. We included some background work on previous efforts and how to operate the testing machines and printers to obtain the data. However, the student end report always left us scratching our heads thinking something more was missing. In the current effort, we included these items as before, but expanded our analysis of the results to include statistical approaches. We also asked the question of why we were doing this study? In other words what was the end state for the use? This was to allow students to rapidly prototype experiments for capstone design, machine design and other material relevant classes. Our observations indicate that students put more effort into projects that they know will benefit other students. In this most recent effort, we were very fortunate that the student who did this work was self-motivated and studious.

Traditionally, 3D FDM printing at the school was primarily done with PLA and ABS prototypes. Nowadays, 3D printing is done with a host of FDM polymers that include flexible and carbon infused materials with wide-ranging plastic types, strengths, hardness, and inherent weaknesses. In doing this study we have started to highlight the importance of layup in the design, but far more importantly, in choosing the best material for a particular prototype goal.

While this study only scratched the surface of possibilities it still found some surprising results that were formerly not known to us. For example, PET exhibits very little degradation due to layup orientation. This attribute was also true of TPU; not included in this report. This paper's body details the methodology used so that others could duplicate and improve. Moving forward in future studies I believe we will continue to focus on only 3-4 different material types and their characterization at a time. In previous years we had included more rather than less material types with mediocre results. Additionally, it might be useful to actually apply knowledge gained by material testing for material types used in specific prototypes. This will undoubtedly require the coordination of the independent study to the end state users in capstone and other material design courses in our curriculum.

Reflections and observations from the student: I wanted to conduct a study on different 3D printed materials for two main reasons. First, I had just completed various constructed prototypes and models for my capstone design project. These included a fixed-wing drone, using 3D printed materials. Our team wanted to gain a better understanding of the material properties and manufacturing. This study helped us gain additional insight into the materials. Also, I had never conducted a study on my own, and figured this would be a valuable experience to gain in my senior year. As expected, the study proved fruitful. I got to experience firsthand what it was like to write up a test plan, review data, and plan for further experimentation. I believe 3D printing is the perfect avenue for a student to conduct independent research, as it allows for rapid prototyping with different materials and printing methods and is also simple to test. For these reasons, I would absolutely recommend other students conduct similar studies on their own, as I believe FDM manufacturing will only grow more widely used in both prototyping and manufacturing as the processes are further refined.

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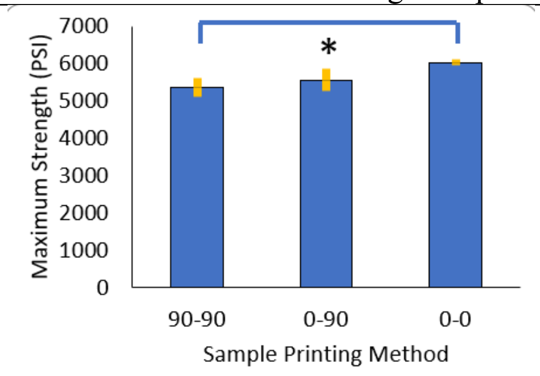
Appendix A

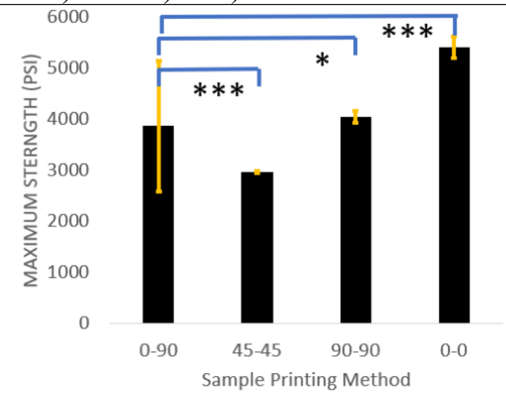
Printer settings per material.

MATERIAL	SPEED (mm/s)	HOTEND TEMP (°F)	BED TEMP (°F)	SPECIAL
PET	4800	225	80	NO JERK
PLA	4800	200	60	
CARBON FIBER	4800	200	40	NO RETRACTION
ABS	3200	245	100	

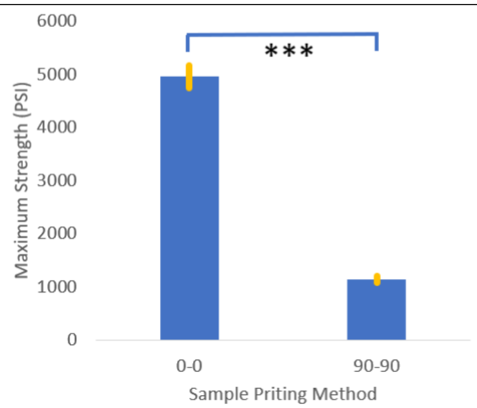
Stress vs elongation plots for a) PET b) PLA c) & d) ABS



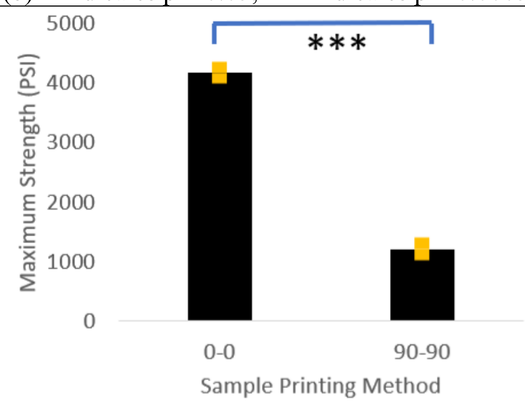
(a) * Indicates $p < 0.05$



(b) * Indicates $p < 0.05$, *** Indicates $p < 0.0005$



(c) *** Indicates $p < 0.0005$



(d) *** Indicates $p < 0.0005$