Using Additive Manufacturing and Finite Element Analysis in a Design-Analyze-Build-Test Project

Dr. William E Howard, East Carolina University

William E (Ed) Howard is an Associate Professor in the Department of Engineering at East Carolina University. He was previously a faculty member at Milwaukee School of Engineering, following a 14-year career as a design and project engineer with Thiokol Corporation, Spaulding Composites Company, and Sta-Rite Industries.

Dr. Rick Williams, Auburn University

Rick Williams is currently a Visiting Associate Professor at Auburn University. His research interests include engineering education and additive manufacturing.

Ms. Sarah Christine Gurganus, NAVAIR Fleet Readiness Center East

Ms. Christine Gurganus is a mechanical engineer at Fleet Readiness Center East in Cherry Point, North Carolina. She received her B.S. in engineering from East Carolina University. While studying at East Carolina University, she interned as a teaching assistant for the Summer Ventures in Science and Mathematics program and performed research to characterize the mechanical properties of 3-D printed materials.

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Abstract

Additive manufacturing (AM), also called rapid prototyping or 3-D printing, has become increasingly available to engineering programs over the last two decades. This paper discusses a design-analyze-build-test project that uses AM to supplement instruction in finite element analysis. Variations of the project have been used with both high school and upper-division undergraduate students.

The project involves the redesign of a bracket. The students follow step-by-step instructions to model a baseline design with SolidWorks software. They then use the SolidWorks Simulation Professional Finite Element Analysis (FEA) program to apply boundary conditions and loads, mesh and run the static (linear) analysis, and view the stress and deflection results. A baseline bracket fabricated by additive manufacturing is then tested for deflection under a specific load and then loaded to failure. Based on the analysis and test results, students are tasked to redesign the bracket, with the goal of producing the lightest design that meets deflection and strength requirements subjected to several geometric constraints.

With high school students, the students are advised to remove material where the stresses are low and to add material where the stresses are high. After allowing the students to work individually on the bracket redesign, groups of two or three students are formed and allowed time to discuss their ideas and produce a design to be built and tested. The testing of the brackets provides a fun competition to conclude the project, and afterwards the results are discussed, with focus on both the usefulness and the limitations of the analysis. Student survey results show that the exercise enhances the students' understanding of the engineering design process, particularly the role of analysis as a design tool.

The bracket project has also been adapted for use in a one-credit elective course for upper-division undergraduate students. The project serves as an introduction to nonlinear analysis, as the ultimate failure load is much higher than the load for which yield is first predicted with linear analysis. Results from mechanical property tests of the AM material (ABS plastic) are used to define the non-linear properties. Another important lesson of the project is that idealized boundary conditions do not always adequately simulate actual displacements.

This project is an example of how additive manufacturing can be used to supplement instruction in finite element analysis. While verification of FEA results by comparison with closed-form solutions is valuable, physical testing of the articles being analyzed highlights effects such as nonlinear (both material and geometric) behavior and inconsistent boundary conditions that are not apparent in the closed-form solutions. Although the bracket appears to be a simple

component, accurately simulating its nonlinear behavior under loading is a challenging problem even for upper-division undergraduate engineering students.

Background

Additive Manufacturing (AM) is a computer-automated process in which objects are built up, generally layer-by-layer, by the addition of material. Since its invention in the mid 1980's, AM (also called rapid prototyping) has advanced in both materials and processes. Early AM used mostly polymer-based materials and was employed mostly for design conceptualization and form and fit checking. More recently, advances in processes and materials have led to a great expansion in the usage of AM to include the direct fabrication of functional products across the aerospace, automotive, medical/dental, and consumer products industries.[1] The ASTM International Committee F42 on Additive Manufacturing Technologies currently classifies AM processes into seven categories based on the techniques used to deposit the layers and the methods in which the layer are bonded. These seven types of AM processes are Vat Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Direct Energy Deposition.[2]

Since its inception, AM has been used as a tool to facilitate engineering education and as a focused topic within design education. More recently, AM has become the central topic of individual courses within both engineering and engineering technology programs.

As a facilitation tool, AM can be thought of as another piece of laboratory equipment that allows students to explore engineering topics without the constraints that may be imposed by the use of other manufacturing processes. In these cases the AM capability is simply a tool that can save students time and effort and allow more focus on other course content; however, in the process of making the part, the students may learn little or nothing about the AM process. Often all the students may know or care about is that they can send a CAD file of a desired part to the AM machine and within a day or so, they are holding the part in their hands. Examples of utilizing AM as a facilitation tool include the fabrication of wind tunnel test models,[3,4] parts for robot projects,[5,6] objects made to induce excitement and interest in the engineering profession,[7,8] visualization tools for classroom use,[9,10] or functional parts for senior design projects.[11,12]

Often AM is a key component within engineering design education. Additive Manufacturing allows students to experience several iterations of the design-build-test process,[13] encourages the students to be more creative by providing the students a larger design space through the removal of some manufacturing constraints,[1] and provides the students 3D models that provide unique advantages over 2D models such as ergonomic testing.[4] In most of these cases the students' exposure level to AM is high and they learn of the many advantages and limitations of AM processes.

The 2014 Wohlers Report[14] lists over 80 academic institutions world-wide with AM capabilities. A review of the institutions on the list indicates that perhaps less than 20% offer a for-credit academic course in AM. Some AM specific courses that have been offered at both the undergraduate and graduate level include the Solid Freeform Fabrication (ME397) course at the University of Texas at Austin, the Introduction to Rapid Prototyping (ME4644/5644) course at Virginia Tech, and the Rapid Prototyping in Engineering (ME 7227) course at the Georgia Institute of Technology. More often than for-credit courses, institutions offer workforce training or certifications such as the Society of Manufacturing Engineers' Additive Manufacturing Certificate Program offered in cooperation with the Milwaukee School of Engineering and America Makes.[15] The lack of for-credit AM courses is not surprising given the challenge of four-year colleges to implement manufacturing into existing curriculum while meeting ABET requirements.[1]

Most AM systems in use at academic institutions utilize material extrusion, which is also called Fused Deposition Modeling (FDM). The term "3-D Printing" also commonly refers to the material extrusion process. Machines utilizing material extrusion can be very inexpensive, with consumer models available for as little as a few hundred dollars. Industrial-grade FDM machines are much more expensive ($20,000+), but offer better reliability and ease of use. The equipment used in this project was a Dimension 1200es machine from Stratasys Ltd. This printer uses a proprietary ABS material called ABSplus, and its use of a soluble support material allows for complex part geometries to be produced.

In the project described in this paper, we utilize AM as a facilitation tool in teaching mechanical design (as opposed to the engineering design process in general) and structural analysis. In our project a small bracket, which is illustrated in Figure 1, is designed and tested by the students. The bracket is mounted to a fixed wall with four screws (tightened finger-tight with wing nuts) and supports a vertical load through the screw eye shown in Figure 1. During the design process, the high school and undergraduate students use FEA to optimize the bracket subject to engineering constraints. The bracket is then fabricated and tested against the design requirements. This project capitalizes on the expanded design space and the inherent ability to quickly build design iterations afforded by the AM process and the material properties of the AM process. We are exploiting the expanded design space and ability to iterate designs in methods similar to many of the projects cited above. Where this project may be somewhat unique is while many other AM projects are constrained by the AM material properties, our project directly utilizes the nonlinear material properties to expose the undergraduate students to additional aspects of nonlinear structural analysis.

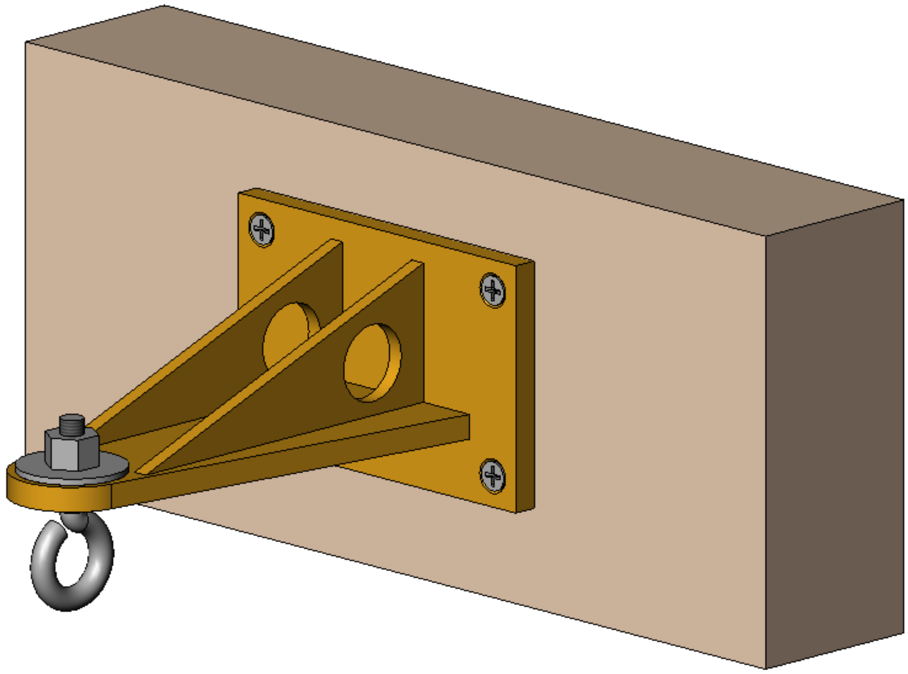

Figure 1 Solid Model of Baseline Design Mounted to Fixed Wall

High School Student Project Description

The high school students who have completed this project were participants in the Summer Ventures in Science and Mathematics program, which is sponsored by the State of North Carolina. Students must be rising juniors or seniors to be accepted into the program. Selected students spend four weeks in residence at a University of North Carolina System campus, with the only cost to the students being the transportation cost to and from the campus. At East Carolina University, students rotate among three different STEM disciplines, including engineering, physics, archeology, computer science, and others, and then focus on one discipline during the final phase. During the year for which the assessment results are reported in this paper the first three weeks were spent in the rotations (two hours in each of the three disciplines each day) and the final week was devoted to a focused project in one discipline. The bracket project was included in the first phase of the program, and so all 31 students with engineering as one of their rotation disciplines completed the project.

The engineering portion of the program began with instruction in the use of SolidWorks solid modeling software. Very few of the high school students had used a solid modeling program, so the first two-hour session of the summer provided basic instruction in creating parts. During the second session, students were given an introduction to FEA. The method was illustrated through the analysis of a simple assembly of springs. Since the springs are one-dimensional elements, they can be used to illustrate basics of FEA:

- Relating nodal forces to displacements with a stiffness matrix
- Assembly of element matrices into a system stiffness matrix by applying equilibrium and compatibility conditions
- Application of boundary conditions (known displacements)
- Application of nodal forces
- Solution of simultaneous equations to solve for the unknown displacements
- Substitution of displacements into system and element equations to find reaction forces and element forces

An assembly of four springs was used to illustrate the procedure. As shown in Figure 2, four springs of different stiffness values were arranged and a force was applied by pulling with a spring scale. The scale was attached at a position such that rotation was minimized and therefore the displacements could be idealized as one-dimensional. Students set up and solved the equations using a spreadsheet, and the predicted deflections matched measured values within a few percent. (The springs were advertised as “precision” springs, and so the stated stiffness values were accurate enough to produce good results.) Also on this second day of the project, the students witnessed a test of a baseline-design bracket.

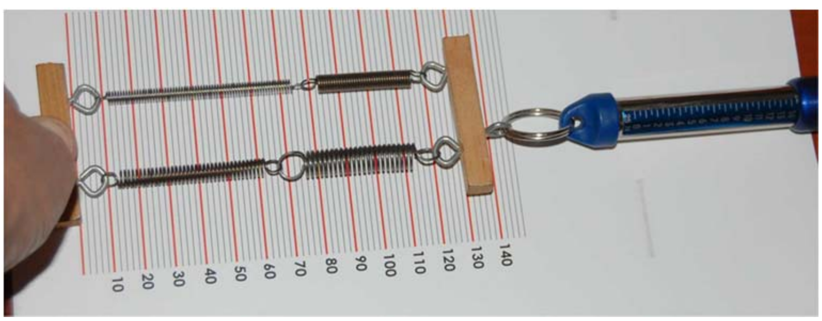

Figure 2 Spring Assembly for FEA Introduction

On the third day of the project, students followed step-by-step instructions to model and analyze the baseline-design bracket in SolidWorks. Two important concepts were introduced in this lesson: 1) the approximation of the behavior of a *continuum* by calculating the behavior of discrete or *finite* parts, and 2) the concept of stress as load per unit area. We found that high school students grasped the concept of stress fairly easily, as least to understand that failure is related to stress level. By default, SolidWorks Simulation displays von Mises equivalent stresses as the stress type. We did not discuss failure theories with the students, but we did introduce yield stress and factor of safety. The von Mises stress distribution of the bracket when subjected to a 5-pound load is shown in Figure 3. The maximum stress occurs near the top of the holes in the ribs, and the test brackets have consistently broken in this region. The maximum stress of about 700 psi corresponds to a factor of safety of 4 when compared to the yield strength of 2800 psi that was measured earlier in a tensile test. The maximum downward deflection was predicted to be about 0.024 inches.

Before proceeding to the redesign phase of the project, we compared the analysis results to the actual test results. For the deflection test, a bucket and weights weighing a total of 5 pounds was hung from the screw eye illustrated in Figure 1, and the deflection was measured with a dial indicator. The deflection of the bracket under the 5-pound load matched the measured deflection to within 0.001 inches. The strength test was conducted by placing the bracket and fixture in an Instron load frame and pushing down on the top of the screw eye at a constant rate of deflection. The load and deflection were recorded during the test. The ultimate strength was about 45 pounds, while the calculated factor of safety of 4 based on the maximum von Mises stress corresponded to a failure load of only 20 pounds. Here we discussed the concept of "failure" in the context of our model. The von Mises criterion allows us to predict yielding of the material, but localized yielding may occur at a considerably lower load than the load that causes fracture.

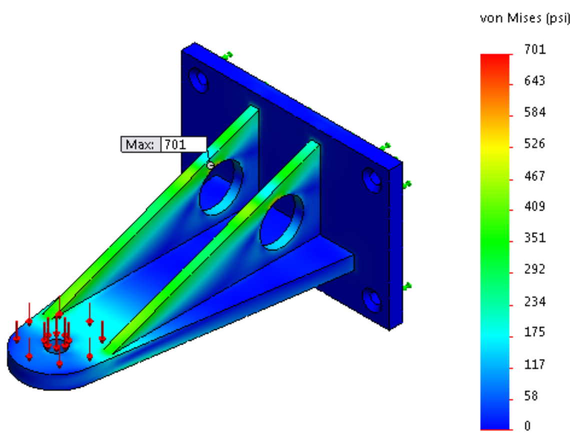

Figure 3 von Mises Stresses in Bracket – 5-Pound Load

The high school students were then given guidelines for the redesign of the bracket. The goal was to produce the lightest 3-D printed bracket that met the following requirements:

- The back plate of the bracket including the hole pattern could not be changed. Because the back plate of the baseline design was relatively thick, bending of the plate when the bracket was subjected to a 5-pound load was minimal.
- The 5/8-inch diameter holes through the ribs were required to allow an electrical conduit to pass through the bracket; therefore, students could not change the location of the holes or decrease the diameter (although they could make the ribs pass completely below the open areas, as long as the conduit could pass through at the same location.)
- The bottom of the horizontal plate was to remain ½ inch above the bottom of the back plate.
- The location and diameter of the load mounting hole could not be changed.

- The diameter of the load application surface could not be changed. In addition, this area was to stay clear of other features such as ribs. (This allowed the load to be applied either by hanging a weight or by applying a downward force in the tensile test machine. A 7/8-inch-diameter washer was used to distribute the load over the area adjacent to the load mounting hole)
- No feature could lie outside of a 2 in X 3 in envelope projected from the back plate.
- The bracket was to support at least 25 pounds before breaking.
- The maximum allowed deflection at the 5-pound design load was 0.020 inches.

Students worked individually on new designs for one day, and then we assigned them to groups of 3 or 4 at the beginning of the next day. This allowed students the opportunity to share their ideas among the group and then produce a design for the group. Forming the groups was beneficial from a logistical standpoint in that it reduced the number of brackets to be made and tested from more than 30 to 10. The brackets could be made four at a time, and each group of four took about a day to build.

Students were instructed to begin by removing material from low-stress areas and adding material to high-stress areas. As a target, we told the students that a factor of safety of 5 against yielding (based on the 5-pound load of the analysis) would ensure that the bracket would withstand the 25-pound load safely, even though the actual failure load would probably be higher if the highest-stress region was localized. For most designs, the deflection limit of 0.020 inches was the critical requirement. Students also demonstrated creativity in their designs, adding decorative hole patterns, their initials, and other features. Three designs are shown in Figure 4; note the smiley faces cut into the bracket on the left. (The bracket numbers correspond to those of the results in Table 1).

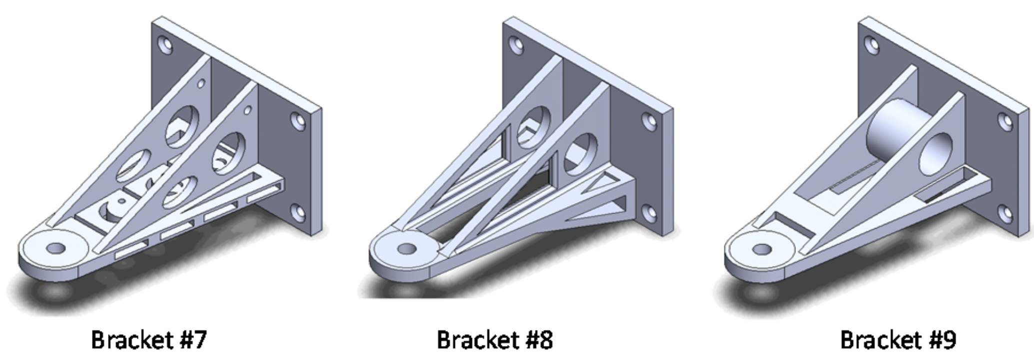

Figure 4 Bracket Designs from High School Students

The bracket analysis and test results are shown in Table 1, ordered from lightest to heaviest. The baseline design had a mass of 41 grams, so seven of the ten groups produced designs that were lighter than the baseline, although three of these did not meet the deflection requirement. Bracket #2, which is shown in Figure 5, was the overall winner as the lightest design that met both the deflection and ultimate load requirements.

Table 1 Bracket Test Summary – High School Students

Bracket #	Mass, grams	Predicted Deflection, in	Actual Deflection, in	OK?	Maximum Stress, psi	Factor of Safety	Predicted Safe Load, lb	Actual Failure Load, lb
1	32	0.022	0.028	No	494	5.7	28.3	27.1
2	38	0.019	0.019	Yes	455	6.2	30.8	47.6
3	38	0.029	0.026	No	664	4.2	21.1	35.2
4	39	0.016	0.018	Yes	354	7.9	39.5	33.7
5	39	0.023	0.027	No	656	4.3	21.3	33.2
6	39	0.020	0.020	Yes	456	6.1	30.7	46.8
7	40	0.018	0.019	Yes	552	5.1	25.4	43.8
8	41	0.019	0.016	Yes	474	5.9	29.5	53.2
9	44	0.018	0.016	Yes	462	6.1	30.3	60.1
10	54	0.023	0.020	Yes	1854	1.5	7.6	36.8

After the tests were completed, we presented to the students an analysis of the results. Among the interesting results were:

- Most of the brackets failed at loads more than 50% greater than the predicted safe load based on the von Mises yield criterion. After witnessing the tests, students seemed to understand the concept of yielding better than before. For some of the designs, yielding could be seen as discoloration of the plastic material before fracture.
- One design, Bracket #10, although not a strong design, failed at a much higher load than the safe load calculated from the yielding prediction of the analysis. That bracket had the group's name cut into the part, and there was an extremely high and localized stress concentration in one of the letters. When the model was re-analyzed with the lettering suppressed, the stresses were closer to those of other brackets.
- Two brackets, Brackets #1 and #4, had failure loads below the calculated safe loads. In Bracket #4, the students were successful in largely eliminating stress concentrations in their design. As shown in Figure 6, the highly stressed areas shown in red extend across the structural elements connected to the ribs. As a result, when these regions reached the yield stress, there was very little adjacent material to absorb more of the loading. Bracket #1 had thin stiffening members below the horizontal plate which buckled during the load test. The linear FEA model cannot predict buckling. Bracket #1 also failed the deflection test due to buckling.

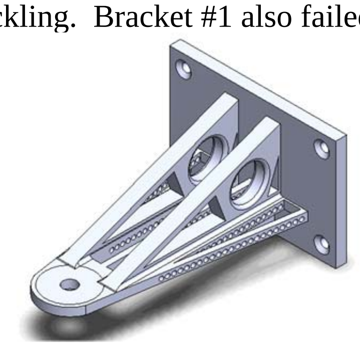

Figure 5 Lightest Bracket Meeting Requirements

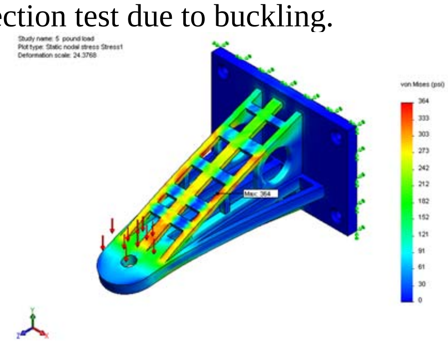

Figure 6 FEA Stresses of Bracket #4

Student surveys were conducted after the completion of the design phase, and after the testing phase. Results of the surveys are shown in Table 2. While student opinions were somewhat mixed regarding the effectiveness of the exercises with the springs, all of the high school students agreed or strongly agreed that the amount of SolidWorks instruction was sufficient for them to redesign the bracket, that seeing the test of the baseline bracket was helpful, and that they understood the value of analysis in the engineering design process. In the survey conducted after the tests, students agreed that seeing the tests of their brackets and discussing the results helped them better understand the design and analysis process.

Table 2 High School Student Survey Results

Rating Scale: 5 = Strongly Agree, 4 = Agree, 3 = Neutral, 2 = Disagree, 1 = Strongly Disagree

Survey After Design Phase, Before Testing		
	Average	% 4 or 5
I found the finite element exercises using the springs and Excel to be interesting.	3.8	67
I was able to understand the mathematics associated with the spring problems.	3.5	47
The spring problems were a good introduction to the topic, and enhanced my understanding of the application of finite element analysis to the bracket.	4.1	87
The physical test with the 4-spring assembly helped me better understand my Excel calculations.	4.2	80
The SolidWorks instruction that I received was sufficient for me to redesign the bracket.	4.7	100
Seeing the test of the baseline design bracket helped me to better understand the finite element analysis results that I obtained with the software.	4.4	100
I understand the value of analysis in the engineering design process.	4.7	100
Survey After Testing		
	Average	% 4 or 5
I found that the bracket tests helped me to better understand the design and analysis process.	4.6	100
I found the discussion of the test results helped my understanding.	4.3	93

Undergraduate Student Project Description

In Spring 2014, we offered a one-credit class called "Advanced Solid Modeling and Simulation" to mostly senior students in our BS Engineering program. The purpose of the class was to give students more instruction in FEA and motion analysis than they receive in their core engineering classes. While our program does not have an FEA class, all students complete two FEA exercises in a junior-level mechanics of materials class, and students in the mechanical engineering concentration use FEA further in their solid mechanics course. The motion analysis portion of the course is used to visualize concepts from dynamics, such as rolling and sliding down a ramp, pendulum motion, and impact.

The bracket exercise was included in the course as an application of nonlinear analysis. In particular, could the undergraduate students use nonlinear analysis to better predict the ultimate failure strength of the brackets? To answer this question, it was necessary to characterize the mechanical properties of the 3-D printed materials. For the high school students, a small number of tensile tests were used to determine the elastic modulus and yield strength. During the 2013-2014 academic year, a senior undergraduate student conducted a study to quantify the material's anisotropic mechanical properties.[16] Tensile tests, compression tests, and bending tests were performed per American Society of Testing and Materials (ASTM) standards. Test specimens were printed in vertical, horizontal, and 45-degree (relative to the build platform) orientations. By varying the build orientations, it was possible to determine the differences in mechanical properties based on build orientation. The following tests were performed: tensile tests for horizontal and vertical builds (ASTM D638), tensile tests for 45-degree angled build (ASTM D3518), compression tests for horizontal and vertical builds (ASTM D695), and bending tests for horizontal and vertical builds (ASTM D6272).

The ASTM D638 specification for tensile tests defines five configurations of specimens, four of which are illustrated in Figure 7 (Type III is for thicker materials; the specimens made for this study all had nominal thicknesses of 0.125 inches). The Type I and Type II specimens have a gauge length sufficient to accommodate an extensometer to record strain and therefore determine the elastic modulus and 0.2% offset yield stress while the Type IV and Type V specimens allow for only the ultimate stress to be determined. The results of the tensile tests for horizontal and vertical builds are shown in Table 3. Note that a size effect is evident: the average ultimate tensile stress increases from Type I up to Type V. The mean ultimate stress is significantly lower for the vertical build (ranges between 1600 psi to 1800 psi) than it is for the horizontal build (ranges between 3200 psi and 4300 psi). The coefficient of variation is larger for the vertical builds than it is for the horizontal builds. The yield stress for the horizontally-built Type I specimen is less than the yield stress for the horizontally-built Type II specimen. The vertically-built Type II specimen fails in a brittle fracture mode, and so no yield stress is reported. Finally, the elastic modulus does vary slightly between horizontally-built Type I and

Type II specimens. However, it is not significantly different. On the same note, the difference between the horizontally-built specimen's elastic modulus and the vertically-built specimen's elastic modulus is negligible.

Table 4 shows the results of the compression tests for the horizontal and vertical builds. Only the compressive yield stress is reported. Note that the yield strength is slightly greater for the vertical build than it is for the horizontal build (the tensile specimens had the opposite relationship). Since the compressive specimens never fractured, there was no reportable maximum compressive strength.

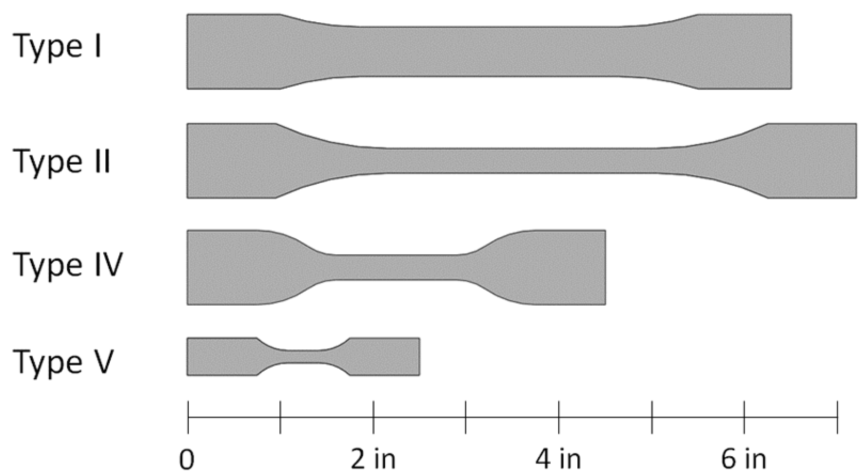

Figure 7 Relative Sizes of ASTM D638 Tensile Specimens

Table 3 Tensile Test Data for Horizontal and Vertical Builds

		Horizontal Build				Vertical Build	
		Type I	Type II	Type IV	Type V	Type II	Type V
Ultimate Stress, psi	Number of Specimens	5	5	1	5	4	5
	Mean	3290	3480	3790	4250	1660	1810
	Coefficient of Variation	3.1%	2.4%	-	4.2%	12.8%	23.4%
Yield Stress, psi	Number of Specimens	2	5	N/A	N/A	Brittle Failure	N/A
	Mean	2800	3060				
	Coefficient of Variation	-	3.7%				
Elastic Modulus, psi	Number of Specimens	2	5	N/A	N/A	4	N/A
	Mean	210,000	221,000			209,000	
	Coefficient of Variation	3.0%	4.7%			15.6%	

Table 4 Compression Test Data for Horizontal and Vertical Builds

		Horizontal Build	Vertical Build
Yield Stress, psi	Number of Specimens	4	4
	Mean	3730	4140
	Coefficient of Variation	3.2%	1.1%

These test results illustrate the challenges of predicting the response of a part made with additive manufacturing, particularly with the material extrusion process. The use of isotropic material properties seems reasonable, as the measured modulus of elasticity was approximately equal in the horizontal and vertical build orientation. However, the strength properties vary in three significant ways:

- The tensile strength between layers is much lower than the tensile strength within layers (evidenced by vertical vs. horizontal build orientation test results).
- There is a size effect in the tensile strength. Although the exact cause of this effect was not precisely determined in this study, it could be due to different density or extrusion patterns for surface layers as opposed to inner layers. In any event, there is no clear way to define an “effective size” of a given part.
- While the yield strengths in tension and compression are similar, the material does not have a clearly defined ultimate strength in compression.

Despite these limitations, a reasonable approximation of the failure of the baseline bracket was made with nonlinear FEA. The idealized stress-strain diagram shown in Figure 8 was used for the analysis. In the SolidWorks Professional Simulation FEA Program, the material properties were entered as nonlinear isotropic, with the points of the stress-strain diagram of Figure 8 defining the material response. A maximum load of 100 pounds was input, with the load applied in 5-pound increments. Therefore, both the material and geometric nonlinearities of the problem were simulated. Ultimate failure was predicted when the maximum von Mises stress exceeded 4200 psi. The baseline bracket was predicted to fail at 47 pounds. Two baseline brackets were tested, and failure loads were 52 and 53 pounds. The FEA results allowed the downward deflection at the loading hole to be found at each load step. The load vs. deflection plots of the two tests and the predicted response from FEA are shown in Figure 9.

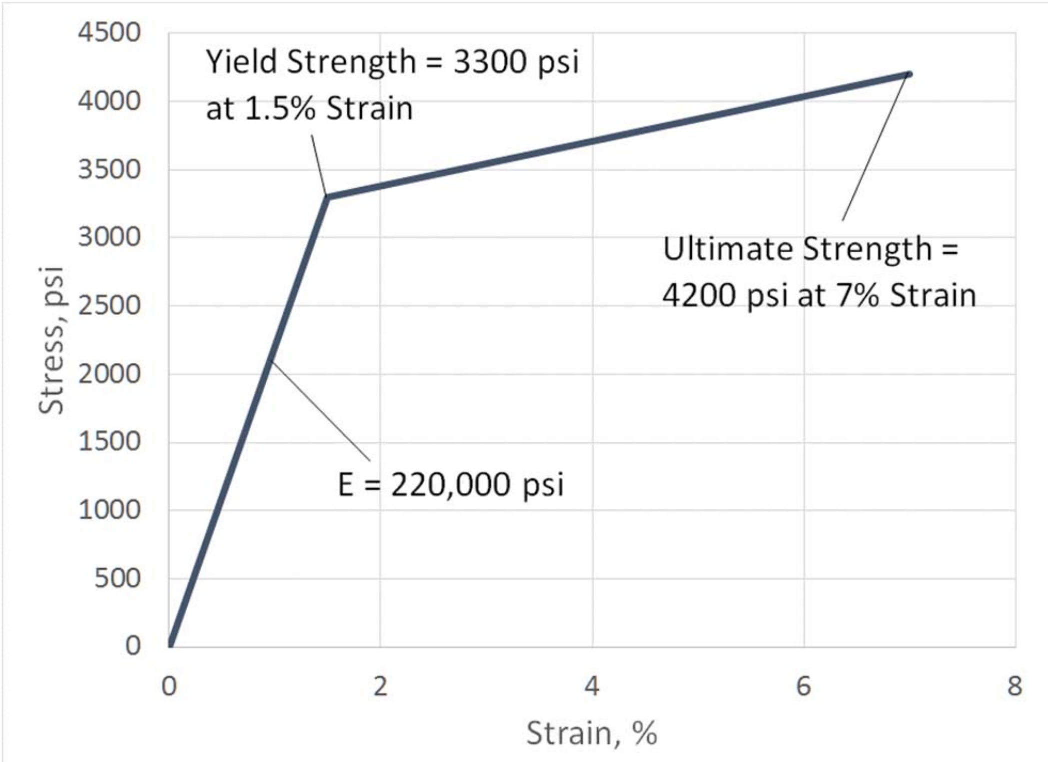

Figure 8 Idealized Stress-Strain Curve Used for Nonlinear FEA

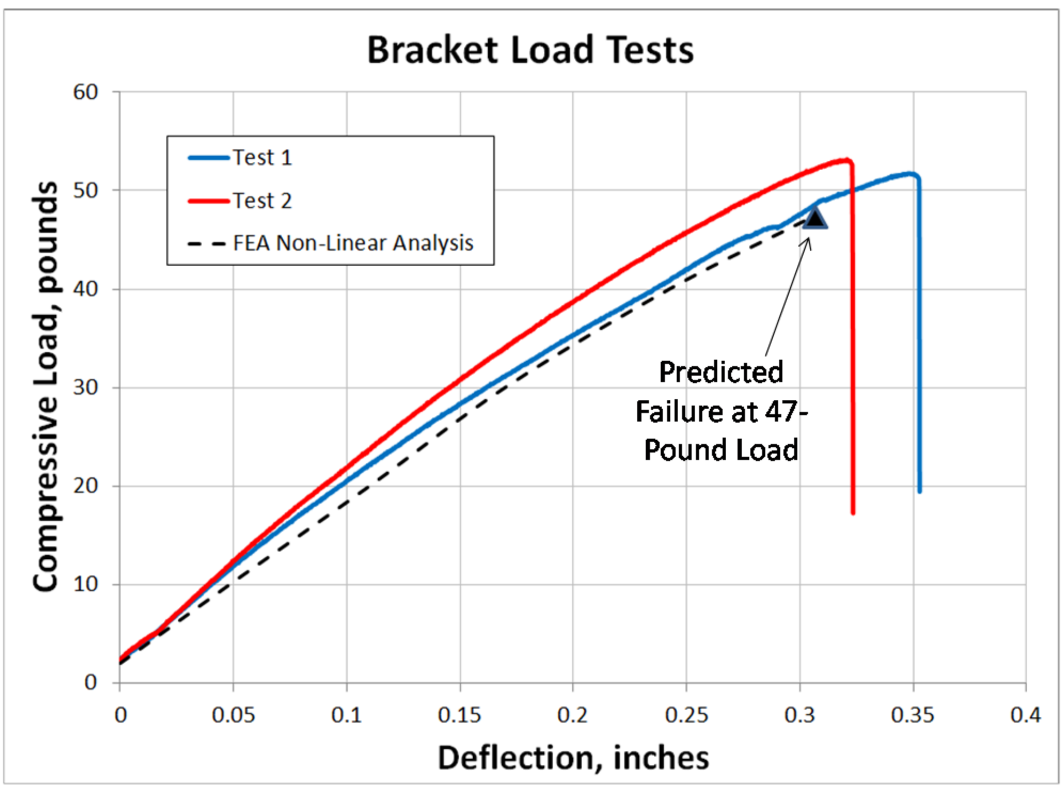

Figure 9 Bracket Load Tests Compared with Analysis Results – Baseline Design

The design requirements for the redesign of the bracket were similar to those given to the high school students, except for these differences:

- Students were allowed to modify the back plate, as long as the hole spacing was maintained.
- The deflection requirement was changed to 0.050 inches when subjected to a 10-pound load.
- The bracket's minimum failure load was 40 pounds.

When working with the high school students, adding a fixed constraint to the relatively thick back plate produced good results for the predicted deflection under a 5-pound load. However, as the load was increased, the bending of the back plate between the top two mounting screws was noticeable, as shown in Figure 10. Therefore, students in the undergraduate class were advised to consider the boundary conditions, especially if they decided to remove material from the back plate.

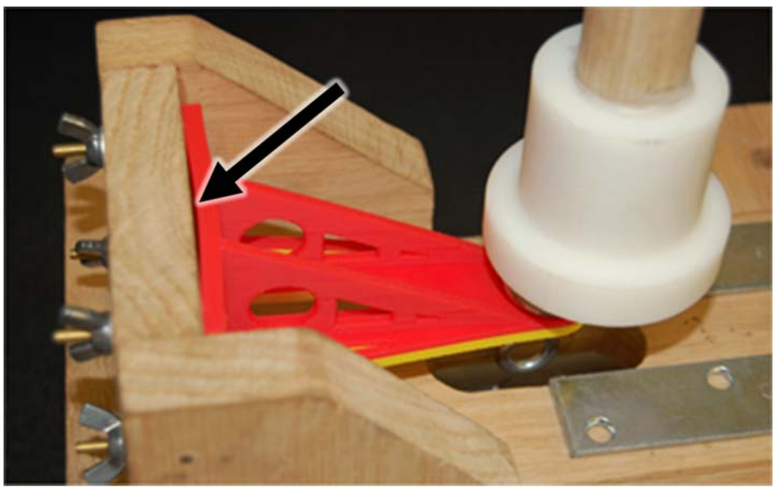

Figure 10 Bracket Test Showing Bending of Back Plate

Test results for the undergraduate students are shown in Table 5, ordered from lightest to heaviest. Four brackets failed the deflection requirement, as the students thinned or cut material away from the back plate and did not adjust the boundary conditions as discussed above. A design (Bracket #8) with material removed from the back plate is shown in Figure 11. When this design is analyzed with the assumption that the back plate is fixed, the predicted deflection is 0.025 inches, well under the maximum of 0.050 inches. When the same design is analyzed with only the conical faces of the screw holes fixed, the predicted deflection is 0.133 inches. The actual deflection was 0.102 inches, illustrating the important concept that boundary conditions are simplified representations of often complex interactions between structures. In this case, fixing the back plate does not allow it to bend, but fixing only the screw holes allows the back plate to bend toward the fixture as well as away from the fixture. In other words, the back plate is able to penetrate into the fixture. A closer approximation of 0.122 inches is obtained by modeling a portion of the fixture and the screws, as shown in Figure 11. In this analysis, non-penetrating contacts are specified between the mating faces of the bracket and the fixture and the mating faces of the bracket and the screw heads. This type of analysis takes much longer to run, as the contact conditions must be evaluated at each load step.

The lightest design that met the requirements was Bracket #1, which is shown in Figure 12. This design removes the back plate altogether, and uses a pair of truss-like structures to transfer the load from the application point to the screws. The trusses make this an extremely stiff yet light design. The failure mode of this bracket is also interesting. To keep the area of the conduit clear, the diagonal members of the trusses are oriented so that they are under compression. In the nonlinear FEA, the analysis fails at a load of 60 pounds, as the deflections from one load step to the next are excessive, indicating buckling. The deflected shape at a 60-pound load is shown in Figure 13. Note the lateral deflections of top corners of the trusses. The deflection of one of the corners as a function of load is shown in Figure 14. As the load approaches 60 pounds, the lateral deflection begins to grow at a rapidly increasing rate, indicating that the buckling load is being approached.

Table 5 Bracket Test Summary – Undergraduate Students

Bracket #	Mass, g	Actual Deflection, in	OK?	Failure Load, lb	OK?
1	22	0.017	Yes	58.2	Yes
2	26	0.102	No	24.0	No
3	28	0.056	No	28.1	No
4	34	0.040	Yes	56.1	Yes
5	40	0.039	Yes	84.8	Yes
6	40	0.037	Yes	77.8	Yes
7	40	0.041	Yes	68.2	Yes
8	40	0.102	No	27.2	No
9	40	0.035	Yes	66.7	Yes
10	46	0.075	No	71.6	Yes
11	42	0.035	Yes	74.6	Yes
12	42	0.157	No	26.0	No
13	50	0.037	Yes	82.6	Yes
14	50	0.022	Yes	86.3	Yes

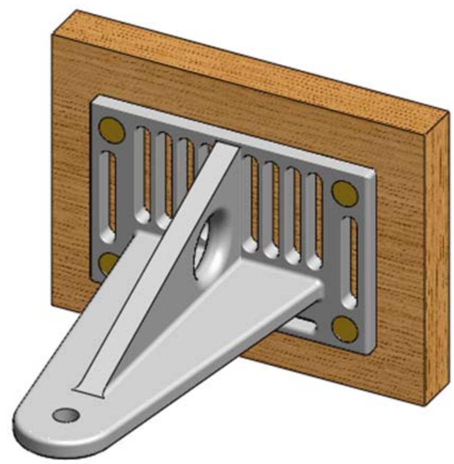

Figure 11 Bracket Design with Significant Material Removal in Back Plate,
Modeled with Screws and Portion of Fixture

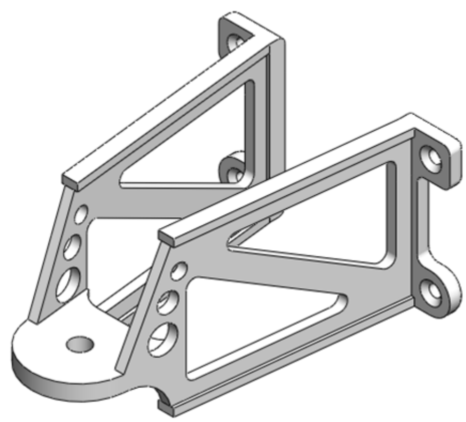

Figure 12 Lightest Bracket to Meet Requirements

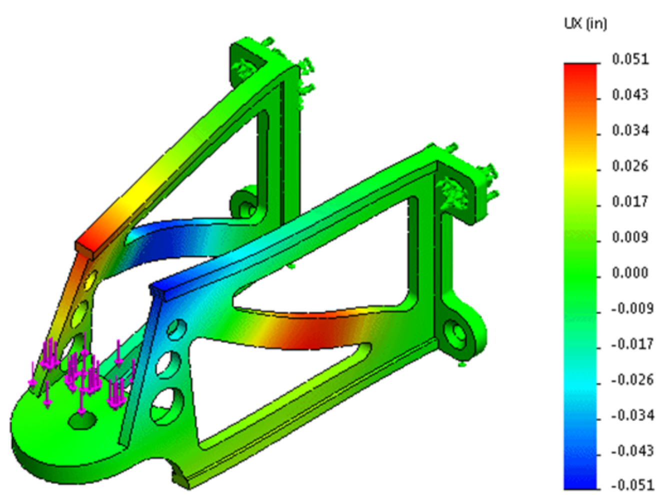

Figure 13 Deflected Shape of Bracket Showing Buckling of Diagonal Members

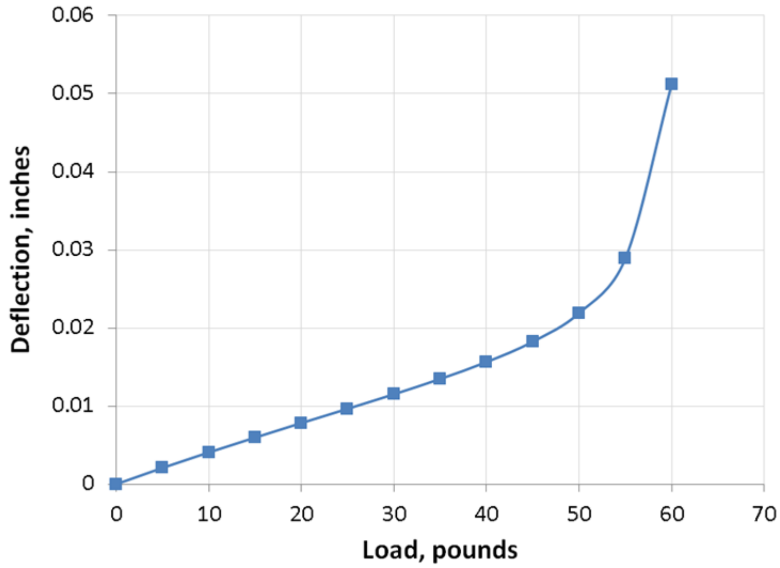

Figure 14 Lateral Deflection at Top of Side Truss

In the other exercises in the one-credit class, FEA results were compared to closed-form solutions from reference books. In the bracket analysis, the comparisons were made to physical test results. This allowed students to see that idealizations such as linear material response and over-simplified boundary conditions may produce results that are inconsistent with actual responses. Students saw that analysis and testing complement each other – testing is necessary to confirm analytical results and analysis can reduce the amount of testing required. For in-class examples, additive manufacturing allows testing to be done economically and quickly. In the end-of-class survey, students rated the bracket exercise as more valuable than all of the other FEA exercises.

Potential Future Work

The accuracy of finite element analysis of parts produced by additive manufacturing is dependent on the accuracy of the input material properties. Specifically for the FDM process, those properties are dependent upon the size parameters of the printed part. Also, FDM parts are anisotropic, as the tensile strength of the layer-to-layer interface is weaker than the in-plane tensile strength. Therefore, while predicting yield or failure based on the von Mises effective stress may work well for some geometries and loadings, in other cases the stress between layers may result in lower failure loads. A failure criterion that takes into account the different strengths in the different directions would be valuable to designers of functional parts made by FDM or other AM processes where lower strength between layers is encountered. Failure criteria used to predict failures of fiber-reinforced composite materials, such as the quadratic criterion described by Tsai[17], are used to predict brittle failure and may be a good starting point for development of a criterion for ductile FDM materials.

From an engineering education standpoint, this project can serve as a starting point for undergraduate students to learn to design more efficient parts with AM. Designers have always had to work within the constraints of the manufacturing processes available to them. Additive manufacturing removes many of the constraints of traditional manufacturing processes, particularly those of complex geometries. However, there are other constraints, such as available materials, size limitations, and interlaminar strength, which must be considered when designing for AM. When students began the project by modeling and analyzing a baseline design that looks like a bracket produced by a molding process, their modified brackets typically looked similar to the baseline. This was expected with the high school students, for whom solid modeling and FEA were new concepts. With the undergraduate students, it was somewhat surprising that only one student's design was radically different from the baseline. This may be an indication of the difficulty of teaching students to apply creativity in the design process when they are focused on the structural performance of the component. It is also possible that allowing students to work in groups can both stimulate more ideas and promote more of the competitive spirit that was evident in the high school students.

Conclusions

Additive manufacturing and finite element are important tools in engineering education. This project enhances the effectiveness of both tools by combining their use. With high school students, additive manufacturing has been shown to increase interest in STEM fields. Introducing FEA as a way to virtually test designs before making them shows students more of the engineering aspect of STEM, and also demonstrates the importance of engineering judgment in evaluating analysis results. With undergraduate students, using AM to augment design and analysis courses allows for verification of FEA results, but also helps to illustrate potential problem areas such as limitations of linear analysis, non-representative boundary conditions, or unexpected failure modes such as buckling. The exercise also provides an introduction to the use of nonlinear FEA as valuable tool. As additive manufacturing becomes a mainstream manufacturing method over the next decade or so, today's students will have an opportunity to design components with a much different set of constraints than those of traditional manufacturing methods. Projects such as this provide students experience in this emerging area of engineering design.

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