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Material Property Variation in an Additive Manufacturing Lab

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Material Property Anisotropy in An Additive Manufacturing Lab

Abstract
Traditional structural analysis is typically covered in statics and strengths of materials courses. New additive manufacturing (AM) techniques allow us to analyze structures free of prismatic constraints, using 'freeform' design and analysis that results in better performance. However, AM structures also exhibit significant variation in material properties that must be considered. Using 'best practice' in engineering analyses is a student outcome that is part of our senior mechanical design course. One lab was modified in this course to improve student performance in achieving this outcome.

Originally the machine design 'lever' lab was a theoretical exercise. Several years ago, this was altered to be an applied lab. The student design was printed using AM and then tested to failure. More recently, the mechanical design 'lever' lab was also modified to include a transition from prismatic to freeform design through the creation of a simple lever. The lab consists of six sequential activities. The first four involve traditional prismatic analysis. The fifth analysis involves a lightweighting exercise, followed by the sixth analysis that is a non-prismatic analysis. All were evaluated with a success criteria equation and test feedback.

Throughout the lever lab activities, students were evaluated on analysis performance. The addition of ASTM anisotropic data was part of the new modifications to the lever lab. Since AM processes induce directional material property variation, this was an aspect of lever performance prediction that was modified and specified for evaluation. This lab improvement answers a need of addressing relevant technical issues, but our metrics did not show substantive improvement currently.

Introduction

A theoretical design of a lever was used for many years in the Mechanical Engineering Technology program in the upper level Mechanical Design I course. In fall of 2015, this was converted to an applied lab to better meet ABET Engineering Technology Accreditation Commission Student Outcome 3a [1]. The lab was modified to include input for anisotropic properties. Coincidently, Zhang at the 2015 ASEE Annual Conference in a conference paper titled "Understanding Additive Manufacturing Part Performance Through Modeling and Laboratory Experiments." [2] suggested having an applied lab for anisotropic properties.

The students created a design that was then manufactured using Additive Manufacturing (AM) method. The AM method used was fused deposition modeling (FDM) [3]; the material was acrylonitrile butadiene styrene (ABS). The levers were failed in a jig using an Instron 1011 testing machine. In 2019, the lever lab was extended into the Finite Element Analysis (FEA) course when lightweighting and 'free-form' outcomes were added. For each lab activity the students were evaluated on how well they met the success criteria. This year, in the FEA course, the students will benefit from ASTM testing conducted on the material printed in the AM machine. A MakerBot Method X [4] was used for the levers and ASTM testing samples. Any improvement in Outcome 3a is indicated by the success formula.

Methods

The process for completing the various levels of design and analysis were covered by six different labs over two courses. The first four labs (2015 to present) were conducted in the Mechanical Design 1 course using prismatic shapes. The final two labs (2019 to present) were conducted in the FEA course. The first FEA lab allows for a prismatic shape and the second lab requires a ‘free-form’ shape.

The outcome being met is ABET Engineering Technology Accreditation Commission Student Outcome 3a (an ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly defined engineering technology activities). This is assessed using the success formula for lever failure (See Appendix B). This formula rewards levers that were lightweight and fail at the target value, 30 pounds. There is an initial penalty of 20% for any lever that fails under 30 pounds. As the failure load diverges from 30, and the heavier the lever is, the greater the penalty. The students were attempting to achieve a tolerance range of minus zero to plus three pounds for the best possible score.

1) In the first lab (Lab 3a), the students were provided with the design criteria for the lab (See Appendix A). The crux of the design is the students were attempting to have the lever fail as close to a 30 lb. load as possible without going under. Each student arrives at a design (which they hand sketch only) after completing their analysis calculations. Analysis calculations will consist of basic statics and mechanics of materials concepts (excluding Mohr’s circle).

2) In the second lab (Lab 3b), the students were randomly placed in teams of three. Using their own criteria, the students use a decision matrix to determine which of the three designs to go forward with. The selected design is modeled using SolidWorks. They were permitted to make design changes if they feel they were necessary to meet the success score (See Appendix B). This equation is used for all subsequent labs and was developed primarily by Applied Math Professor, Jean Marie Linhart, Ph.D.

3) In the third lab (Lab 4), the students apply Mohr’s circle analysis to their design. The students can modify their design as they see fit. This design is submitted as a .STL [5] to be printed, placed in the jig (See Figure A-3), and loaded to failure. The result is then scored per the success score.

4) In the fourth lab (Lab 5), armed with failure load and their failed lever, the students conduct a failure analysis and reassess their design calculations. They were then provided the opportunity to modify their design and resubmit another design (.STL) for printing and failure. The new design is scored via the success score.

5) In the fifth lab (Lab 6a), the students use one of their previous designs, but now they must reduce the weight by 5%. They can use FEA analysis to assist with reducing the weight (they were not using Topology optimization [6]). They submit their design for printing and failure. This design is also scored with the success score. For 2021, the students were provided ASTM flexure data from samples printed in the same orientation, same filament, and on the same machines as the levers would be printed.

6) In the sixth lab (Lab 6b), the students were now required to redesign their lever using a free-form design and further reduce the weight by 5%. The new free form design must utilize curved shapes in at least two of three planes (xy, yz, & xz). They use FEA analysis to assist them in formulating their design. They submit their design for printing and failure. This design is also scored with the success score.

Results

Data was generated for the 2021 students, prior to labs 6a & 6b, in compliance with ASTM D790 Flexure Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials (Three-point bend). The students could then compare the manufacture's published data to the data produced in Table 1. The printing orientation of the levers corresponded the Table 1 data which corresponds to the orientation in Figure 1.

Table 1. ABS Material Specifications from Vendor and in-house Testing – Flat Orientation.

ABS Material	ASTM D790 1/8 x 1/2 flat (0.05"/min)	ASTM D790 1/8 x 1 flat (0.05"/min)	MakerBot Tech Spec (ASTM D790 15mm/min)	MakerBot Precision ABS (Method 1, 0.05"/min)
Flexural Strength (psi)	7798	7314		9427
Flexural Modulus (psi)	197000	193400	377000	112000
Strain at Yield (%Elongation)	>5.6	>5.7	>5.6	2.6
Tensile Strength - ASTM D638 (psi)			6236	6236
Tensile Modulus -ASTM D638 (psi)			348000	348090
Notch - ASTM D256 (ft-lb/in)			3.6	0.48

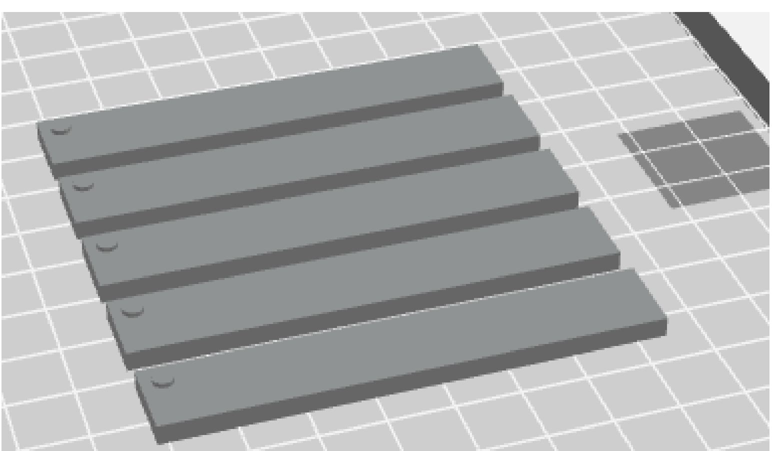


Figure 1. ASTM D790 samples on printer bed – flat orientation.

The students were shown Table 2 to demonstrate the anisotropic properties of AM. When comparing Table 1 and Table 2, there is a 38 percent difference in material flexure properties based on printed orientation per the testing. Figure 2 shows the vertical orientation on the print bed.

Table 2. ABS Material Specifications from Vendor and in-house - Vertical Orientation.

ABS Material	**ASTM D790 1/8 x 1/2 vert (0.05"/min)**	**ASTM D790 1/8 x 1 vert (0.05"/min)**	**MakerBot Tech Spec (ASTM D790 15mm/min)**	**MakerBot Precision ABS (Method 1, 0.05"/min)**
Flexural Strength (psi)	10100	10690		9427
Flexural Modulus (psi)	254000	242300	377000	112000
Strain at Yield (%Elongation)	>8.2	>6.6	>5.6	2.6
Tensile Strength - ASTM D638 (psi)			6236	6236
Tensile Modulus -ASTM D638 (psi)			348000	348090
Notch - ASTM D256 (ft-lb/in)			3.6	0.48

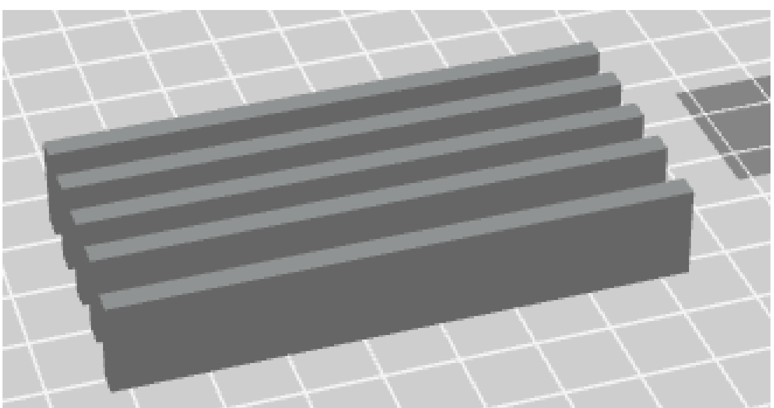


Figure 2. ASTM D790 sample on printer bed – vertical orientation.

The trend of the success scores can be seen in Figure 3. The average success score increased by 26 percent, but not as well as might be expected. Conducting a T-test (two-sample assuming unequal variances) between 2020 and 2021 lab 6a test data indicated there was a 95% chance the means were the same.

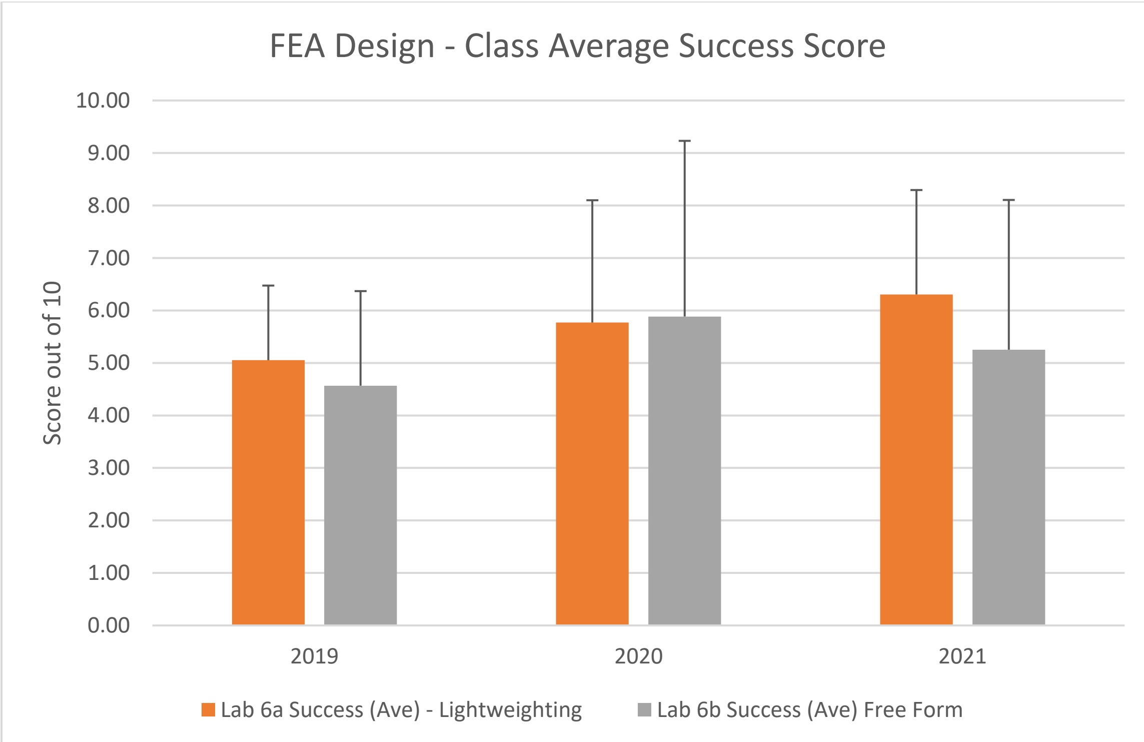


Figure 2. Class average success score for FEA course.

Discussion

This demonstration of anisotropic properties provides the students with varied material data sets. The students must apply engineering judgement in selecting an appropriate material property for their analysis. As seen in Table 1, the flat orientation specimens, the flexure data was approximately 20% lower than published data. In Table 2, the vertically oriented specimens, the flexure data was approximately 10% higher than published data. Our hypothesis is that addressing these double-digit percent differences in directional properties during design predictions would make a substantive improvement in engineering methodology.

Historically the students continue to miss the tolerance per the success formula scores. The best possible score when the lever fails below 30 pounds is eight out of ten. The class average continues to be lower than eight per Figure 2. This indicates the levers were not failing above 30 pounds and they were also heavier than necessary. If the students were achieving the specified tolerance, the success scores would be nine or higher.

ABET Outcome 3a was met but not improved. The student outcome is improved because the scores went up per the assessment. However, the T-test reveals the scores were not significantly different. In fact, there is a 95% chance they were the same.

The difference between Lab 6a and 6b labs was not obvious. It was unclear if this was due to lack of understanding in applying FEA or if their assumed failure mode was not reflected in their chosen orientation properties. With the flat orientation there was the occasional “delamination” failures which would not match the chosen material properties.

The hypothesis of providing anisotropic data about the filament on machine being used for printing the levers should allow the students to significantly improve their success scores. This does not appear to have happened. There was an improvement of 26%, but not what might be considered significant per the T-test. There were other issues affecting the success score as indicated by the large standard deviation that requires investigation.

Future work should include some survey questions to assist in determining where the students may be going wrong. More discussion of failure modes would also be appropriate. Changing the orientation of the print to eliminate the potential for delamination failure would also be appropriate.

Conclusion

The following conclusion were found:

- The students were evaluated on analysis performance through each lab activity.
- The students were further evaluated on tolerancing of their success scores to be minus zero, plus three pounds.
- Student performance in the success outcome improved 26 percent but was within the standard deviation. This indicates that ABET Outcome 3a was met but not improved.

References

[1] Criterion 3a an ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly-defined engineering technology activities. https://www.abet.org/wp-content/uploads/2015/05/T001-15-16-ETAC-Criteria-05-04-15.pdf

[2] Y. Zhang, J. Wang, and M. Mamodapur, "Understanding additive manufacturing part performance through modeling and laboratory experiments," in 122nd ASEE Annual Conference & Exposition, T523B·Integrating Curriculum and Labs in ET Programs, Seattle, WA June 14-17, 2015.

[3] Fused filament fabrication, https://en.wikipedia.org/wiki/Fused_filament_fabrication

[4] MakerBot Method X, https://www.makerbot.com/3d-printers/method/

[5] STL (file format), https://en.wikipedia.org/wiki/STL_(file_format)

[6] Topology optimization, https://en.wikipedia.org/wiki/Topology_optimization#:~:text=Topology%20optimization%20(TO)%20is%20a,the%20performance%20of%20the%20system.

Appendix A

You are employed by “Wildcat Enterprises” in the design department as an engineer. A problem (below) is assigned to you. If approved, this part will go into production.

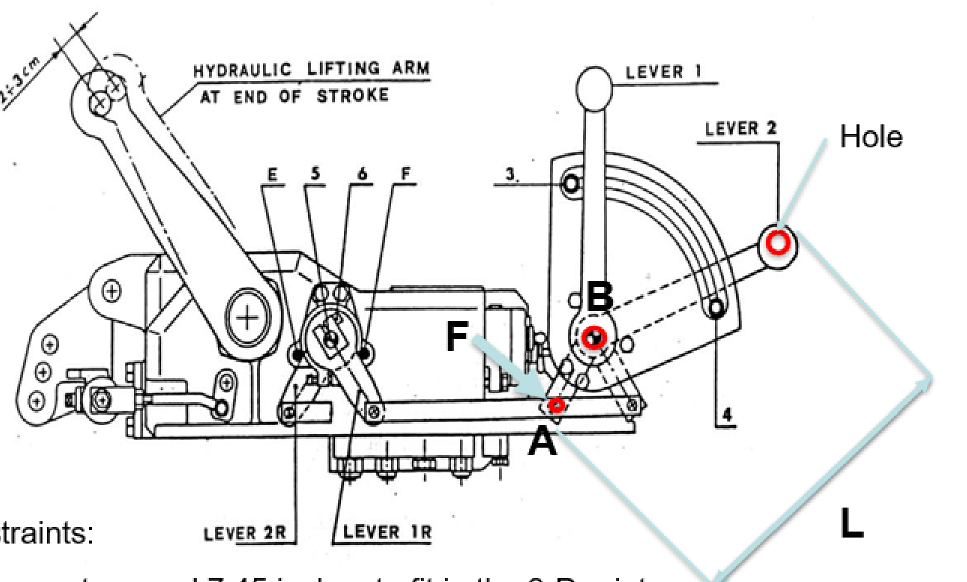
You are tasked with designing a 3D printed lever (An example is provided on the next slide). Perform the necessary analysis.

It consists of a short arm, pivot, and long arm. The pivot fits on a stub attached to the machine frame. Pivot is 5.5 inches from the lever load. The force F (20 lbs) is applied at the hole in the end of the handle. This allows the lever to be designed for failure at 1.5 times the load of 20 pounds. Reactions to the load are the output force on the other side of the pivot (short arm), which is always perpendicular to the short arm.

All parts are 3D printed. No stress concentrations for failure are allowed.

The lever must also support a 2-1/2 pound side load (from B to C) prior to testing to failure. No safety factor associated with this load.

Figure A-1. Page one of Lever lab specifications.



Dimensional Constraints:

Overall length (L) cannot exceed 7.45 inches to fit in the 3-D printer.
Distance from center of pivot to center of hole at end of long arm must be 5.50 inches.
All three holes (short arm, pivot, long arm) must be 0.25 inches in diameter.
To locate the lever on the fixture, holes A, B, and Hole must be 0.99 inches in depth (into the paper).
Holes A & B are 1.5 inches apart, and 30 degrees from horizontal.
Long/short arm and around holes may be any shape or size that fits the constraints.

Figure A-2. Page two of Lever lab specifications.

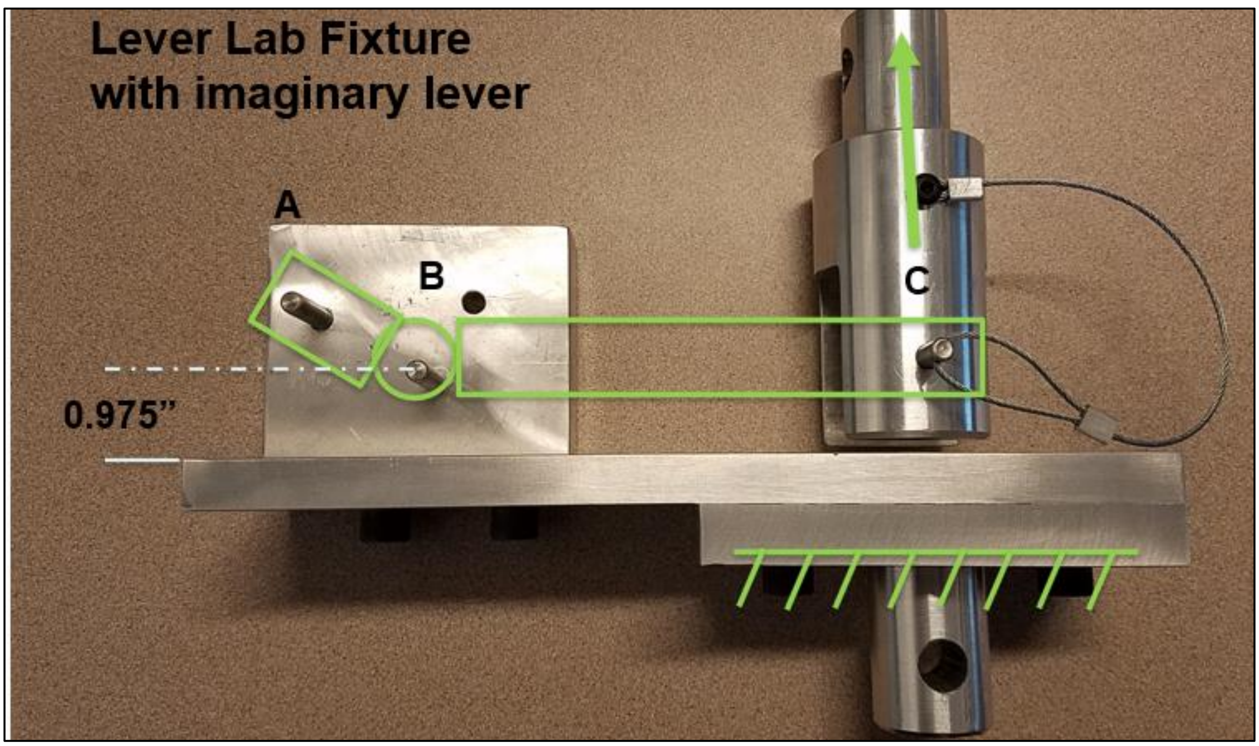


Figure A-3. Lever lab fixture for Instron 1101.

Appendix B

$$Success = IF\ F < 30, \frac{3.5}{1 + \ e^{.5*(24-F)}} + \frac{4}{1 + \ e^{.3*(x-32)}} + .5$$

$$Success = \ IF\ F > 30\ \ \frac{4.1}{1 + \ e^{.3*(x-32)}} + \frac{3.1}{1 + \ e^{.5*(F-36)}} + 6$$

F = Failure force
x = weight of lever

Figure B-1. Success equation for lever failure