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Finite Element Analysis as an Iterative Design Tool for Students in an Introductory Biomechanics Course

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ABSTRACT

Insufficient engineering analysis is a common weakness of student capstone design projects. Efforts made earlier in a curriculum to introduce analysis techniques should improve student confidence in applying these important skills toward design. To address student shortcomings in design, we implemented a new design project assignment for second-year undergraduate biomedical engineering students. The project involves the iterative design of a fracture fixation plate and is part of a broader effort to integrate relevant hands-on projects throughout our curriculum. Students are tasked with (1) using computer-aided design (CAD) software to make design changes to a fixation plate, (2) creating and executing finite element models to assess performance after each change, (3) iterating through three design changes, and (4) performing mechanical testing of the final device to verify model results. Quantitative and qualitative methods were used to assess student knowledge, confidence, and achievement in design. Students exhibited design knowledge gains and cognizance of prior coursework knowledge integration into their

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designs. Further, students self-reported confidence gains in approaching design, working with hardware and software, and communicating results. Finally, student self-assessments exceeded instructor assessment of student design reports, indicating that students have significant room for growth as they progress through the curriculum. Beyond the gains observed in design knowledge, confidence, and achievement, the fracture fixation project described here builds student experience with CAD, finite element analysis, 3D printing, mechanical testing, and design communication. These skills contribute to the growing toolbox that students ultimately bring to capstone design.

INTRODUCTION

Undergraduate engineering curricula generally culminate in capstone courses that require student teams to undertake significant design challenges. Courses delivered earlier in the curriculum, particularly laboratory courses, present opportunities to prepare students for team-based design projects. Recently, many undergraduate engineering programs have implemented “design throughout the curriculum,” the integration of hands-on design experiences from the freshman through senior years, in order to better prepare students for design-oriented roles in industry [1-4]. Continually engaging students in the design process is particularly vital to undergraduate biomedical engineering programs, as the design of medical devices is subject to increased scrutiny and control due to the highly regulated nature of these products. Despite this, there are relatively few published examples of design projects aimed at undergraduate students that are relevant to a biomedical engineering curriculum [5-7]. Within biomedical engineering opportunities for such dissemination are limited; nonetheless, more widespread use of evidence-based pedagogical approaches to active learning – such as those described here – has been identified as an unresolved challenge in undergraduate biomedical engineering education [8].

The types of design projects that may be incorporated into undergraduate engineering curricula are often open-ended or challenge-based, meaning that instructors do not employ traditional deductive teaching methodologies to drive student learning. In fact, inductive teaching methods have been shown to improve acquisition of problem solving skills [9], teamwork and communication [10], and confidence during design prototyping [11] among engineering students. When paired with the resurgence of hands-on learning in engineering education [12], inductive teaching methods allow instructors to incorporate real problems that require physical prototype solutions. One specific inductive teaching method, project-based learning (PBL), is generally employed when integrating design experiences into laboratory courses, and this pedagogy may result in student cognitive growth among students [13-15], which can be applied when design challenges become more difficult.

In addition to the general skills that students build throughout an undergraduate engineering curriculum (critical thinking, problem solving, teamwork, communication, etc.), there are more specific skills that may benefit students as they encounter design challenges. These include prototyping, computer programming, computational analysis, and testing. Moreover, familiarity with different software tools, programming languages, and testing equipment can make approaching design less intimidating for students. In particular, we have observed weaknesses in engineering analysis that can limit the success of student teams in capstone design. Further, senior-level engineering students have been shown to more thoroughly apply the engineering design process and to produce higher quality design solutions, in comparison to their less experienced peers [16]. Improving student skill and confidence in approaching analysis should allow capstone design teams to have more success, particularly during the early phases of projects when building and testing a prototype may be unwarranted.

Here we present a fracture fixation design project aimed at sophomore-level students majoring in biomedical engineering, mechanical engineering, or a similar field. Fracture fixation plates are relatively simple biomedical devices that have clear mechanical functions, which makes them an ideal target for a design project in an introductory mechanics course. The project encompasses computer-aided design, finite element analysis, iterative design, 3D printing, and mechanical testing, and it can be completed by student teams over the course of a semester. In this manuscript we present data and reflections from the first iteration of this student project, discuss changes that we have made in response to student feedback, and consider potential adaptations moving forward.

METHODS

Assignment Context

Biomedical engineering undergraduate students enrolled in a 200-level introductory biomechanics course (n = 49) completed a fracture fixation design project. The course encompasses lecture and laboratory components and is typically the first biomedical engineering course taken by our students in the undergraduate program. The lecture component of the course covers statics and mechanics of materials, and the lab component guides students through tissue harvesting and mechanical testing of synthetic and biological materials. The project exists as the first of four design projects that students encounter in 200- and 300-level biomedical engineering laboratory courses [3, 4], between freshman and capstone design experiences.

Accredited undergraduate engineering programs must demonstrate student ability to identify, formulate, and solve complex engineering problems [17]. This project is a first step toward this goal in our biomedical engineering curriculum. By incorporating the project into a sophomore-level biomechanics course, we intentionally address course-level learning outcomes, including student abilities to (1) infer state of stress and strain at a given point in a structure under bending loads and (2) work with a team to conduct experiments and collect and analyze data.

The students have access to the ANSYS software suite (ANSYS Inc., Canonsburg, PA) in campus computer labs and use universal testing machines (TestResources, Shakopee, MN) within the context of other laboratory assignments. Two lab activities included in prior iterations of the course – one homework assignment related to finite element analysis and one lab involving mechanical testing of 3D printed designs – were removed from the syllabus in order to accommodate the project.

Assignment Details

Student teams of 3-5 students complete the design project in three parts, each of which culminates in a graded deliverable. The project is assigned in the third week of a sixteen-week semester and student teams have approximately one month to complete each part of the project. Instructors provide written feedback between deliverables so that student teams can improve their finite element models, data presentation, and design communication skills throughout the process. Revised student work is reassessed with the submission of each deliverable.

In Part I of the project, student teams develop problem descriptions and gain familiarity with finite element analysis. Teams are tasked with developing one-page narratives that summarize relevant background information, clearly state the design problem, and address constraints and requirements that govern the design. Students are provided with a rudimentary fracture fixation plate design (Figure 1), and they first reproduce the design using computer-aided design (CAD) software and import the design into finite element software (e.g., ANSYS). Next, students are tasked with developing a finite element model of 3-point bending of the fixation plate. The students are encouraged to build a model that approximates the mechanical testing (in position control mode) to failure of fixation plates that are 3D printed using ABS plastic. The instructors provide resources to help students learn ANSYS, including how and where to apply appropriate boundary conditions, but student teams navigate the software without direct classroom instruction. The deliverable for Part I encompasses a problem description, an explanation of the developed finite element model, and modeling results for the rudimentary fixation plate under 3-point bending.

In Part II of the project, student teams perform iterative design and modeling to arrive at a final fracture fixation plate design. First, students make adjustments to their finite element models based on instructor feedback from Part 1 of the project. After finalizing the model parameters, student teams can begin making design changes to the rudimentary fixation plate. The instructors provide three constraints that limit design choices, which include fixed length (100 mm), maximum cross-sectional area (60 mm^2), and the need to accommodate six screws with provided dimensions. The instructors encourage students to make design changes that can be succinctly described (i.e., that change just one variable or feature), that may improve the performance of the fixation plate, and conform to the provided constraints. Student teams implement a total of three design changes, iteratively, performing finite element analysis with each change. Student teams document design changes (Figure 2) and modeling results (Figure 3) throughout the process. Finally, students interpret modeling results to develop failure hypotheses, predicting how (i.e., where, and under how much force) the devices will fail. The deliverable for Part II includes the iterative design and modeling documentation, a final design to be 3D printed, and the failure hypothesis.

In Part III of the project, student teams perform mechanical testing to verify model results. First, student designs and rudimentary fixation plates are printed using ABS plastic with 100% infill; a uPrint SE Plus 3D printer (Stratasys, Eden Prairie, MN) was used for this first iteration of the project. Next, students load their designs and control devices to failure in 3-point bending, using a universal testing machine (TestResources, Shakopee, MN). Finally, students analyze and interpret results in order to (1) compare the performance of their design to the control design and (2) compare mechanical testing results to modeling results (i.e., test their failure hypotheses). The deliverable for Part III is a complete team design report comprising revised sections from Parts I and II (students may address instructor feedback), a description and analysis of performed testing, and a team reflection on the design process. A summary of all team deliverables is displayed in Table 1.

Assessment

A mixed methods approach was employed to assess student knowledge, confidence, and achievement in design. This study was fully approved by the Indiana University Institutional Review Board (IRB, Protocol #1805726889), and students provided informed consent before participating.

A quiz (8 questions worth 10 points total) was used to assess student design knowledge and applications toward medical device design. Topics covered on the quiz include the design process, specifications, requirements, constraints, and verification and validation. The quiz was given to students both before and after completing the project, with minimal didactic instruction regarding design. The student quizzes were marked for correctness by one of the authors, and overall scores were tabulated. Sample questions from this design quiz are included in Table 2.

Survey questions asked students to report their perceived self-confidence on a Likert scale (1-not very confident, 3-neutral, 5-very confident), before and after each project, in four categories: (1) approaching design, (2) working with hardware, (3) working with software and interfacing with hardware, and (4) communicating results. The exact question text was: ‘On a scale of 1-5, how confident do you feel in the categories below?’ In addition, focus groups were held by representatives from the campus Center for Teaching and Learning to assess student engineering design confidence going forward. Additional survey questions asked students to rate how worthwhile and enjoyable they found the project using a reflection grid [18] and to remark on the integration of prior coursework into their designs.

Student design reports were scored by instructors using a rubric influenced by AAC&U VALUE Rubrics [19] and the Informed Design Teaching and Learning Matrix [20]. The rubric scores were summarized to assess student abilities in five areas: 1) Research & Problem Formation, (2) Idea Generation & Representation, (3) Iteration & Experimentation, (4) Design Reflection, and (5) Communication of Design. Finally, this rubric was adapted so that students could self-report design mastery via survey. These student responses were compared to instructor rubric scores. Two-sample unpaired

Student’s t-tests were used to determine statistical significance for all quantitative comparisons.

RESULTS & DISCUSSION

Overall, the project was well-received by both students and instructors. In addition to the assessment data and student artifacts collected, the authors made a number of observations that demonstrate the success of the developed project. First, student teams mostly responded well to instructor feedback from the first two deliverables, ultimately performing appropriate mechanical models and submitting coherent documentation. Second, student teams employed a diverse set of strategies when making design changes, including mimicking current devices on the market, attempting to convey mechanical advantages, and making haphazard or aesthetic changes. Finally, students recognized the challenge of independently learning finite element methods and provided appropriate feedback to the instructors. This feedback will lead to the development of enhanced instructional resources for future instances of the course.

The following sections relay assessment data regarding student knowledge, confidence, and achievement in design.

Student Design Knowledge

Students demonstrated engineering design knowledge gains after completing the project, specifically related to the design process, requirements and constraints, and verification and validation ($p < 0.05$ for each). The overall pre/post performance on the design quiz is summarized in Table 3, and while the gains are not quite statistically significant, it appears that students have begun to build the type of design knowledge that will be applied throughout the rest of the curriculum. The relatively low scores, overall, can be attributed to the limited design experience of second-year engineering students and to limited space for didactic instruction on the design process early in our curriculum. Further, the emphasis of this particular design project assignment was placed on building experience with analysis techniques, rather than toward building specific design knowledge.

In response to open-ended survey questions, students (n=23) identified fundamental knowledge used in accomplishing their designs and where they learned this information. Students most frequently referenced the introductory biomechanics course (48%) or a freshman engineering course (57%) as being useful to the design process. Skills or tools identified included CAD software or equivalent (35%), MATLAB (17%), and the design process (22%).

Student Design Confidence

Students self-reported significant confidence gains in all four surveyed areas ($p < 0.05$ for each): (1) approaching design, (2) working with hardware, (3) working with software and interfacing with hardware, and (4) communicating results. The results of these surveys are summarized in Table 4. Students reported the largest perceived confidence gains with regards to working with hardware and software. Interestingly, students reported the highest overall confidence with regards to communicating results, an area that instructors have identified as a relative weakness.

Focus group responses, overall, support the observed quantitative improvements in student design confidence. These sessions allowed students to elaborate in ways that would not come across from responses to Likert scale survey questions. Table 5 lists all student comments made in response to a question about design confidence.

Two other focus group questions asked the students to comment about teamwork and the approachability of the assignment. Student responses related to teamwork were predictable; some teams worked well together, while some students had complaints about unequal workloads, ineffective communication, and scheduling challenges. The primary feedback regarding the assignment was that too much independent learning was required in order to perform adequate mechanical modeling. The instructors did provide supplementary resources regarding finite element analysis, but students would have preferred more direct instruction. These student comments have been taken under consideration as we delivered the project to further classes, and some changes we have made are noted in the Reflection and Outlook section to follow.

Student Design Achievement

Student self-assessed design mastery scores considerably exceed instructor scores from the assessment of student design reports. The categories from the adapted design rubric [19, 20] were condensed into five total categories: (1) Research & Problem

Formation, (2) Idea Generation & Representation, (3) Iteration & Experimentation, (4) Design Reflection, and (5) Communication of Design, and the scores are summarized in Figure 5. While students appear to consistently overrate their abilities, the effect is most pronounced with regards to communication and reflection. These comparisons relate individual student self-assessment to instructor assessment of team documents, but the results are stark nonetheless. Ultimately, the divergence in student and faculty assessment of design mastery indicates that students have significant room for growth as they progress through the curriculum and additional design projects.

Student Reception

When asked to rate how worthwhile and how enjoyable they found the project, the majority of students (68%) found the experience worthwhile to some degree. In fact, 55% of students found the project to be both worthwhile and enjoyable. These responses are depicted as a heat map as Figure 6. For many students this project was the first time that they were challenged to work on an assignment with no direct answer or defined lab protocol, so it is not surprising that some did not enjoy the projects. However, these data indicate that better delivery of the project and better management of teams could improve the overall student outcomes and perceived enjoyment.

Reflection and Outlook

The assessment data and student reception indicate that this project is a worthy component of an undergraduate biomechanics curriculum. Furthermore, the project's requirements for iteration and analysis make it a compelling early-curriculum component of design training. Although this first iteration of the project delivery was deemed to be successful, we have since reflected on instructor and student feedback to suggest possible improvements to the project going forward. We have implemented some of these changes in our curriculum, but we have also considered ways to make the project more accessible to a more diverse range of programs and students. Some of our thoughts are outlined in the paragraphs that follow.

First, the predominant student feedback that we received after the first project delivery was related to struggles working with ANSYS. Consequently, in subsequent project instances we have included more robust and straightforward training resources for this software package. At times, this has involved demonstrations and direct instruction by faculty or teaching assistants, but we have also made use of recorded video demonstrations. We also continue to consider options besides ANSYS that might make the project more widely accessible. ANSYS is an expensive software package that may not be available to students at all institutions, so instructors may consider guiding students to use free and/or open-source finite element software packages (e.g., Code-Aster, Elmer). This recommendation might also be useful when delivering the project to students via distance learning, as access to institutionally licensed software may be more challenging in this scenario.

Second, the use of plastic 3D printed designs as stand-ins for metallic fixation plates during mechanical testing can create issues; however, we have found the mechanical testing of these devices to be valuable to the project. The 3D printing portion of this project is particularly likely to create issues if the parts are printed to be mostly hollow, as is often a default setting on many 3D printers. Factors such as print direction and infill percent have been shown to significantly impact the behavior of 3D printed parts under mechanical testing [21]. Our experiences with printing fully solid plates have been mostly good, with the devices generally failing at or near the predicted ultimate force and displacement. However, even in a case where the fixation plate is printed in a relatively stiff plastic with 100% infill, the device is likely to exhibit anisotropic mechanical properties and unintended stress concentration due to printing artifacts that are not representative of metal implants. Nonetheless, we have found that students who set the material to ABS plastic during finite element analysis are able to predict failure stress with modest accuracy.

Finally, biomedical engineering students in our undergraduate program who complete the described design project go on to complete three additional projects before reaching a two-semester capstone design course in their senior years. Due to its emphasis on iterative design, analysis, and technical communication, this project should effectively prepare students for these future assignments. Not all undergraduate programs have the same goals related to engineering design instruction, but this assignment could be delivered as a standalone component of any mechanics of materials course, or it could be easily adapted for other disciplines. Even in a less design-oriented curriculum, it is still desirable to build student skills in modeling, teamwork, and communication. Overall, the project is mostly approachable for students and has low ongoing costs, assuming access to finite element software and mechanical testing equipment.

The work we have presented establishes the value of this fracture fixation design project to undergraduate students; however, there are limitations to our claims. The project requires students to engage with CAD, finite element analysis, 3D printing, and mechanical testing; however, we did not specifically assess student abilities in these areas as part of this study. Some of these mechanical skills are assessed toward course learning outcomes in our undergraduate program. Tracking student skills throughout our curriculum and in response to design projects is a possible future direction of our work. An additional limitation is the lack of a control group for this study. Given the relatively small size of the student cohort and not wanting to exclude students from a potentially valuable experience, a control group was not included. Nevertheless, future work will aim to examine student ability, communication, and confidence toward design based on the amount of early-curriculum design curriculum to which they were exposed.

CONCLUSION

There is growing evidence that engineering educators can develop curriculum that builds student confidence in approaching complex problems [3, 4, 22, 23]. Students self-assessed design confidence and achievement levels after completing this design project, but self-assessment can be inherently unreliable. The fact that instructors delivered a more sober assessment of student abilities suggests that student self-assessment may outpace reality. Moving forward, developing instruments or methods that measure student self-efficacy toward design is warranted. This will allow engineering education researchers to build a theory of student design confidence gains that is grounded in social cognitive theory [24].

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Figure Captions List

Fig. 1	Students are provided with a rudimentary fracture fixation plate design (100 mm x 15 mm x 4 mm) with six evenly spaced elliptical screw holes (10 mm semi-major diameter, 7 mm semi-minor diameter, 16 mm center-to-center spacing)
Fig. 2	Student teams perform three total design changes (top). In the depicted example, a student team (1) softened sharp edges, (2) rounded plate ends, and (3) removed material between screw holes, resulting in the final design (bottom)
Fig. 3	Student teams perform finite element analysis after each design change. In the depicted example, a student team (1) thickened the rectangular cross-section, (2) rounded all edges, and (3) decreased the size of the screw holes. The students used ANSYS software to calculate von Mises stresses in the provided rudimentary plate (a) and in the plate after each design change (b-d), under 3-point bending. Note: because these figures are taken directly from student-submitted work, we are unable to include legible scales; however, the iterative nature of the modeling is depicted.
Fig. 4	Student teams perform mechanical testing to verify modeling results. In the depicted example, students used benchtop universal testing machines to load 3D printed fixation plates in 3-point bending (top) until failure (bottom). Scale bars = 20 mm.

Fig. 5 Comparison of student self-assessment of design achievement (n = 31) with faculty assessment of final design reports (n = 12 teams), each on a scale from 0-4. Student self-assessment consistently outpaces instructor scores.

Fig. 6 Heat map showing student perceptions of the design activity with respect to being worthwhile and enjoyable (n=31). Grey squares indicate zero responses; increasing red intensity indicates increasing number of responses (per scale at bottom).

Table Caption List

Table 1	Summary of student project deliverables
Table 2	Sample questions from the design quiz
Table 3	Pre-/post-test design quiz mean scores and improvement ($n = 41$), $^{\dagger}p = 0.0625$
Table 4	Student self-reported confidence (out of 5) before and after project ($n = 35$), *$p < 0.05$
Table 5	Student focus group comments given after project completion

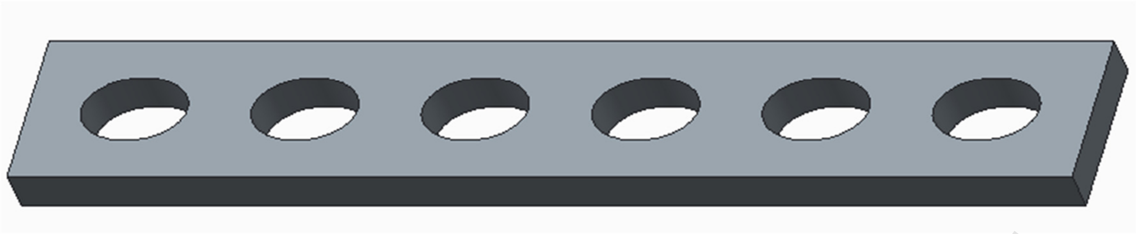


Fig 1

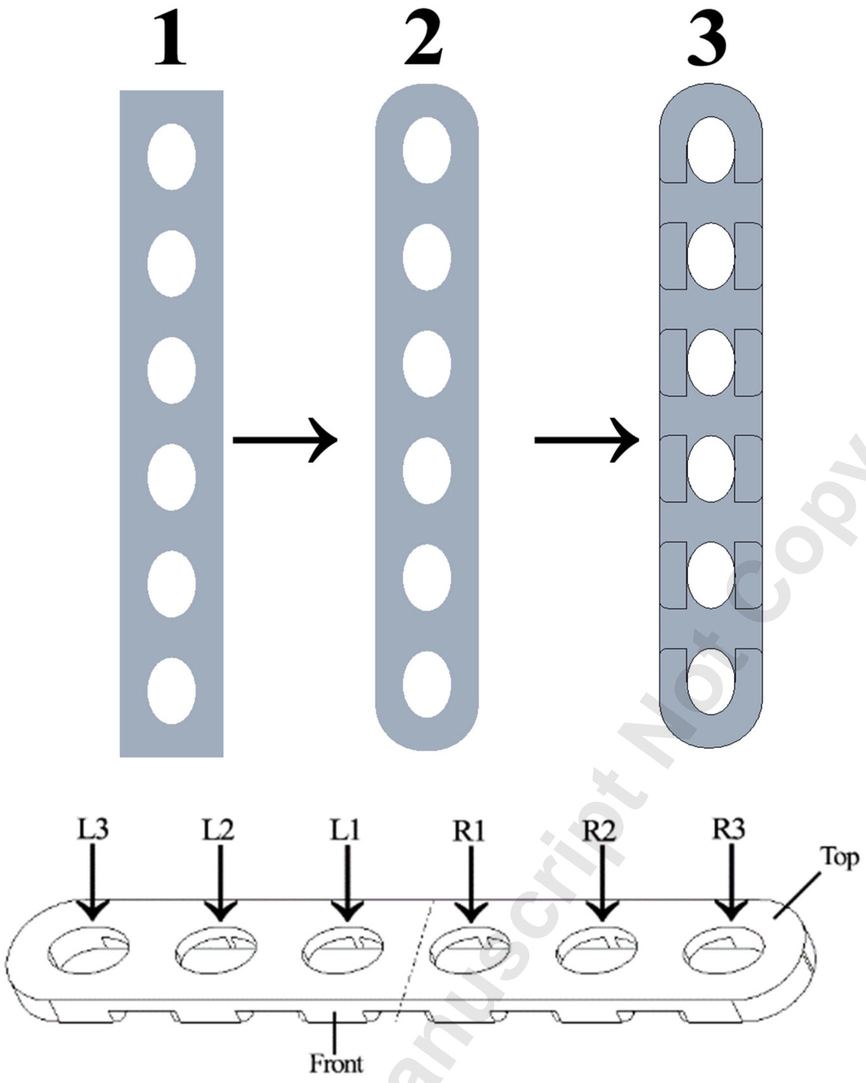
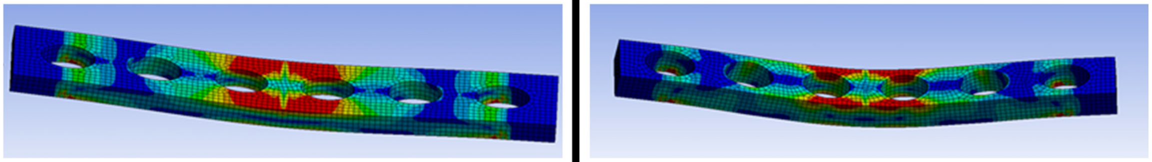
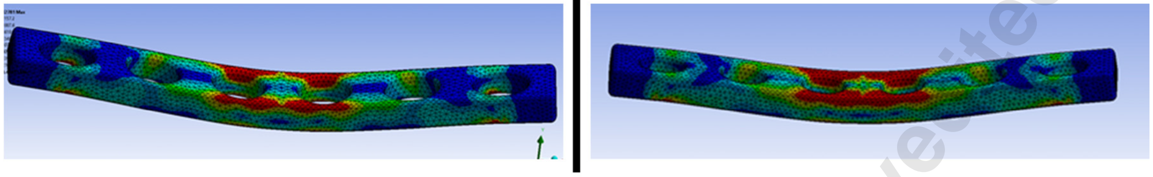


Fig 2



(a) Original Plate

(b) Design Change 1



(c) Design Change 2

(d) Design Change 3

Fig 3

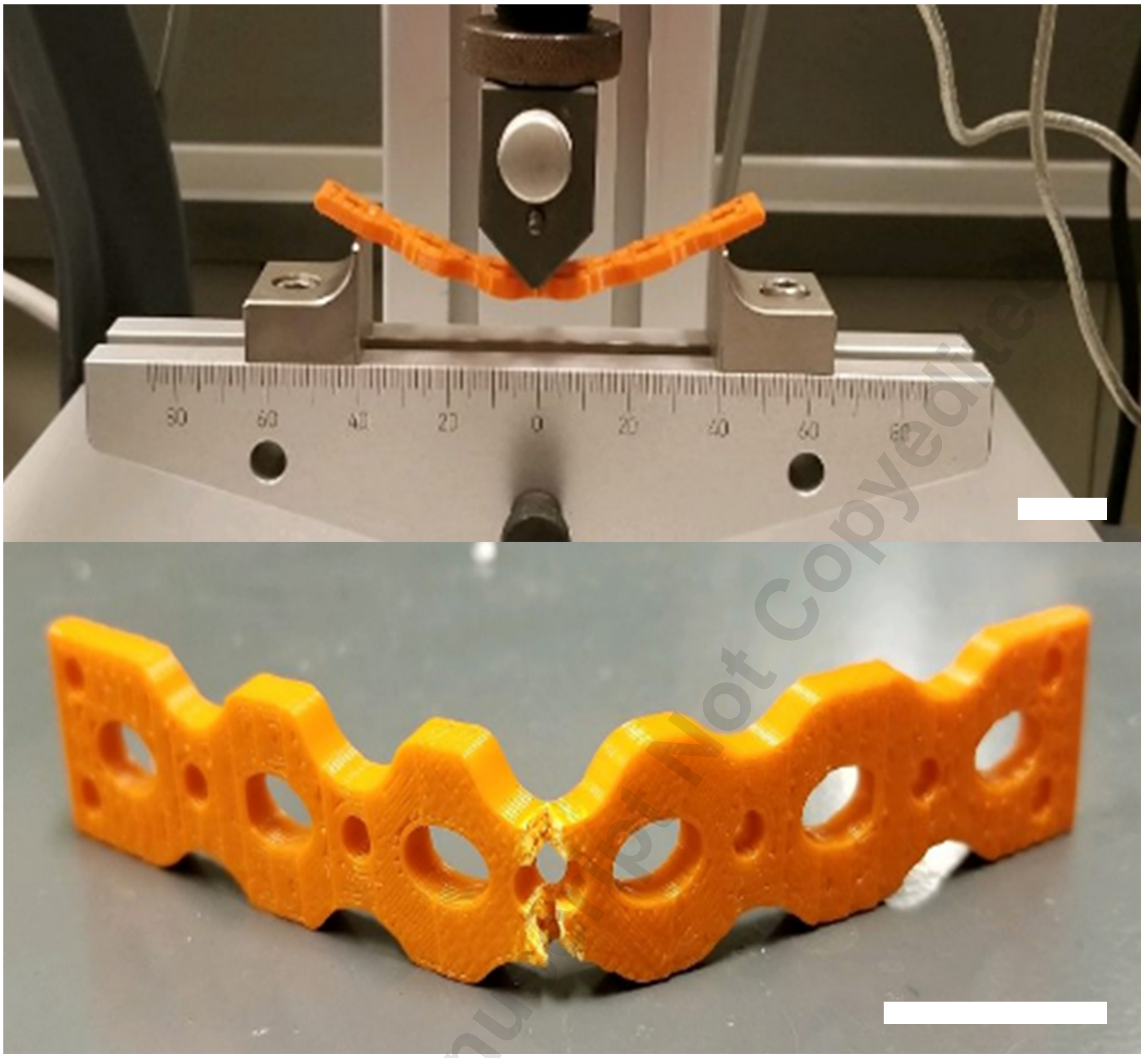


Fig 4

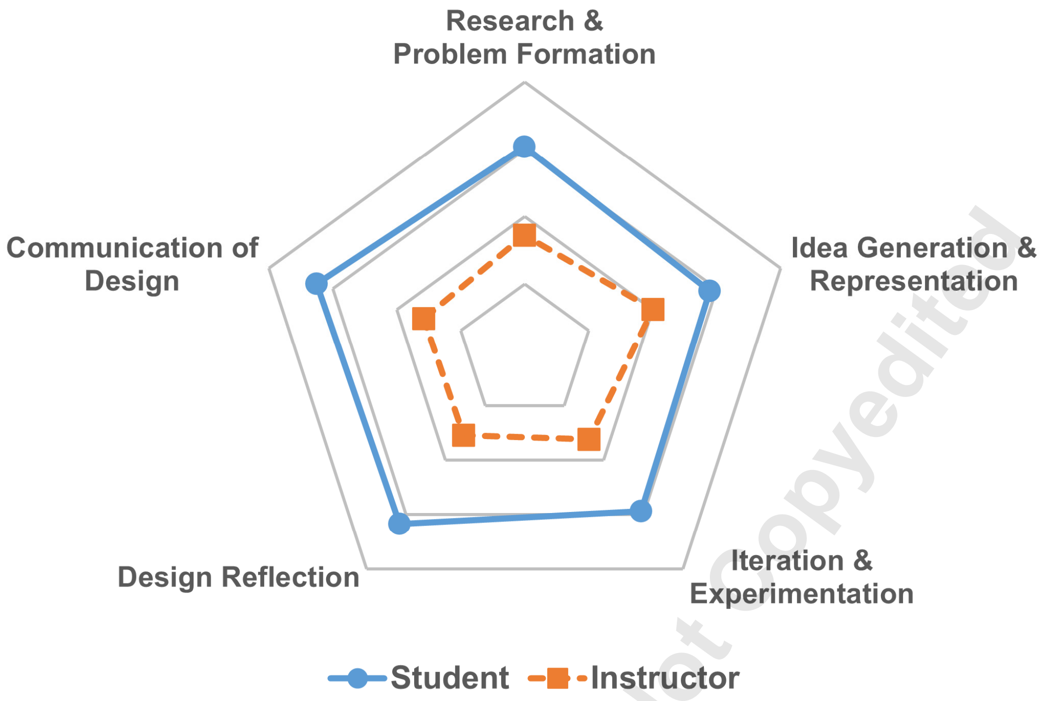

Research &
Problem Formation
Idea Generation &
Representation
Iteration &
Experimentation
Design Reflection
Communication of
Design
Student
Instructor

Fig 5

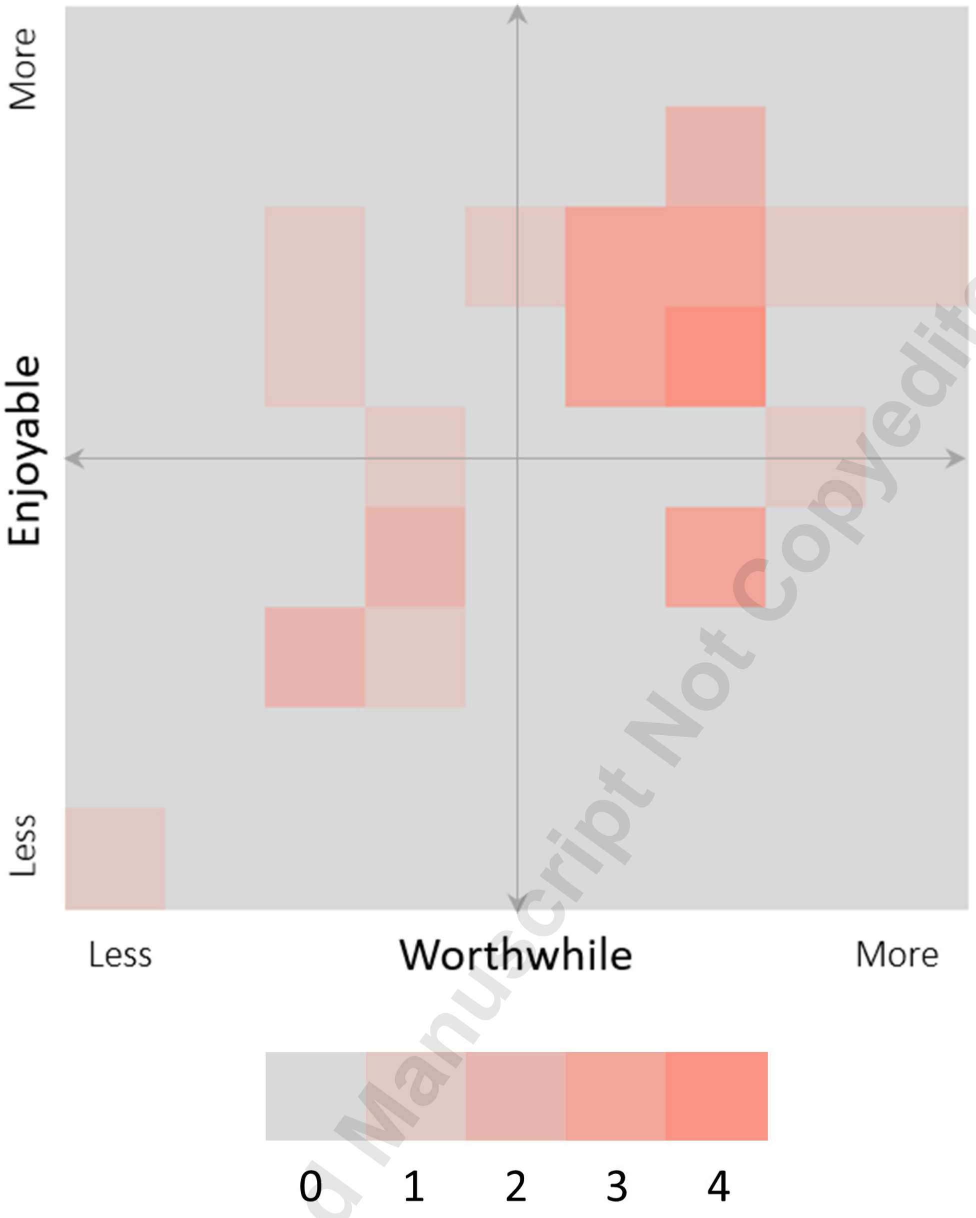


Fig 6

Assignment *Due*	***Part I*** *Oct*	***Part II*** *Nov*	***Part III*** *Dec*
Problem Description	X	X	X
Mechanical Model	X	X	X
Iterative Design		X	X
Final Design		X	X
Failure Hypothesis		X	X
Testing & Analysis			X
Reflection			X

Table 1

Sample Questions from Design Quiz
Draw a classic waterfall diagram that describes the engineering design process, identifying the key design phases, activities, and the relationships between them.
What are the characteristics of a well written design requirement?
Within the context of engineering design, define constraint.
Within the context of engineering design, define specification.
A trace matrix summarizes which of the following? *Options: Design Requirements, Verification Testing, Validation Testing, All of the Above*
Tests that provide objective evidence that specified requirements have been fulfilled constitute: *Options: Verification Testing, Validation Testing, Both, Neither*

Table 2

Design Knowledge	*Pre-test*	*Post-test*	*Mean Improvement*
Design Quiz (10 total points)	3.53 ± 1.72	4.27 ± 1.85	0.74[†]

Table 3

Design Confidence	*Confidence* ***Before*** *Project*	*Confidence* ***After*** *Project*	*Mean Improvement*
Design Process/Approach	2.69 ± 1.12	3.63 ± 0.90	0.94*
Hardware/Physical Parts	2.29 ± 1.08	3.69 ± 1.04	1.40*
Software/Interfacing with Hardware	2.06 ± 1.01	3.40 ± 1.13	1.34*
Communicating Results	3.60 ± 1.02	4.14 ± 0.72	0.54*

Table 4

Question: Having completed the design project, has your confidence in approaching a design problem changed? If so, how?
Compared to beginning of semester, we are a lot more comfortable using the approach to a design project.
Confidence level has changed because of the great amount of freedom and independence given.
Having this experience helped increase confidence. Working through the iterative process flowchart helped introduce us to design and revision process.
No, if we were given more information on what the objective was all along with better instructions at how to approach the problem.
Overall, confidence did not increase because the process was messy.
Somewhat yes, but working with ANSYS was confusing and complicated.
Still unsure of specific steps in design process, but still used them.
The process is less daunting, so yes, more confidence.
Would benefit from doing it individually. It would suck, but would learn more.
Yes, more practice on this process helped.

Table 5