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Understanding additive manufacturing part performance through modeling and laboratory experiments

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Understanding Additive Manufacturing Part Performance through Modeling and Laboratory Experiments

Abstract

Additive manufacturing (AM) has attracted extensive attention in recent years due to its wide applications in academia and industry. As most of the AM parts are built layer by layer, it is clear that parts manufactured from AM processes would perform differently compared to parts manufactured from conventional processes such as casting and injection molding. Since students often rely on AM for part fabrication in courses and capstone projects, and industries could adopt AM to produce components for their products, there is a need for students to understand the mechanical performance of parts manufactured from AM processes. As such, an AM laboratory exercise, with a focus on experiential learning on the behavior of different materials, is introduced.

This paper presents an effort of developing and implementing laboratory materials for students to conduct experiments with AM parts and to understand the anisotropic nature of the material. In this development effort, tensile specimens of Acrylonitrile Butadiene Styrene (ABS) are printed using Fused Deposition Modeling (FDM), one of the most popular AM technologies, from three different building configurations. In the first lab, students are assigned to characterize the tensile behavior of the specimens. The test results are then compared to the bulk ABS property. In the follow-up labs, the constitutive model of AM ABS, adopted from a graduate research project, is presented to students. New parts including a beam and an L wrench which also fabricated using FDM are then tested under three-point-bending and combined bending and torsion test, respectively. Students are instructed to compare the performance of the AM parts to that of the parts with bulk ABS property. Student feedback of the learning experience is summarized. From surveys, it was found that the laboratory exercises can enhance students’ understanding of AM part performance. The developed materials can be adopted by others teaching in engineering technology programs.

Introduction

Additive manufacturing (AM) is a powerful technology that has the potential to revolutionize parts manufacturing industry. It has attracted great attention during the past few years due to its wide applications in various industries.[1,2] The technology involves joining of materials to build parts strand by strand, and layer upon layer.[3] As such, parts fabricated by AM processes have different mechanical behaviors compared to those produced by conventional manufacturing technologies such as injection molding and casting. Since students often rely on AM for parts fabrication in courses and capstone projects,[4,5] and industries could adopt AM for distributed manufacturing and production of parts on-demand, [6,7] AM education is of critical importance. Engineering and engineering technology students need to understand the performance of parts manufactured from AM processes.

The Strength of Materials course is a critical course in typical engineering and engineering technology curricula where students acquire the fundamental principles and develop problem solving skills for stress analysis and mechanical design of structural and machine elements.[8,9] Often, laboratory exercises are designed to demonstrate the basic principles and abstract concepts through a series of experiments. Students perform experiments to characterize the tensile behavior of steel, aluminum, or plastic samples. They also test the mechanical performance of specimens through three-point bending and combined bending and torsion experiments. The laboratory exercises promote active, experiential learning.[10-12] The laboratory experience helps students to better understand the theories learnt from lectures. In order to introduce students to the mechanical behavior of AM parts, it is appropriate to incorporate an AM laboratory exercise in the course.

In recently years, efforts have been made to develop courses to enhance students' knowledge in AM applications.[13,14] However, most of work focused on the design or fabrication of parts without addressing the performance of AM parts, particularly the anisotropic nature of the AM part behavior. For example, Fused Deposition Modeling (FDM) is one of the most popular AM technologies commonly used for prototyping and physical modeling. In the FDM process, partially melted filament is extruded from a nozzle and deposited onto a platen to form objects.[15-17] The motion of the nozzle is controlled by computer software from 3D model data to deposit material strand by stand and layer by layer. As such, this "composite like" anisotropic material has a different mechanical behavior compared to isotropic bulk material.[18,19] To stay current, it is necessary for engineering technology students to have the knowledge of anisotropic.

This paper presents an effort of developing and implementing laboratory materials for students to conduct experiments with AM parts. Three laboratory exercises were included in this project. The constitutive model of AM parts, adopted from a graduate level research project, was presented to students. Through experiments, the performance of various AM specimens was characterized. Students were instructed to summarize their observation. Pre and post lab surveys were carried out to investigate students learning experience. In the following sections, the lab activities and assessment methods are described; and the evaluation of student learning, including the lessons learned, are presented.

Method and laboratory description

In order to fully assess students' understanding of the performances of AM specimens under different tests, three labs were designed and integrated into the regular Strength of Materials Lab. The three labs were tensile test (AM Lab #1), three-point-bending test (AM Lab #2), and combined bending and torsion test (AM Lab #3) as shown in Table 1. Note that during the three-point-ending and combined bending and torsion labs, regular metal specimens were also tested. All the AM specimens were made from Acrylonitrile Butadiene Styrene (ABS) and were printed by FDM with different building configurations.

Table 1 Strength of Material Lab Description

Lab Description
Lab Policy, Group Formation, Intro to Strain Gages
#1, Installation of Strain Gages (Bars & Coke Can)
#2, Installation of Strain Gages (Bars & Coke Can) Cont.
#3, Tensile Test with United Model SFM Test System
#4, Tensile Test of Anisotropic Materials (**AM Lab #1**)
#5, Torsion Tests (Finding Torsional Rigidity)
#6, Determining Modulus of Elasticity & Poisson's Ratio
#7, Stress Concentration
#8, 3-Point Bending Test and **AM Lab #2**
#9, Thin-Walled Pressure Vessels
#10, Principal Stresses and Strains
#11, Combined Bending & Torsion and **AM Lab #3**

AM Lab#1 – tensile Test

In AM Lab #1, student teams were assigned to characterize the tensile behavior of the FDM ABS specimens. Three dogbone-shaped parts with three different building configurations, horizontal, vertical, and 45 degree, were tested by each team. A United SFM Test System was used to perform tensile tests. Figure 1 shows the schematic of the build of the specimens. After AB Lab #1, students were asked to compare the test results to specimens with different configurations as well as to the bulk ABS property in their lab report.

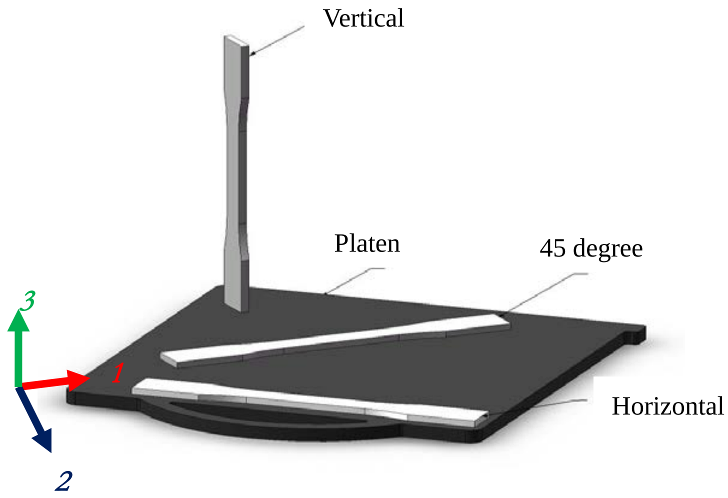
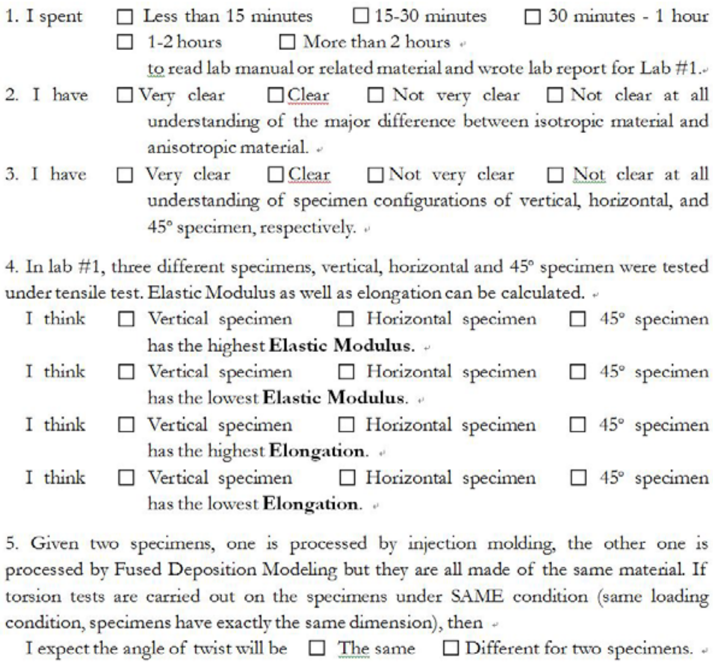


Figure 1 Schematic for the specimen tested under tensile test.

Survey #1 was conducted one week after AM Lab #1 and the data was collected. In Survey #1, both objective and subjective questions were included. The former was used to assess students' acquisition and retention of the knowledge learnt in AB Lab #1, and the latter was used for students' self-assessment. Figure 2 shows an example for Survey #1.



1. I spent ☐ Less than 15 minutes ☐ 15-30 minutes ☐ 30 minutes - 1 hour ☐ 1-2 hours ☐ More than 2 hours
to read lab manual or related material and wrote lab report for Lab #1.

2. I have ☐ Very clear ☐ Clear ☐ Not very clear ☐ Not clear at all
understanding of the major difference between isotropic material and anisotropic material.

3. I have ☐ Very clear ☐ Clear ☐ Not very clear ☐ Not clear at all
understanding of specimen configurations of vertical, horizontal, and 45° specimen, respectively.

4. In lab #1, three different specimens, vertical, horizontal and 45° specimen were tested under tensile test. Elastic Modulus as well as elongation can be calculated.

I think ☐ Vertical specimen ☐ Horizontal specimen ☐ 45° specimen
has the highest **Elastic Modulus**.

I think ☐ Vertical specimen ☐ Horizontal specimen ☐ 45° specimen
has the lowest **Elastic Modulus**.

I think ☐ Vertical specimen ☐ Horizontal specimen ☐ 45° specimen
has the highest **Elongation**.

I think ☐ Vertical specimen ☐ Horizontal specimen ☐ 45° specimen
has the lowest **Elongation**.

5. Given two specimens, one is processed by injection molding, the other one is processed by Fused Deposition Modeling but they are all made of the same material. If torsion tests are carried out on the specimens under SAME condition (same loading condition, specimens have exactly the same dimension), then

I expect the angle of twist will be ☐ The same ☐ Different for two specimens.

Figure 2 An example of Survey #1.

Survey #2 was carried out before AB Lab #2 aiming at evaluating students' AM knowledge. Students were asked to predict the performance of FDM ABS specimens before conducting three-point bending experiments. The results of this "pre-AB Lab#2" survey were used to compare that of "post-AM Lab#2" survey (Survey#3) and to assess the knowledge gain students made during AM Lab #2.

AM Lab#2 – three-point bending experiment

In AM Lab #2, the students were introduced to a constitutive model for FDM ABS, adopted from a previous graduate research project. Theoretically, the FDM specimens can be considered as linear elastic orthotropic material.[20] Three mutually orthogonal axes are shown in Figure 1. The 1, 2 and 3 axes are the directions along which the mechanical properties of FDM ABS have been characterized. The material properties in direction 1 are the same as that in direction 2, but are different from direction 3. The constitutive equation for an orthotropic material is shown in Eq. (1).

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \times \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} \qquad (1)$$

where is ε_i the normal strain, γ_{ij} is the shear strain, E_i is the Young's modulus along *i* axis, ν_{ij} is the Possion's ratio that corresponds to transverse strains in the *j*th direction when load is applied in the *i*th direction, G_{ij} is shear modulus in the *i-j* plane, σ_i is the normal stress, τ_{ij} is the shear stress in the *i-j* plane.

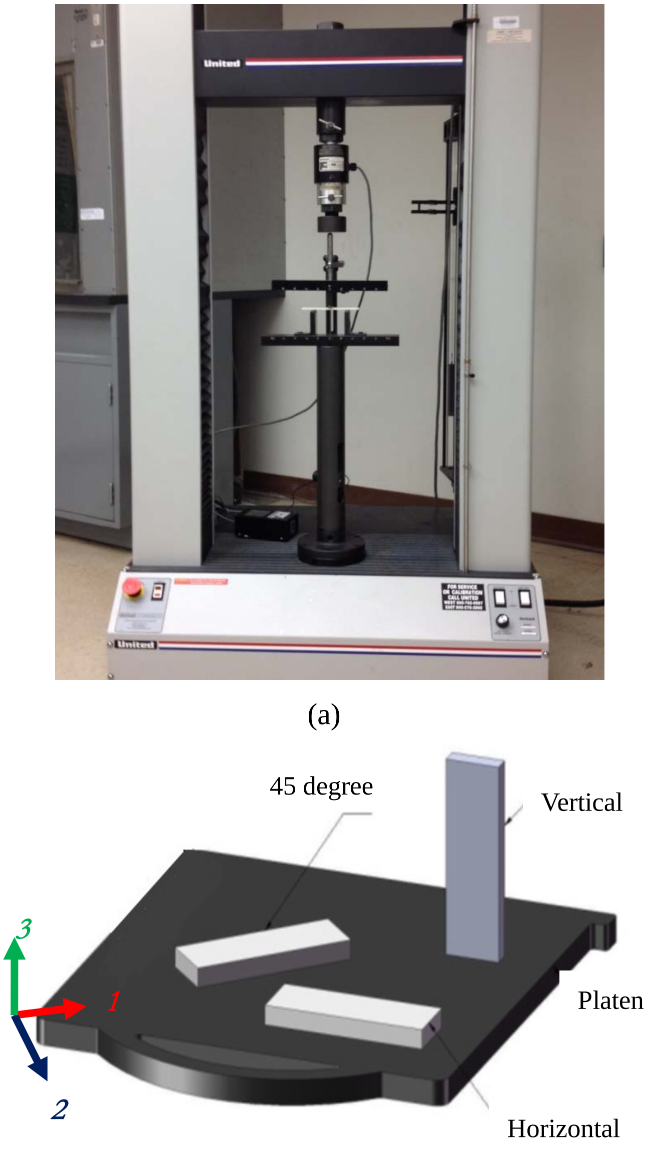
In the previous research project, the material properties of FDM ABS were carefully characterized. Tensile tests were used to determine the Young's moduli and the corresponding Poisson's ratio, and torsion tests were carried out to determine the shear moduli. All the tests were conducted in accordance to the ASTM standard. The constitutive behavior for FDM ABS is presented in Eq.(2).

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} 3021.56 & 1844.59 & 1800.48 & 0 & 0 & 0 \\ 1844.59 & 3021.56 & 1800.48 & 0 & 0 & 0 \\ 1317.34 & 1317.34 & 2171.83 & 0 & 0 & 0 \\ 0 & 0 & 0 & 618.00 & 0 & 0 \\ 0 & 0 & 0 & 0 & 618.00 & 0 \\ 0 & 0 & 0 & 0 & 0 & 676.00 \end{bmatrix} \times \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} \qquad (2)$$

where stress σ_{ij} is in MPa.

The information presented above is a homogenization process for this "composite like" AM material. The detailed strand by strand and layer by layer configuration can be greatly simplified. The anisotropic FDM ABS can now be considered as a homogeneous material with the effective stiffness matrix shown in Eq. (2). To predict part performance, finite element analysis (FEA) can be conducted based on material property input shown in Eq. (2).

In AM Lab #2, parts with different build configurations (horizontal, vertical, and 45 degree) were used to study the mechanical behavior of FDM ABS under three-point-bending. The tests were conducted on the United SFM Test System shown in Figure 3(a) and the schematic of specimens are shown in Figures 3(b).



(a)

(b)

Figure 3 (a) Equipment and (b) Schematic for the specimen tested under three-point bending test.

FEA results of the three-point bending experiments were introduced during the lab. The deflection contour plots for bulk ABS and specimens with different configurations were presented to the students. Figure 4 depicts an example of the deflection contour in *z* direction when the applied load was 200 N. Table 3 lists FEA predictions. It is clear that the deflection of the FDM ABS was larger than that of the bulk ABS due to the "porous like" property of the FDM ABS. Introduced the theoretical background and given the FEA predictions, the students were asked to conduct experiments and collect and report the displacement data. An example of experimental result is shown in the last row of Table 3. The FEA prediction agreed with the experimental measurement well. It was expected that, with the hands-on testing experience, student can better understand the concept of material anisotropy.

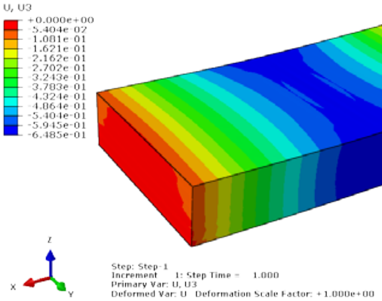


Figure 4 An example of the deflection contour in Z direction.

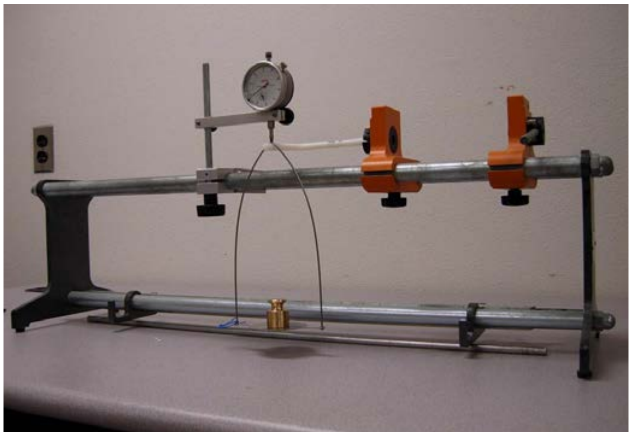
Table 3 Deflections (in mm) for FDM ABS specimens and the bulk ABS specimen tested under three-point bending at 200 N

Specimen configurations	45 degree	Horizontal	Vertical	Bulk ABS
Deflections (from FEA)	0.3884	0.4064	0.5420	0.3372
Deflections (from experiments)	0.3956	0.4918	0.5249	-

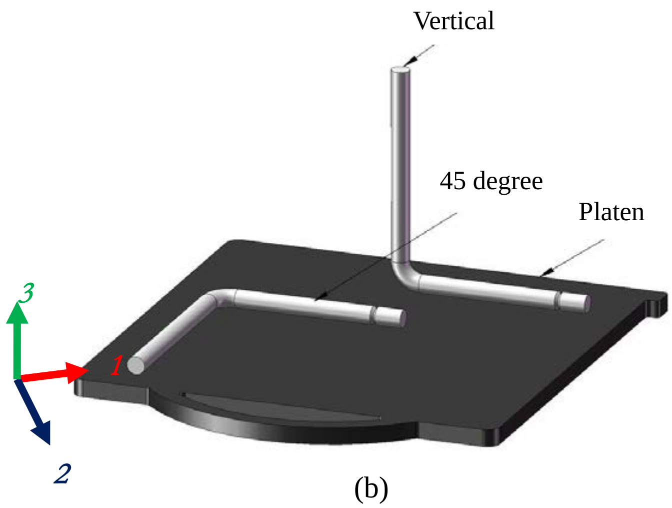
Survey #3 was carried out after AM Lab #2 for both assessing students' understanding of AM Lab #2 and their ability to properly apply the knowledge to predict AM Lab #3 (combined bending and torsion) results.

AM Lab#3 – combined bending and torsion experiment

In AM Lab#3, each student team performed combined bending and torsion tests on two L-wrench parts built in two configurations (vertical and 45 degree). The tests were conducted on the TERCO Twist and Bend Testing machine and the schematic of the specimens are shown in Figures 5(a) and (b), respectively. FEA results for FDM ABS specimens and the bulk ABS specimen under combined bending and torsion at 100g weight at one end were also presented in the lab. Figure 6 depicts the deflection contour in *z* direction for the FDM ABS specimen with 45 degree configuration; and Table 4 lists the deflections of all the specimens predicted by FEA. It is seen that the specimen with bulk ABS property had least deflection. Again, students were asked to conduct experiments and report the displacement data. An example of experimental result is shown in the last row of Table 4.



(a)



(b)

Figure 5 (a) Equipment and (b) schematic of the specimens for combined bending and torsion experiment.

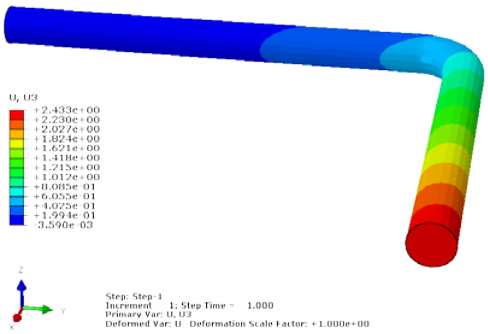


Figure 6 Deflection contour for the specimen with 45 degree configuration

Table 4 Deflections (in mm) of FDM ABS specimens and the bulk ABS specimen tested under combined bending and torsion tests at 100g weight at one end

Specimen configuration	45 degree	Vertical	Bulk ABS
Deflection (from FEA)	2.33	2.22	1.75
Deflection (from experiment)	2.29	2.40	-

Student feedback of the learning experience was summarized from their response to both objective and subjective questions. The answers to objective questions were graded to assess their understanding of basic principles. The students' self-assessment was obtained from the answers to subjective questions. It should be noted that, besides the student performance (good/fair/poor), the timing of knowledge gain (before or after the AM Labs) is also an important indicator of the effectiveness of the laboratory exercise.

Evaluation of student learning and discussion

Student learning was assessed based on the surveys. A total of 61 students participated in the study. The objective assessment evaluated students' performance before and after the AM Labs. The subjective assessment was used to find students' interest and attitude toward this project. The objective questions in the surveys were designed to test whether they understand two principles. Principle 1 is "the difference of material behavior between anisotropic and isotropic material under mechanical tests," and Principle 2 is "the difference of material behavior among specimens with different build configurations under mechanical tests." Students' scores in pre and post lab surveys were calculated. The levels of their acquisition of knowledge were classified into "Excellent", "Fair", and "Poor." Students who answered all the questions correctly were classified as "Excellent"; those whose correct answers reached 60% were marked as "Fair"; and the rest are considered as "Poor." The percentage of student in each group was calculated.

Table 5 shows the student performance in Survey #1 (post AM Lab#1). Note that since it is the first AM lab, students were only required to know "the material behavior of anisotropic material is different from that of isotropic material," not necessarily "how they are different from each other." It is observed that the majority of students noticed that the mechanical behavior of FDM ABS is different from that of bulk ABS, however, the level of most students' acquisition of knowledge in FDM ABS remains "Fair" after conducting tensile test in AM Lab#1.

Table 5 Student performance in Survey #1 (post AM Lab#1)

	Principle 1: difference between isotropic and anisotropic materials in tensile test	Principle 2: difference among specimens in three build configurations		
After AM Lab #1	91.53%	Excellent	Fair	Poor
		9%	53%	38%

Table 6 demonstrates the student performance in Survey #2 (pre and post AM Lab#2). It is observed that students' understanding for both principles were improved after AM Lab#2. The improvement of their understanding in the principles can be attributed to the three-point bending experiments they carried out during the lab. As there was no lecture to cover the theories (material anisotropy) and the majority of students achieved "Excellent/Fair" rating, it indicates that the laboratory activities helped them to acquire the knowledge of AM material properties.

Table 6 Student performance in Survey #2 (pre and post AM Lab#2)

	Principle 1: difference between isotropic and anisotropic materials in 3-point bending			Principle 2: difference among specimens in three build configurations		
	Excellent	Fair	Poor	Excellent	Fair	Poor
Before AM Lab#2	27%	42%	31%	7%	32%	61%
After AM Lab#2	32%	54%	14%	18%	56%	26%

Similarly, student performance in Survey #3 (pre and post AM Lab#3) is shown in Table 7. Again, laboratory enhanced students' understanding in both principles. While the percentage of the students achieved "Excellent/Fair" rating was not as high as in Survey #2, it should be noted that, compared to 3-point bending, combined bending and torsion is a more difficult concept for student to grasp.

Table 7 Student performance in Survey #3 (pre and post AM Lab#2)

	Principle 1: difference between isotropic and anisotropic materials in bending and torsion			Principle 2: difference among specimens in three build configurations		
	Excellent	Fair	Poor	Excellent	Fair	Poor
Before AMLab#3	22%	57%	21%	25%	43%	32%
After AMLab#3	26%	54%	20%	42%	29%	29%

Based on the responses to the subjective questions in the surveys, efforts were made to summarize students' self-evaluation on knowledge gain and their attitude towards the experiential learning exercise. The questions include:

Q1. I am very clear about the major difference between isotropic material and anisotropic material in their mechanical behaviors.
Q2. I am very clear about the major difference of mechanical behaviors among specimens with configurations of vertical, horizontal, and 45^o specimen.
Q3. This project helps me to better understand how an anisotropic part is being fabricated by Fused Deposition Modeling (or other rapid prototyping machine).
Q4. I think this lab helps me to better understand Additive Manufacturing (such as FDM, 3-D printing, and Selective Laser Sintering).
Q5. I will be able to apply my knowledge of Additive Manufacturing learnt from this project to other projects or tests in future.
Q6. I am more interested in Additive Manufacturing technology now than before I took the lab.

The first two questions were used to investigate the perceived knowledge gain in material anisotropy. Q3 and Q4 were used to evaluate students' knowledge in FDM process and AM technologies. The last two questions were related to future applications of and interests in the AM technologies. The answers of "Strongly Agree" and "Agree" were considered as "Positive Feedback." The results of student survey are shown in Table 8.

Table 8 Summary of students' feedback and attitude toward the project

	Positive Feedback
Q1	70%
Q2	95%
Q3	44%
Q4	22%
Q5	58%
Q6	55%

It can be observed from the first two questions that most students deemed their understanding of the theories and principles very good. It is interesting to note that comparing the results from Tables 5 to 7 to that of Table 8, students' self-assessment of their knowledge gain went beyond their actual performance, as the percentages of students who were "Excellent" in Tables 5 to 7 are lower than that of "Positive" in Table 8. The reason could be that the students under-estimated the complexity of the topic.

The lack of positive response in Q3 and Q4 indicates that given a short instruction and conducting experiments on AM parts were not adequate for students to learn *AM processes*. It appears that there is a need to offer a hands-on AM laboratory exercise in a manufacturing processes course to enhance student learning.

The results from Q5 and Q6 show that while the majority of the students felt positive towards the experience, the lab exercises did not generate enthusiastic response. This could be improved by allowing students to design and build AM parts (instead of providing the parts) and organizing competitions to test the performance of the parts or systems.

Conclusions

This paper presents an effort of developing and implementing laboratory materials for students to carry out experiments with AM specimens. The main objective was to introduce students to material anisotropy of AM parts. Pre and post lab surveys were conducted to investigate students' performance, as well as their interest and attitude toward the project. It is shown that students' understanding of mechanical behaviors of the AM specimens was enhanced through laboratory exercises. From the indirect/subjective assessment, it can be found that the students' perceived knowledge gain was higher than their actual achievement most likely due to they under-estimated the complexity of the topic at hand. To increase students' interest, a design-build-test type of hands-on exercise is suggested. Competition can be organized for students to design more complicated part geometry and select build configuration to achieve best part performance. With various AM machines widely available, the work presented in this paper can be adoptive by others teaching AM technologies and/or Strength of Materials.

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