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Teaching Design and Strength of Materials via Additive Manufacturing Project-Based Learning

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ABSTRACT

Graduating approximately 150,000 engineering and engineering technology students per year, the engineering education system seeks to teach students to solve problems via analysis and design. Unfortunately, many curricula emphasize analysis at the expense of design, often relegating design activities to cornerstone and capstone design courses and leaving students ill-prepared for substantive capstone projects and post-baccalaureate practice. This work seeks to address this problem by introducing an appropriately-scaffolded design-analyze-build-test spine within an existing Mechanical Engineering Technology second-year Strength of Materials course. The 33-student cohort self-selected into 11 teams of 3 students per team to design, analyze, and additively manufacture 6-inch-long by 1-inch-maximum-width by 1-inch-maximum-height 3D-printed polylactic acid (PLA) beams weighing ≤ 45 grams. Beams were then three-point loaded during a culminating competition. The project intentionally rewarded multiple, competing objectives, including beam mass, maximum force at a 0.050-inch deflection, accuracy of analysis, and creativity. Over 29 calendar days, the project consumed approximately 1.5 in-class hours and was completed using only commonly-available university hardware, *e.g.*, 3D printers and a load frame. Formative and summative surveys were administered to assess student task value, self-efficacy, and opinions. Results indicated that students were primarily motivated by utility and intrinsic task value. Despite 74% of the students having minimal experience with additive manufacturing, 75% of students felt their team had appropriate skills to complete the project. In addition to 84% of students stating the project reinforced their understanding of strength of materials, 95% of students stated that the project increased their understanding of open-ended design and the interconnection between material properties, materials processing, and strength of materials. This work is important in that it demonstrates a case study on how to incorporate design concepts within an engineering analysis course and that analysis and design concepts may coexist within a course.

Key words: Rapid prototyping, sophomore, design

INTRODUCTION

Design is a fundamental engineering activity in which engineers create new processes and products to satisfy one or more than one performance requirement. Satisfying performance requirements requires three sets of skills: soft skills (*e.g.*, problem definition, communication, teamwork, project management) (Atman et al. 2007; Atman et al. 2008); deductive engineering analyses (Carroll 1997); and inductive reasoning to identify feasible domains and preferred regions within feasible domains (Olson 1997). The three sets of skills vary in utilization of discipline-specific knowledge and in the uniqueness of solutions. For example, whereas soft skills and inductive reasoning apply to all engineering disciplines, engineering analysis is discipline specific. As another example, although soft skills and inductive reasoning rarely result in unique solutions, engineering analysis seeks to accurately predict a unique solution given a set of assumptions.

Undergraduate engineering education often focuses on analytical solutions to well-posed problems, meaning design is a relatively minor component of most engineering programs (Duderstadt 2010). Typically, design is associated with three undergraduate courses: a one-semester first-year “cornerstone design” course and a two-course “capstone design” sequence taught in the fourth year (Dym et al. 2005). Introduced in the 1990s, cornerstone design courses provide a means to connect engineering students with engineering faculty (Dym et al. 2005). As cornerstone design students lack requisite engineering analysis skills, cornerstone design projects are conceptual and exercise neither analytical nor inductive reasoning. In contrast, capstone design contains real design projects consisting of research, concept generation, analysis, inductive reasoning, down selection, fabrication, and testing (Howe et al. 2017), often framed in a *design thinking* paradigm.

As described by Dym et al. (2005), design thinking is an analytical and creative process involving divergent-convergent questioning, systems design concepts (*e.g.*, system dynamics, uncertainty, estimates, experimentation), and making design decisions often in team environments while using dedicated design language. Importantly, design thinking is a learnable process that can be taught via case studies (Richards 2017), reverse engineering (Dym et al. 2005), and project-based learning (Akili 2014). The maturity of design thinking has been qualitatively assessed by comparing behaviors of experts and novices, indicating that expert design thinkers clarify performance requirements, challenge assumptions, prioritize requirements, and flexibly utilize problem-solving strategies more so than novice design thinkers (Razzouk and Shute 2012).

Researchers and professional organizations have concluded for decades that design pedagogy and courses preparing students for capstone design need improvement. The National Research Council (1991) states that “[o]ften too much is expected of these senior design courses when prior courses have failed to provide sound preparation for them. When, for example, a senior design course is a student’s only exposure to integrated design activities such as concurrent design … the experience is likely to be shallow.” More recently, Dym et al. (2005) stated, “the most important recommendation is that engineers in academe, both faculty members and administrators, make enhanced design pedagogy their highest priority.” The 2011 American Society of Mechanical Engineers (ASME) Vision 2030 Phase I Report (ASME 2011) states that 82% of all respondents think that mechanical engineering programs should require all students to have more design/build or other practical engineering experience prior to graduation. Further, the ASME Vision 2030 Phase I report recommends the incorporation of progressively difficult design-build-test spines in the first, second, and third years prior to culmination with the capstone design course (ASME 2011). Despite these calls to action, engineering education has yet to largely integrate design concepts and progressively more difficult projects prior to capstone design.

This research seeks to address this problem by introducing a design-analyze-build-test spine within an existing Mechanical Engineering Technology second-year Strength of Materials course. Additionally, the proposed framework addresses common credit-hour restrictions by incorporating the design project within course- and faculty-contact-hour restrictions. Lastly, the design project allows students to complete all phases of the design-analyze-build-test spine while simultaneously targeting all three skill sets – *i.e.*, soft skills, engineering analysis, and inductive reasoning – at appropriate levels. An additive manufacturing project was chosen due to the geometric freedom produced by and proliferation of 3D printers within academia. Although this project was conceived for mechanical engineering and mechanical engineering technology students, the principles may be extended to other engineering disciplines. The remaining sections of this paper are organized into a literature review, project description, project results, discussion, and conclusions.

ADDITIVE MANUFACTURING LITERATURE REVIEW

Additive Manufacturing (AM), also known as 3D printing, is a breakthrough manufacturing process in which material is amalgamated to form 3D macrostructures. AM processes are classified via raw material (*i.e.*, liquid based, solid based, powder based) and amalgamation method (*e.g.*, melting, polymerization, binding) (Wong and Hernandez 2012; ASTM 2015). Of the seven AM processes identified in ASTM 52900 (2015), material extrusion, or fused deposition modeling (FDM), processes are relatively inexpensive and easy to use while permitting short manufacturing times and geometric freedom (Wohlers et al. 2018), thus making FDM ideal for pedagogical settings.

The manufacture of FDM polymer artifacts begins with a computer-aided drafting (CAD) model, which is exported to a slicing program such as Ultimaker Cura (2019). The slicing program calculates tool paths based upon user inputs such as part orientation, shell thickness, infill pattern, infill density, extruder temperature, bed temperature, maximum extruder speed, and cooling fan usage. The tool path is then converted to g-code, an ASCII-based programming language interpreted by FDM printers. The FDM printer executes the g-code and extrudes a polymer filament – typically either poly-lactic acid (PLA) or acrylonitrile butadiene styrene (ABS) – to form a layer. Successive layer deposition forms the 3D macrostructures.

Part performance depends upon the material properties, which depend upon the micro- and meso-structure (or “structure”) resulting from the manufacturing process. These cause-and-effect bottom-up relations, defined here as process-structure-properties-performance (PSPP) relations, need to be quantified to accurately predict performance. FDM’s directional and temporal extrusion of rasters within each layer and FDM’s layer-upon-layer build sequence imbue directional material properties. For example, Letcher and Waytashek (2014) report directionally-dependent in-plane properties with 0°- and 90°-raster-angle specimens having 8.7% and 15.6% reduced tensile strengths, respectively, than 45°-raster-angle specimens. Kim and Oh (2008) report out-of-plane (*i.e.*, perpendicular to deposited layers) tensile strengths approximately 41% less than in-plane (*i.e.*, parallel to deposited layers) tensile strengths for FDM-produced polymer specimens. The influence of process on structure is also important. For example, the enclosure temperature, extruder temperature, bed temperature, and raster pattern affect the inter-raster bond area and bond strength (Sun et al. 2008; Compton et al. 2017).

The literature shows multiple examples of AM utilization enhancing engineering education. Within first- and second-year courses, researchers found that AM primarily increases student motivation (Barr et al. 2000) and improves spatial visualization (Zecher 1998). AM in third- and fourth-year courses and graduate school allowed students to conduct faster learning cycles and reduce manufacturing times for geometrically complex components (Maletsky and Hale 2003; Bøhn 1997).

Design for additive manufacturing remains a difficult task (Gao et al. 2015; Huang and Leu 2014). The challenges arise due to AM’s ability to produce geometrically complex parts, coupled PSPP relationships, and reliance upon interdisciplinary knowledge in material science, mechanics, and application-specific requirements (*e.g.*, biomechanics, aerospace, injection molding) (Huang and

Leu 2014). For beams subject to 3-point-loading, topology optimization has been employed to design AM beams having variable-density cellular structures (Rezaie et al. 2013; Cheng et al. 2017) and lattice infills (Gopsill et al. 2018). Although topology optimization methods commonly utilize isotropic material properties, 3D-printing processes result in non-isotropic properties.

FDM-based projects are ideally suited for sophomore-level pedagogical open-ended design projects for four reasons. First, FDM machines are relatively easy to use and inexpensive to operate, thus allowing students to experience a complete design-analyze-build-test spine. Second, AM is poised for significant economic growth, meaning that engineering students will likely encounter AM and FDM during their professional careers and will therefore benefit from college-level exposure. Third, FDM machines can produce geometrically complex parts, thus motivating questions regarding material placement and topology optimization. Fourth, the coupled PSPP relations motivate student questions regarding materials science.

PROJECT DESCRIPTION

The project consisted of eleven teams of students designing, analyzing, manufacturing, and testing AM beams. Each team consisted of three students who self-selected their teammates. The project's in-class activities spanned 29 calendar days and required a total of approximately 1.5 hours of in-class lecture time. The first half hour was spent introducing the project on the first day of the project and answering student questions during subsequent lectures; the final hour of lecture time was spent testing as-manufactured beams at an end-of-semester competition. The project had three primary learning objectives:

1. Improve student design skills via a sophomore-level open-ended design project requiring appropriately-scaffolded engineering analysis and soft skills. Although required to complete the project, inductive reasoning skills were neither taught nor assessed;
2. Reinforce strength of materials analysis concepts (*e.g.*, 2nd moment of inertia, Young's modulus, neutral axis, yield strength, and shear and bending diagrams) via project-based learning; and
3. Expose students to AM and the engineering challenges associated with functional AM components, such as understanding process-structure-property-performance relations and material placement.

Student Cohort

The cohort consisted of 33 male students enrolled in a sophomore-level Mechanical Engineering Technology (MET) Strength of Materials course. A review of previously-completed courses indicated students possessed appropriately-scaffolded engineering analysis, soft skills, and design skills prior to project initiation.

Student analysis skills were appropriate as demonstrated by enrollment in the Strength of Materials course, completion of Statics and Calculus I prerequisite courses, and enrollment in a corequisite Calculus II course. Additionally, 32 of the 33 students, or 97% of the cohort, had already completed their first college-level CAD course, in which students recreated predefined objects in SolidWorks.

The vast majority of students had completed courses addressing soft skills and design concepts at the cornerstone design level. For example, 32 of the 33 students, or 97% of the cohort, had previously completed an engineering cornerstone design course. Of these 32 students, 18 students had already completed the MET cornerstone design course, and 14 students completed a cornerstone design course in another engineering program. Twenty-three of the 33 students, or 70% of the cohort, had obtained additional design experience by completing a second CAD course involving the open-ended design of a mechanical vise.

The review of previously-completed courses also indicated a lack of in-class exposure to additive manufacturing and inductive reasoning concepts. Given that students could have obtained additive manufacturing and inductive reasoning experience from outside-of-class activities, formative and summative surveys were administered mid-way and at the conclusion of the project, respectively, to characterize student self-assessed capabilities.

Project Description

The project consisted of designing, analyzing, manufacturing, and testing an AM beam for three-point bending as shown in Figure 1. In Figure 1, the light gray right rectangular prism represents the volumetric envelope of 6.000 inches ± 0.200 inches in length, ≤ 1.000-inch width, and ≤ 1.000-inch height. The lower

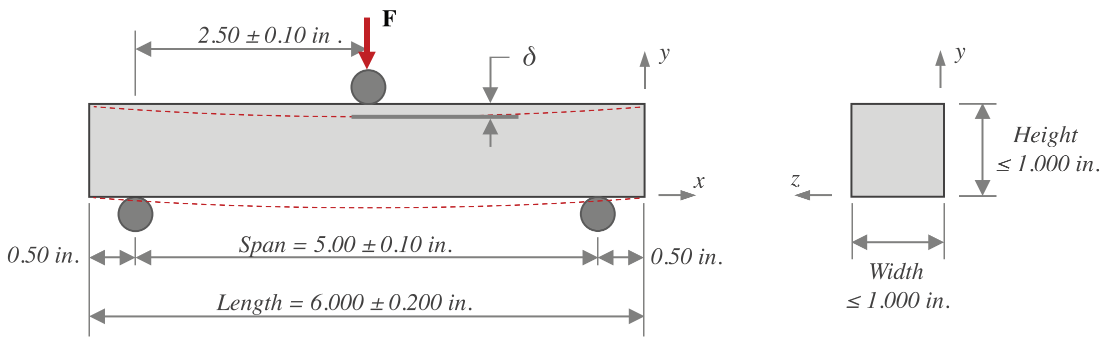


Figure 1. Three-point flexure test setup showing right rectangular prism volumetric envelope (light gray), supports, location of deflection measurement δ, and 3-point loading configuration.

supports, shown as dark gray circles below the beam, were spaced at 5.00 ± 0.10 inches. The upper contact, located 2.50 ± 0.10 inches in the positive *x* direction from the bottom left support, displaced in the negative *y*-direction at a uniform rate of 0.18 in/min, thus imposing a quasi-static, displacement-controlled load. Beams could weigh a maximum of 45 grams and had to be manufactured from PLA. Slicing method, infill density, post-printing treatments (*e.g.*, annealing) were intentionally unspecified to encourage students to explore their effects on performance. Students were unable to access the load frame and three-point loading fixture prior to the competition. Although the on-campus 3D Print Club had six 3D printers available, students could utilize any 3D printer.

Students submitted five deliverables during the 29-calendar-day-long project as shown in Table 1. The first deliverable was a list of team members for each team. For the second deliverable, each team had to submit an initial SolidWorks sldprt file showing each team's initial beam design. The pedagogical intent was to encourage student engagement and determine if and how students altered their beam geometry during the design process. The third deliverable was for each team to submit their final SolidWorks sldprt file showing final beam geometry. Final beam geometries were due 5 days before the competition, thus allowing all teams time to print their beams prior to the competition. The fourth and fifth deliverables, *i.e.*, 3D-printed beams and written reports analyzing the 3D-printed beams, respectively, were due the day of the competition. Although their due dates are indicated in the last column in Table 1, the formative and summative surveys were optional, and thus not defined as deliverables.

Written reports described the geometry of the final beam and the manufacturing and design processes via ten required sections:

1. **Dimensioned drawing of final beam** – Dimensioned drawing showing geometry and major dimensions.
2. **Manufacturing information** – The description should include at least seven pieces of information: (1) make, model, and location of 3D printer; (2) orientation of beam within printer including

Table 1. Project activities and deliverables.

Day	In-class activity	Deliverable	Survey
1	Project introduced		
6		1) Self-selected team members (3 students / team)	
20		2) INITIAL beam designs in sldprt format (1 / team)	Formative (1 / student)
24		3) FINAL beam designs in sldprt format (1 / team)	
29	Beam competition	4) 3D-printed beams (1 / team) 5) Written report (1 / team)	
36			Summative (1 / student)

a screen shot from slicing software; (3) as-manufactured print time; (4) nozzle tip diameter; (5) nozzle temperature; (6) manufacturer and part number of PLA; and (7) estimated weight of print.

3. **Describe design approach** – Articulate the team's thought process to design the beam. For example, what did the team consider most important, what did the team consider least important, and how did the design change during the project?
4. **2nd moment of inertia calculations** – For prismatic beams, calculate the 2nd moment of inertia. For non-prismatic beams, calculate upper and lower bounds for the 2nd moment of inertia.
5. **Shear and bending diagrams** – Calculate and show shear and bending diagrams assuming a 100-lb_f applied force.
6. **Stress element 1** – Estimate and show the stresses acting on an x–z oriented stress element located on the beam's bottom surface (*i.e.*, negative y face) at the mid-span.
7. **Stress element 2** – Estimate and show the stresses acting on an x–y oriented stress element located at the mid-height of the beam and immediately to the left (*i.e.*, negative x direction) of the beam's mid-span. If the beam has a void at this point in space, pick a non-void point along the beam's longitudinal direction at the mid height.
8. **Expected failure** – Estimate where and at what applied force the beam will fail. Include supporting calculations and assumptions.
9. **Suggested changes** – If you did this project again, what would you do differently? Suggested changes could include technical (*e.g.*, thicker wall sections, different geometry, infill density, different extruder temperature) and project management (*e.g.*, start earlier, review analyses) changes.
10. **Peer grading** – Describe the contributions made by each team member and assign a percent contribution per team member. Each 3-person team was allotted 300% to distribute as desired. For example, a team may award each member 100%, indicating team success should be equally distributed. Alternatively, a team may have awarded one team member 120% and the remaining two team members 90%, thus indicating that the team member awarded 120% was more responsible for the team's success.

Project points were defined and communicated to students via the rubric shown in Table 2. The rubric consists of eight categories with associated available points, assessment methods, and comments for each category. Of the 11.25 maximum available points, 6 points were based upon tasks (*e.g.*, submission of preliminary and final beam designs, report, geometric conformance), and 5.25 points were based upon competition performance (*e.g.*, minimizing beam weight, maximum force for a 0.050″ deflection, most accurate prediction, and most creative design). Students were allowed to earn a maximum of 10 points per student on the project. If a student earned more than 10 points, points were truncated to 10 points.

Table 2. Rubric for additive manufacturing beam project.

Category	Maximum Available Points	Assessment method	Comments
Preliminary sldprt beam design	0.5	Email time stamp	–0.2 points for each day or fraction thereof late E.g., An email received 24 hours and 5 minutes late results in a loss of 0.4 points
Final beam sldprt beam design	0.5	Email time stamp	–0.2 points for each day or fraction thereof late
Report	4.0	Instructor	–0.5 points for each day or fraction thereof late
Beam weight	1.25	Mass scale	Points = (0.05 point / gram) (45 grams – weight (grams)) for beam weights between 20 and 45 grams Beam weights will be rounded to nearest 0.1 gram 0 points = beam weighs > 45 grams
Geometric conformance	1.0	Calipers	1 points = height, width, and length conformance and <u>matching</u> final sldprt emailed on Dec. 1; 0.5 points = height, width, and length conformance but <u>not matching</u> final sldprt emailed on Dec. 1; 0 points = height, width, or length does not conform to guidelines
Maximum force for a 0.050” deflection	2.0	MTS force and position	2.0 points = max force 1.7 points = 2nd max force 1.5 points = 3rd max force 1.3 points = 4th max force 1.1 points = 5th max force 1.0 points = 6th max force 0.9 points = 7th max force 0.8 points = 8th max force 0.7 points = 9th max force 0.6 points = 10th max force 0.5 points = 11th max force 0 points = if beam mass > 45 grams, beam not printed, or if any dimension does not conform to guidelines
Most accurate prediction	1.0	% difference in measured and estimated force causing 0.050″ deflection	% difference = (measured – estimated) / estimated To be eligible, the analysis in the report has to be reasonable 1.0 points = most accurate 0.8 points = 2nd most accurate 0.6 points = 3rd most accurate All teams within 10% difference awarded at least 0.4 points
Most creative geometry	1.0	Instructor	1.0 points = most creative 0.6 points = 2nd most creative 0.2 points = 3rd most creative
Sum	11.25		

The rubric intentionally presents competing objectives for students to consider. For example, a team designing a prismatic beam might have an easier time earning 4 points for the report and 1 point for the most accurate prediction due to simpler 2nd moment of inertia calculations. However, a team designing a non-prismatic beam might be more likely to earn 2 points for maximum force for a 0.050-inch deflection and 1 point for the most creative geometry while having the opportunity to earn 4 points on the report. As another example, teams could choose to design a 20-gram beam, thus earning 1.25 points for beam weight yet potentially sacrifice 1.5 points for maximum force for a 0.050″ deflection. By incorporating competing objectives, the rubric encourages inductive reasoning, consideration of satisfying versus optimum criteria, and presents a design task similar to a real-world design problem.

PLA Tensile Data

To reinforce strength of materials analysis concepts and suggest appropriate PLA properties, students were supplied force-deflection data for eight PLA tensile coupons. The tensile coupon geometry conformed to ASTM D638 Type I (ASTM 2014) with a 0.155-in thickness. Coupons were drawn in SolidWorks, sliced in Cura, and printed on an Ultimaker 2+ printer. Figure 2 shows the orientation of the *x*-, *y*-, *xy*-, and *z*-oriented specimens as-printed in the Ultimaker 2+. All specimens were printed with two conformal wall layers and 100% infill, which alternated at +/– 45° by layer.

Tensile coupons widths and thicknesses were measured via calipers at three locations: near the top of the gage length ("A"), near the center of the gage length ("B"), and near the bottom of the

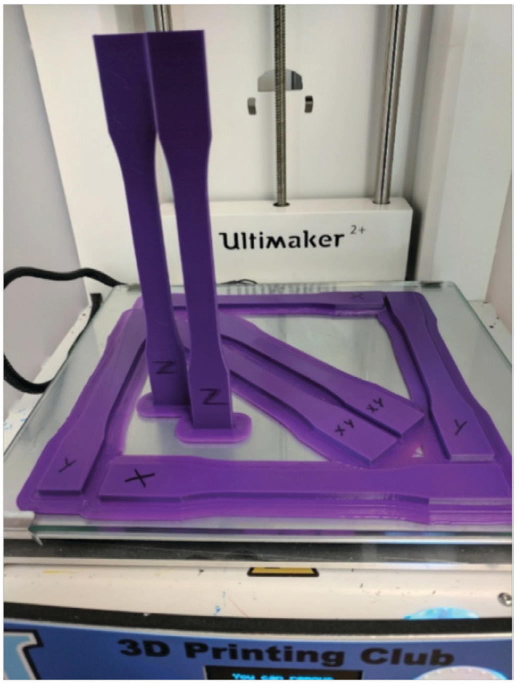


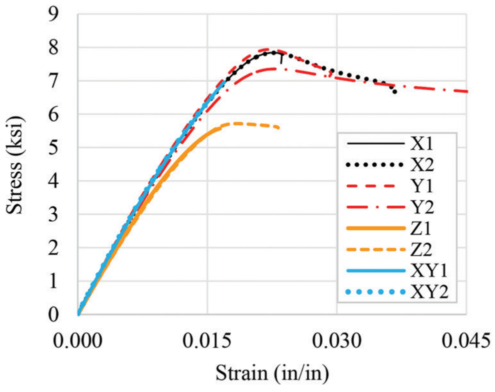
Figure 2. As-printed PLA tensile coupons.

Table 3. Geometric dimensions of PLA tensile coupons.

	Width				Thickness				
Coupon (—)	***A (in)***	***B (in)***	***C (in)***	***Avg. (in)***	***A (in)***	***B (in)***	***C (in)***	***Avg. (in)***	**Gage Length *(in)***
X1	0.514	0.514	0.515	0.514	0.153	0.154	0.155	0.154	1.968
X2	0.512	0.513	0.514	0.513	0.149	0.151	0.153	0.151	1.968
Y1	0.510	0.511	0.514	0.512	0.149	0.151	0.153	0.151	1.968
Y2	0.510	0.510	0.513	0.511	0.161	0.159	0.158	0.159	1.968
XY1	0.513	0.513	0.513	0.513	0.150	0.152	0.154	0.152	1.968
XY2	0.509	0.509	0.509	0.509	0.149	0.152	0.152	0.151	1.968
Z1	0.511	0.513	0.513	0.512	0.158	0.159	0.157	0.158	1.968
Z2	0.513	0.513	0.512	0.513	0.157	0.159	0.158	0.158	1.968

gage length (“C”). Specimens were then monotonically tensile tested by applying a 0.20 in/min extension in general accordance with ASTM D638 (ASTM 2014) on an MTS C43.504 50-kN load frame and a 1.968-in MTS 634.25F-24 extensometer. Students were supplied raw load frame data (*i.e.*, time, load cell force, cross-head displacement, extensometer gage length, and extensometer displacements), an image showing the orientation of coupons within the 3D printer similar to Figure 2, and as-measured coupon geometry shown in Table 3.

Starting from instructor-provided raw data, students calculated moduli, yield strengths, ultimate strengths, and % elongations for the eight PLA specimens. Figure 3 shows instructor-calculated stress-strain curves, moduli, yield strengths, and ultimate strengths, and % elongations. Neither Figure 3 nor values from Figure 3 were shown to students. The mean yield strength for the in-plane specimens (*i.e.*, X1, X2, Y1, Y2, XY1, and XY2) was 6.53 ksi, and the mean yield strength for the out-of-plane specimens



	Specimen	**Modulus** *(ksi)*	**Yield strength** *(ksi)*	**Ultimate strength** *(ksi)*	**% elongation** *(--)*
——	X1	479	6.54	7.85	2.4%
••••••	X2	475	6.65	7.84	3.7%
– – –	Y1	491	6.62	7.94	2.9%
–·–	Y2	462	6.25	7.35	6.5%
——	XY1	478	6.61	6.96	1.7%
•••••	XY2	483	6.49	7.16	1.8%
——	Z1	444	5.07	5.60	1.7%
----	Z2	434	5.12	5.72	2.3%

Figure 3. Stress-strain curves for PLA specimens (not shown to students).

(*i.e.*, Z1, Z2) was 5.09 ksi. The decrease in mean yield strength between in-plane and out-of-plane specimens was a consequence of print bed orientation and inter-layer bond strength (Kim and Oh 2008; Wong and Hernandez 2012).

RESULTS

Student Beam Designs

All 11 teams submitted SolidWorks drawings of their final beam designs as shown in Figure 4. Four of the 11 beams (*i.e.*, B06, B07, B09, and B10) had symmetric lower and upper flanges separated by a shear web, similar to commercially-available "I" or "W" beams. Six of the 11 beams were prismatic (*i.e.*, B03, B06, B07, B09, B10, and B11). Although B04's external geometry is prismatic, the team utilized non-prismatic infill, which caused the internal structure to vary along the beam's length.

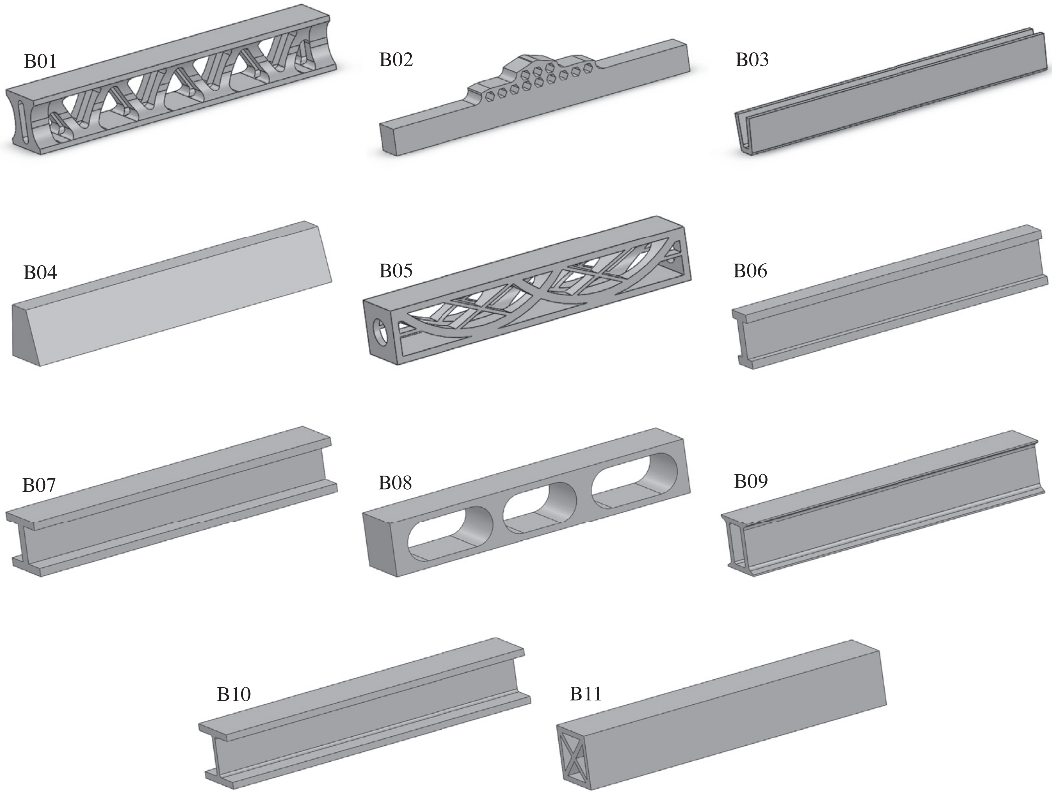


Figure 4. Renderings of final beam designs shown in as-tested orientation. Although shown, B11 was neither manufactured nor tested.

Competition

On the date of the competition, 10 teams submitted beams for inspection and testing. Inspection consisted of measuring the mass and dimensions of all 10 submitted beams via a 0.005-g resolution mass balance and 0.0005-in resolution calipers, respectively. Height, width, and length were measured thrice, with height and width measured at three different positions along the longitudinal axis. The measured mass, maximum height, maximum width, and length for each beam are shown in Table 4. Of the 10 submitted beams, all 10 beams were within the 20–45 g tolerance, and eight beams were within geometric specifications. Beams B04 and B10 had dimensions outside of the geometric specifications. Although the heights of seven beams were >0.98 inches, beams B03, B04, and B07 had heights ≤ 0.886 inches. Widths were more disperse with only four teams having widths >0.98 inches.

Table 4. Measured beam mass, height, width, and length.

Beam	Mass (g)	Height (in)	Width (in)	Length (in)
Requirement	*20–45 g*	*≤1.000 in*	*≤1.000 in*	*5.8–6.2 in*
01	44.8	1.000	0.993	5.943
02	35.1	0.994	0.504	6.001
03	20.7	0.696	0.517	6.012
04	41.7	0.886	0.905	6.350
05	38.5	0.999	0.994	5.991
06	28.3	1.000	0.508	5.994
07	43.8	0.797	0.601	6.094
08	43.5	1.000	0.994	6.007
09	38.0	0.987	0.940	6.030
10	29.4	1.003	1.027	5.980
11	n/a	n/a	n/a	n/a

Testing consisted of 3-point flexural testing as shown for B05 in Figure 5. Prior to testing each beam in a random run order, each team stated their preferred beam orientation. A constant crosshead deflection rate of 0.18 in/min in the downward direction was imposed upon the center support to provide the 3-point loading. During the competition, the force-deflection curve and a live video of the beam similar to Figure 5 were shown via overhead projector, thus allowing all 33 students to observe each beam's real-time force-deflection curve, beam deflection, and failure.

Figures 6a and 6b show the force-deflection curves for all 10 submitted beams for overall displacements and displacements ≤ 0.075 inches, respectively. From Figure 6a, the minimum observed peak force for all beams was 213 lb_f for B03, and the maximum peak force for all beams was 614 lb_f

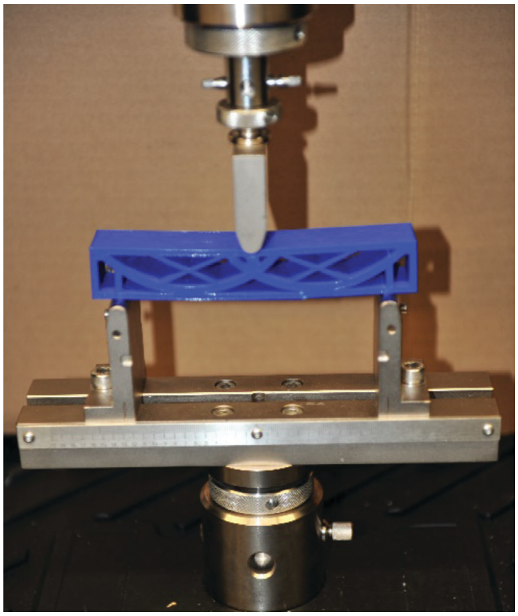
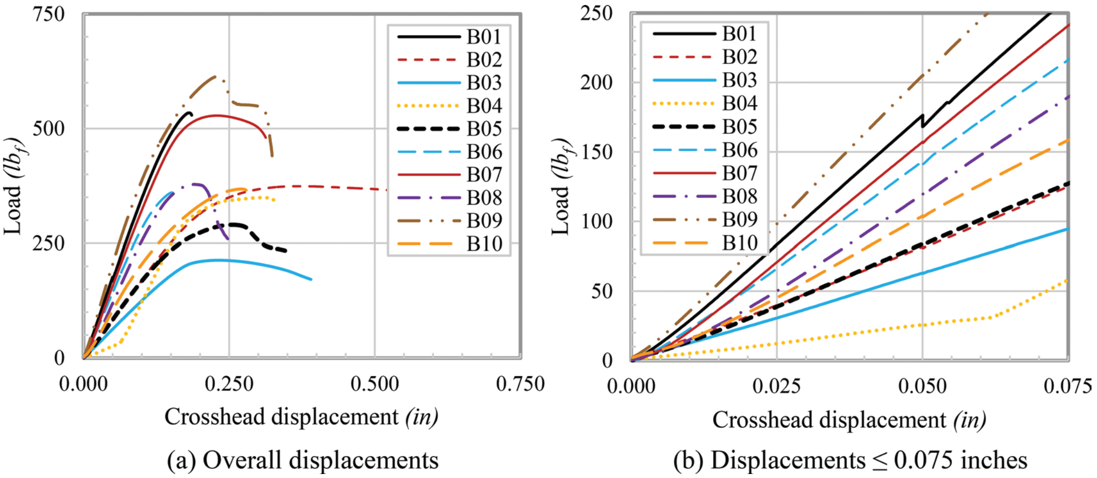


Figure 5. Three-point flexure testing of B05.

for B09. Figure 6b shows the forces at 0.050-in deflections for the 10 submitted beams which were rank-ordered to allocate points for the "Maximum force for a 0.050 deflection" rubric category described in Table 2.



(a) Overall displacements

(b) Displacements ≤ 0.075 inches

Figure 6. Force versus crosshead displacement curves for the 10 submitted beams for (a) overall displacements and (b) displacements ≤ 0.075 inches.

Formative and Summative Surveys

Formative and summative surveys were administered nine days before and seven days after the competition, respectively. The formative survey consisted of 17 multiple choice questions and three open ended questions divided into four categories as shown in Table 5. The ID # shown in

Table 5. Formative survey questions, response prompts, and student response rates.

ID #	Category	Question	Prompts and response rate				
			Strongly agree	Agree	Neutral	Disagree	Strongly disagree
2	Task Value	It is important to me to do well on the beam project	70%	30%	0%	0%	0%
3		It is important to me to do well on the beam project because I like to do well on all tasks	50%	45%	5%	0%	0%
4		It is important to me to do well on the beam project because I enjoy activities in this project	35%	45%	15%	5%	0%
5		It is important to me to do well on the beam project because I want bonus points	80%	10%	10%	0%	0%
8		In total, I anticipate devoting approximately how many hours to the beam project	0–4 hrs 0%	4–8 hrs 30%	8–12 hrs 40%	12–16 hrs 25%	>16 hrs 5%
15		The skills (e.g., open-ended design, team work, materials processing) I've learned in this project are applicable to working as a mechanical engineer	35%	65%	0%	0%	0%
1	Self-efficacy	I understand the rules of the beam project	15%	75%	5%	0%	0%
6		I am confident I have the necessary skills to do well on the beam project.	10%	55%	35%	0%	0%
7		I am confident my team has the necessary skills to do well on the beam project	20%	55%	25%	0%	0%
10		Out of a total of 10 possible points, I expect to earn the following grade on the beam	0–2 0%	2–4 0%	4–6 10%	6–8 50%	8–10 40%
11	Outcomes	Overall, my experience with the project has been positive	15%	55%	20%	5%	5%
12		Overall, my experience with my team has been positive	15%	65%	15%	0%	5%
9		So far, I have devoted how many hours to the project	0–1 hrs 20%	1–2 hrs 35%	2–3 hrs 25%	3–4 hrs 10%	>4 hrs 10%
16		This project has improved my understanding of open-ended design problems	10%	60%	30%	0%	0%
17		This project has improved my understanding of 3D printing.	25%	50%	20%	5%	0%
18		This project has improved my understanding of strength of materials	15%	70%	10%	5%	0%
19		This project has improved my understanding of how material properties, materials processing (*e.g.*, print direction, secondary operations), and strength of materials are interconnected.	20%	60%	20%	0%	0%
13	Open-ended	Is there anything you would change about the project?	Open ended response				
14		Is there anything you want to keep in the project?	Open ended response				
20		This survey was intended to capture a small snap-shot of your educational experience. Please add any additional comments below.	Open ended response				

the far-left column indicates the question sequence in the survey. Of the 33 students, 20 students submitted responses to the formative survey. Being administered nine days before the competition, the formative survey represents student opinions after submission of initial designs and before submission of final designs.

Expectancy-value theory postulates task value and self-efficacy drive student attainment of goals (Eccles et al. 1983; Wigfield and Eccles 2000). Task value, or how a student values a task, is delineated into four categories: attainment task value indicates a student's personal importance to doing well; intrinsic value indicates a student's enjoyment of the task; utility task value indicates the alignment of a task with a student's future goals; and cost task value indicates a student's understanding of negative effects of engaging in the task (Wigfield and Cambria 2010). In contrast to task value, self-efficacy indicates a student's belief that they can successfully accomplish the assigned task.

Responses to the formative survey's task-value questions indicate students were motivated by and valued the project. Utility task value was the primary motivation with 80% and 10% of the students strongly agreeing and agreeing, respectively, that the extra points offered for this project were important (*cf.* Table 5, ID# 5). Potentially indicating a long-term utility task value, 35% and 65% of the students strongly agreed and agreed, respectively, that the skills obtained in the project are applicable to working as a mechanical engineer (*cf.* Table 5, ID# 15). Attainment task value was of secondary importance with 50% and 45% of the students reporting they strongly agreed or agreed, respectively, that they like to do well on all tasks (*cf.* Table 5, ID# 3). Intrinsic task value was of third importance with 35% and 45% of students reported that they strongly agreed and agreed, respectively, with the statement that they enjoyed activities related to the project (*cf.* Table 5, ID# 4). Cost task value was not assessed in the formative survey.

Student responses to the self-efficacy questions indicated students understood the task and were confident they could accomplish the task. For example, 10% and 55% of students reported they strongly agreed or agreed, respectively, that they had the necessary skills to do well on the project (*cf.* Table 5, ID# 6). Students were slightly more confident that their team had the necessary skills to do well on the project with 20% and 55% of students strongly agreeing or agreeing, respectively (*cf.* Table 5, ID# 7). Student confidence was also indicated in that 90% of the students expected to earn 6 or more points via the project (*cf.* Table 5, ID# 10).

Administered seven days after the competition, the summative survey consisted of 14 multiple choice questions and 3 open ended questions partitioned into four categories as shown in Table 6. Similar to Table 5, the as-asked question sequence is indicated by question ID # in the far-left column. Nineteen of the 33 students submitted responses to the summative survey. Administered

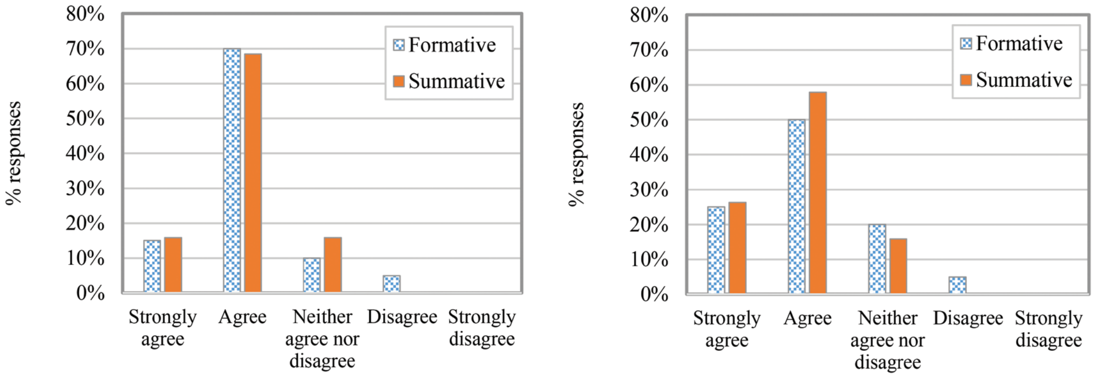
Table 6. Summative survey questions, response prompts, and student response rates.

ID #	Category	Question	Prompts and response rate				
			Strongly agree	Agree	Neutral	Disagree	Strongly disagree
9	TV[1]	The skills (*e.g.*, open-ended design, team work, materials processing) I've learned in this project are applicable to working as a mechanical engineer	37%	58%	5%	0%	0%
1	SE[2]	I understood the rules of the beam project	32%	58%	10%	0%	0%
3		Out of a total of 10 possible points, I expect to earn the following grade on the beam project	0–2 0%	2–4 5%	4–6 26%	6–8 32%	8–10 37%
4	Outcomes	Overall, my experience working with my team has been positive	42%	47%	5%	5%	0%
10		The project has improved my understanding of open-ended design problems	32%	63%	5%	0%	0%
11		The project has improved my understanding of 3D printing	26%	58%	16%	0%	0%
12		The project has improved my understanding of strength of materials	16%	68%	16%	0%	0%
13		The project has improved my understanding of how material properties, materials processing (*e.g.*, print direction, secondary operations), and strength of materials are interconnected.	32%	63%	5%	0%	0%
7		Prior to this project, my experience with 3D printing was most approximately[3]	N-E 0%	Novice 74%	Develop 16%	Inter 11%	Advanced 0%
8		After completing the project, my experience with 3D printing is most approximately[3]	N-E 0%	Novice 11%	Develop 74%	Inter 5%	Advanced 11%
2		In total, I devoted approximately how many hours to the beam project	0–4 hrs 0%	4–8 hrs 53%	8–12 hrs 21%	12–16 hrs 16%	>16 hrs 11%
5	Open-ended	Is there anything you would change about the project?	Open ended response				
6		Is there anything you want to keep in the project?	Open ended response				
14		This survey was intended to capture a small snapshot of your educational experience. Please add any additional comments below.	Open ended response				

[1] TV: Task value
[2] SE: Self-efficacy
[3] N-E: Non-existent (*i.e.*, no knowledge)
Novice Aware of 3D printing, but never printed any objects
Develop: Developing, printed < 5 objects
Inter: Intermediate, routinely print objects
Advanced: Expert, routinely slice and print objects

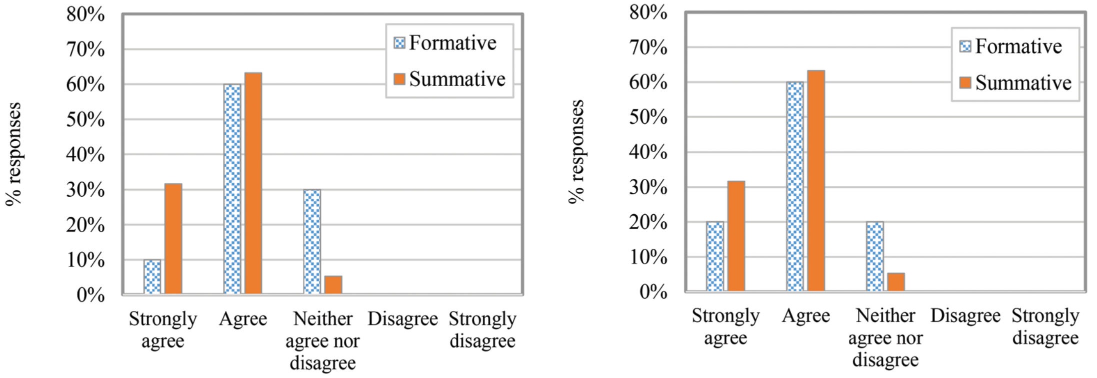
after the competition, the summative survey represents student opinions after reflecting upon the entire project.

The formative and summative surveys each contained four questions related to understanding of strength of materials; 3D printing; open-ended design; and how material properties, materials processing (*e.g.*, print direction, secondary operations), and strength of materials interconnect. Results from these four questions on both surveys are shown in Figure 7. For strength of materials



(a) Strength of materials

(b) 3D printing



(c) Open-ended design

(d) Interconnection between material properties, materials processing, and strength of materials

Figure 7. Student responses regarding if the project helped students understand: (a) strength of materials, (b) 3D printing, (c) open-ended design, and (d) interconnection between material properties, materials processing, and strength of materials.

(*cf*. Figure 7a) and 3D printing (*cf*. Figure 7b), students indicated that the project improved their understanding prior to the formative survey with minimal additional gains between the formative and summative surveys. In contrast, open-ended design (*cf*. Figure 7c) and the interconnection between material properties, materials processing, and strength of materials (*cf*. Figure 7d) showed gains between the formative and summative surveys. These continued improvements are reasonable given that these topics are higher-level concepts, potentially benefitting from additional exposure.

Responses to open-ended questions on both surveys were generally positive and contained four commonalities. First, students requested additional time to complete the project. This request for additional time varied from one to ten weeks and was supported by comments stating that students felt rushed, especially given that prior to the project 74% of the students had minimal 3D printing experience. Although 50% of responses requested more time, only 10% of the responses stated a use for the extra time, *i.e.*, experimentation and iteration. Second, students asked for one or two class lectures to formally introduce 3D printing and 3D printing concepts such as slicing, infill, internal supports, and raster patterns. Third, students thought the project reinforced strength of materials concepts such as 2nd moment of inertia and failure theories. Fourth, several students asked for the ability to test beams prior to the competition date.

It is informative to view student responses to open-ended questions in light of design thinking. For example, the first and fourth commonalities were implicitly and explicitly, respectively, aligned with conducting experiments, an aspect of systems dynamics within design thinking (*cf.* Dym et al. 2005). Notably, student responses to the open-ended questions lacked responses addressing other design thinking aspects, such as divergent-convergent questioning and uncertainty analysis, estimation, and decision making. As discussed in the next section, additional insights into student design thinking maturity may be observed via a thematic analysis of the design processes self-reported by students.

Thematic Analysis of Student Design Processes

Each team submitted a written project report containing final beam geometry, analytical calculations, and narratives describing the team's design process and suggested changes, *i.e.*, the team's reflections upon the team's design process. After completion of the competition, teams were ranked according to overall awarded points, resulting in two distinct tiers. The narratives from teams within Tier 1 and Tier 2 were analyzed for themes.

The first tier, Tier 1, consisted of four teams having the greatest number of overall points, ranging from 7.7 to 8.6 points. Teams in Tier 1 exceled in at least one category (*e.g.*, minimum mass, creativity), predicted the force required to cause a 0.050″ deflection more accurately than teams in Tier 2, and satisfied the remaining categories. Although causality cannot be ascribed, it is plausible to argue that teams in Tier 1 improved designs more quickly than teams in Tier 2 via an ability to more accurately predict or estimate results. A review of student self-described design processes and suggested changes suggests that teams in Tier 1 engaged in, or would have liked to have engaged in, one or more than one aspect of design thinking. For example, all four of the teams in Tier 1 explicitly considered and described divergent questions, *i.e.*, two teams intentionally considered point distributions and decided to pursue lightweight beams, and two teams intentionally considered point distributions and decided to pursue creative designs. As another example, one of the teams in Tier 1 constructed a rudimentary flexure fixture and experimented with prototype beams.

Tier 2 consists of the remaining six teams that tested beams at the competition; teams in Tier 2 were awarded between 5.3 and 6.8 overall points. A qualitative review of self-described narratives indicated two unifying themes. First, teams in Tier 2 failed to articulate divergent questions within their narratives. Although it is possible that teams considered divergent questions in their design processes, the lack of a clear articulation in the team's narrative indicates either a lack of explicitly considering divergent questions or the team considering divergent questions to be less important than other questions (*e.g.*, How to increase strength?). Second, the percent differences between calculated and experimentally-determined forces required to deflect beams 0.050″ were significantly greater than similar percent differences for teams in Tier 1. Though unproven, it is possible that the inability to accurately calculate (or estimate) the force required to deflect their beam hindered Tier 2 teams from asking and answering the divergent questions commonly asked and answered by teams in Tier 1.

DISCUSSION

This project required students to make intentional material placement decisions and challenged students to consider material placement in context of processing parameters. Seven teams chose prismatic external geometries (*i.e.*, material placement varied in the *y-z* cross section and was invariant in the *x*-direction) and four teams chose non-prismatic external geometries (*i.e.*, material placement varied in *x*-, *y*-, and *z*- directions). Interestingly, none of the 11 teams employed a material placement strategy that shortened the length of the load-carrying-portion of the beam to match the span of the supports. For example, most beams could have weighed almost 1/6th less by reducing the load-carrying length to approximately 5 inches and adding 0.5-inch-long light-weight extensions to comply with the 6-inch-overall-length requirement. The non-utilization of such a material-placement strategy is especially odd for the four teams that choose non-prismatic external geometries. Atman et al. (2007) suggests a potential explanation in that students spend far less time in problem scoping and information gathering (*e.g.*, identifying constraints, information gathering, stating assumptions) than experienced engineers.

Cast in terms of design thinking, students demonstrated novice to emerging, here defined as a level between novice and expert, behaviors. Within the first element of design thinking, divergent-convergent questioning, teams in Tier 2 demonstrated novice behaviors by not discussing divergent questions within the project report narrative. Teams in Tier 1 demonstrated emerging behaviors by asking and answering a divergent question concerning point distribution strategies, but failed to demonstrate expert behaviors, such as questioning the allocation of mass along the *x*-direction within the build envelope, especially outside of the 5-inch span.

The second element of design thinking, thinking about design systems, is delineated into four subelements: thinking about system dynamics, reasoning about uncertainty, making estimates, and conducting experiments. Regarding thinking about system dynamics, most of the teams considered 3D printer bed orientation, with some teams exploring post-processing activities such as annealing. However, none of the teams considered more advanced systems dynamics concepts such as extruder temperature or gradient infill. The lack of addressing more advanced systems dynamics concepts was unsurprising considering that this project was the first exposure to 3D printing for many of the students.

The second and third subelements, uncertainty and estimation, may be assessed via beam height. From a strength of materials perspective, beam height should generally be maximized to minimize beam bending stresses at the top and bottom of the beam. Referencing data in Table 4, six of the eleven teams demonstrated an emerging level of maturity for uncertainty and estimation as demonstrated by beam heights being between 0.987 inches and 1.000 inches tall. Three of the teams had heights between 0.696 and 0.886, potentially indicating a lack of estimation. Beam 10 was too tall, suggesting the team correctly estimated the influence of height, but failed to account for geometric uncertainty. As the four teams manufacturing beam heights between 0.999 and 1.000 inches lacked a discussion of uncertainty in their project reports, it could also be argued that these four teams failed to consider uncertainty, but were lucky.

The fourth subelement, conducting experiments, is integral to design thinking and allows designers to iterate based upon acquired data. Although not included as an in-class component of this study, one team conducted their own formative experiments utilizing a self-fabricated flexure fixture. Further, 50% of the summative survey responses requested extra time, which presumably could be utilized for conducting experiments. Hence, students generally demonstrated a novice level of design thinking concerning experimentation.

Effectiveness of the Studied Project-Based Learning Activity

The qualitative and quantitative data from this study suggest that this project-based learning activity effectively reinforced strength of materials concepts and introduced concepts related to 3D printing, open-ended designs, and the interconnection between material properties, materials processing, and strength of materials. This finding is consistent with Balemen and Keskin (2018), which conducted a meta-analysis of project-based learning literature and concluded that project-based learning is approximately 86% more effective than traditional teaching methods. Lacking further pedagogical experimentation with a control cohort subject to a traditional teaching method and additional cohorts subject other teaching methods (*e.g.*, case study, problem-based learning), it is impossible for this study to compare the effectiveness of different teaching methods. That said, preferred teaching methods are those that engage and motivate students (Herreid 2006; Glassey et al. 2020; Connor, Karmokar, and Whittington 2015).

LIMITATIONS AND FUTURE CONSIDERATIONS

Although promising, results from this first-run study are subject to at least four limitations. First, this first-run study lacks temporal context that can be obtained via longitudinal studies. For example, a longitudinal study could examine the persistence of gains in open-ended design from the sophomore to the senior year, or could examine the changes to sophomore student outcomes depending upon methods employed within the project (*e.g.*, inclusion of introductory 3D printing videos, in-class formative testing of beams, case study of failed 3D-printed beams). Second, extrapolation of results is limited by population validity. Specifically, the student cohort within this first-run study was taken from a single cohort which may or may not be representative of other cohorts within this program or at other programs. Third, results from this study are limited by a potential experimenter bias resulting from the instructor’s interests in 3D printing, engineering materials, and mechanics. Fourth, formative and summative surveys were submitted by 20 and 19 of the 33 students, respectively, meaning that responding students may have self-selected based upon unknown criteria.

Future Considerations

Based upon competition results, student surveys, and review of student-self-reported design processes, future offerings could be improved via four suggested changes. The first suggested change is to create and share videos to introduce students to 3D printing. The videos will fulfill students’ requests for a formal introduction to 3D printing without allocating in-class time. Topics could include exporting files to a slicer, slicing, and printing their first print. The second suggested change is to require each team to submit as-printed g-code. By having the as-printed g-code, additional beams could be manufactured to prepare case study exemplars and study process parameter dependency.

The third suggested change is to add 14 extra days at the beginning of the project to allow for two design-analyze-manufacture-test sequences. The first design-analyze-manufacture-test sequence would be formative, encouraging students to focus on 3D printing their first beam and reflecting upon discrepancies between as-predicted and as-tested results. A formative round may also motivate students to pursue more sophisticated strategies such as incorporating an orthotropic material assumption into their material placement strategy. Orthotropic material models can mimic experimentally-observed behavior in FDM-processed PLA, such as in-plane properties being preferred to out-of-plane properties (Torres et al. 2016) and PLA’s propensity to delaminate between layers when loaded in shear (Torres et al. 2015). Separating the two test dates by 14 days would allow students to reflect and implement changes after the first round of testing.

The fourth suggested change is to introduce a 30- to 50-minute in-class activity exploring divergent questioning and estimating, which were two of the primary qualitative differentiators between teams from Tier 1 and Tier 2. A potential divergent thinking in-class activity for a strength of materials course is the case study of Groovebook, a company that reduced shipping costs of bound photobooks by approximately 80% be reducing the flexural resistance of the book binding (Chowdhry 2014). The remainder of the in-class activity would be for students to work in their teams to quickly estimate important factors and then perform initial designs for a strength of materials design problem.

Beyond suggested changes within the existing 3D-printed beam project, findings from this first-run study may be extended to the entire mechanical engineering technology program. For example, the cornerstone design course could be extended to include case studies highlighting divergent questioning and open-ended questions related to an existing analyze-build-test project. Although the program's capstone design course already includes a multi-physics case study addressing system dynamics, uncertainty, and estimation (Ellis and Berube 2017), this study clearly indicates a need for additional integration of design thinking concepts into other courses.

Findings from this study also extend to other universities. In particular, other universities are encouraged to implement a project-based learning design project within a traditional analysis course. For mechanical engineering and mechanical engineering technology programs, the demonstrated 3D-printed beam contest is an appropriate project. Due to the relative ease of digital file transmission and use of relatively simply experimental equipment, this project could be extended to a regional or national design contest, thus likely increasing student motivation.

CONCLUSIONS

There is a recognized need to incorporate additional design content, particularly appropriately-scaffolded design-build-test spines, within undergraduate engineering curricula. Recognizing credit hour constraints, this research seeks to address this need by incorporating an appropriately-scaffolded design project within an existing analysis course. This approach has the additional benefit of demonstrating that analysis and design can and should be taught simultaneously. Although demonstrating an exemplar project for mechanical engineering and mechanical engineering technology students, the approach of incorporating design projects into analysis courses can be applied to all engineering disciplines.

This work is significant for two reasons. First, despite a long-recognized need to incorporate design elements into the engineering curricula, this work demonstrates *how* a design-build-analyze-test spine can be integrated into an analysis course. In this case, a three-point-loaded additive manufactured beam project was integrated within a sophomore-level Strength of Materials course. The project was completed in 29 calendar days and required only 1.5 hours of in-class time and utilized commonly available university equipment, such as 3D printers, calipers, mass balance, and a load frame. Importantly, the project exercised students' analysis, soft, and inductive reasoning skills within an open-ended project and intentionally created tradeoffs for students to consider.

The second reason this work is significant is that student opinions were assessed via formative and summative surveys administered during and after the project, respectively. Survey results indicated that students were primarily motivated by utility task value from the extra points offered and by intrinsic task value expressed as a desire to do well on all tasks. Despite 74% of the students self-assessing their 3D printing experience as novice, 65% of students agreed or strongly agreed that they had the appropriate skills to complete the project. Further, 75% of the students agreed or strongly agreed that their 3-person team had appropriate skills to complete the project. Regarding learning outcomes, 84% of the students agreed or strongly agreed that the project improved their understanding of strength of materials and 3D printing concepts. More importantly, 95% of the students agreed or strongly agreed the project improved their understanding of open-ended design problems and how material properties, materials processing, and strength of materials concepts interconnect.

The student surveys suggest two significant findings. First, student understanding of open-ended design problems and the interconnection of material properties, materials processing, and strength of materials concepts increased markedly during the last portion of the project. Second, analysis and design should not be viewed as adversarial content within engineering curricula. To the contrary, students are capable and potentially have more meaningful educational experiences when analysis and design are taught concurrently.

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