How to engage engineering students in teaching linear elasticity through entrepreneurially minded bio-inspired projects

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Abstract: Student engagement in course learning aids in their motivation to learn and subsequent skill development. Yet, engineering students often feel disengaged when learning math-intensive engineering topics in mechanics courses. As a result, students may de-prioritize learning, do just enough to get by, or transfer out of a degree program altogether. The purpose of this study is to demonstrate how student perceptions of learning and the learning environment, impact engineering student engagement by using entrepreneurially-minded. bio-inspired projects as a foundation for teaching linear elasticity of engineering materials, a mathematically intensive mechanics course. For this project, students were required to conduct a literature review and use entrepreneurial mindset (curiosity, connections, and creating value) to describe applications of bio-inspired architecture materials throughout time. Students researched current development and challenges, how materials were influenced by biological inspiration, and incorporated humanities and arts into design. Upon completion, students were also required to write photovoice reflections about what they learned and how it applies to the real-world. These qualitative data were analyzed using thematic analysis to detect patterns within the reflections. The results show that the bio-inspired projects engaged students by connecting theory, practice, and application when teaching mathematically intensive engineering subjects, while also instilling an entrepreneurial mindset among students, enhancing their creativity by combining art and STEM, and sharpening their professional skills. The study concludes with details related to the instructor's intervention and lessons learned so that other engineering instructors can easily replicate in the classroom.

1. Introduction

1.1 Problem Identification

For engineering students, it is very important to take mathematically intensive engineering courses to understand engineering subjects deeply. Without a strong foundation in math concepts and underlying governing equations, engineering students will not understand more complex, higher-level concepts in their future graduate studies and future careers. When teaching mathematically intensive engineering courses, professors usually show detailed derivations of theorems, principles, and governing equations to demonstrate how theorems, principles, and governing equations are obtained.

However, during this process, engineering students often feel bored and disengaged because examples of how the educational content is applied in their daily lives are lacking [1]. In another words, engineering students are not able to appreciate the value of learning these "boring" theorems, principles, and governing equations, even though they clearly understand that these mathematical fundamentals are essential to their future careers.

The problem that this paper addresses is how to engage students by connecting theories to practice when teaching mathematically-intensive engineering courses.

1.2 Current Approaches to the Problem (and Gap)

It is important to acknowledge there are several approaches (or initiatives) currently underway to engage students within the higher education environment. First, many engineering schools/programs offer two very important courses in their engineering curriculum: one is Introduction to Engineering and the other one is Senior Capstone Design. Introduction to Engineering usually provides engineering students with a better understanding of engineering disciplines through hands on experience and can engage students. Senior Capstone Design courses offer rich opportunities for engineering students to work in teams or individually on industrial and real-world projects [2][3]. However, Introduction to Engineering is usually offered at the beginning of freshman year, and Senior Capstone Design is usually offered during a student's senior year. As a result, there are commonly limited design opportunities for engineering students in between.

Second, many universities are emphasizing experiential learning and encourage engineering students to apply their knowledge to solve real-world problems via internships and co-ops. However, most universities do not require their engineering students to complete internships and co-ops before graduation. Consequently, learning outcomes from internships and co-ops are not consistent [4][5].

Third, to better engage engineering students in the engineering classroom, the KEEN foundation has organized numerous workshops and seminars to teach engineering faculty members how to conduct problem/project-based learning (PBL) [6][7], Entrepreneurially minded learning (EML) [8], and experiential learning (EL) [9]. All these learning pedagogies have the potential to enhance engagement in engineering education. However, these pedagogies have limited scholarly evidence of learning.

1.3 Study Overview

In this study, bioengineering and bio-inspired design project and materials are introduced to engage engineering students by connecting theories with practice (biomaterials' applications) in teaching mathematically-intensive linear elasticity of engineering materials, which is one of the required mechanics topics/courses for many engineering students. This project also aims to enhance entrepreneurially minded learning (EM) in engineering education and integrate STEAM (science, technology, engineering, art, math) by incorporating artistic elements in commonly accepted STEM.

The project requires engineering students to take one exam covering theories of linear elasticity of engineering materials, conduct literature reviews about applications of biomaterials for EM and development of bio-inspired materials and write two summaries, write reports and give presentations for the designed structures made of bio-inspired materials. Finally, each student needs to finish assessment in the form of photovoice reflection after finishing this interdisciplinary applied learning project, which asks students to provide feedback about how entrepreneurial mindset (EM), STEAM, and bio-inspired design and materials have been incorporated in the newly developed curriculum/courses, as well as how this interdisciplinary learning experience (EM, STEAM, and bio-inspired design) affect students' ability to engage with the newly developed curriculum; what important skills (both professional and technical skills) they have learned.

The guiding research question to be answered by the data collection instrument [10] is as follows: *How does Entrepreneurial Mindset and STEAM along with bio-inspired design motivate engineering students and enhance engagement of engineering students in teaching of mathematically-intensive engineering subjects*?

2. Literature Review

2.1 Lack of Applied Learning in Engineering

Many engineering education researchers have concluded that applied and experiential learning can enhance students' learning outcomes [11]. In the US higher education environment, applied learning is defined as the learning activities that provide students to apply technical knowledge and skills learned from traditional classroom learning to solve real-world problems [12][13]. These activities include internships and co-ops, studying abroad experiences, service learning, creative projects or independent or directed undergraduate research, capstone senior design projects [14].

In engineering education, students are required to take a certain number of credits of mathematics courses in addition to some mathematically-intensive engineering courses. These courses are very useful for students' learning of subsequent courses, graduate school and/or their future careers. However, because engineering faculty members have (or perceive they have) limited time, often they focus on teaching concepts, theorems, principles, and governing equations and seldomly ask students to apply these fundamentals to solve real-world engineering problems. While upper-level engineering courses often meet the ABET criteria 1, 2, and 7, which require engineering students to be able to apply the concepts they have learned, the learning outcomes of engineering courses offered during freshman and sophomore years typically do not meet these three ABET criteria.

The lack of applied learning early in the engineering curriculum can make mathematically-intensive subjects very boring and unmotivating. Thus, students' disengagement can impact them negatively by making it hard for engineering students to learn these important fundamentals, which can be critical to their future education and profession. Therefore, some engineering professors who are teaching mathematically intensive engineering subjects are seeking effective pedagogical approaches to motivate students [15].

2.2 Current Approaches for Motivating Engineering Students

KEEN is a US nationwide network of more than 30 undergraduate engineering programs that are committed to the mission of graduating engineers with an entrepreneurial mindset (curiosity, connections, and creating value-3Cs) so they can create personal, economic, and societal value through a lifetime of meaningful work [16][17].

KEEN has organized numerous workshops/seminars to teach engineering faculty members fundamental pedagogical techniques of Entrepreneurial Minded Learning (EML), Active/cooperative Learning (ACL), and Problem/project-based learning (PBL) [18-20] to instill an entrepreneurial mindset into engineering students. It is believed that with an entrepreneurial mindset engineering students will be more eager and motived to learn engineering concepts, identify new opportunities, and contribute more to the companies, communities, and society of which they will be a part.

Introduction to Engineering and Senior Capstone Design are two commonly offered courses in US undergraduate engineering programs. They offer design opportunities for engineering undergraduate students where they are able to apply engineering knowledge and skills to solve real-world engineering problems. The former is usually provided during students' freshman year, and the latter during senior year. Many other engineering courses are offered in between, however, students seldomly have a chance to apply what they have learned in courses to solve real-world problems.

Internships and coops are two good opportunities for engineering students to apply learned engineering knowledge and skills in solving real-life problems in industry [21][22]. They provide students with the opportunity to gain relevant work experience within their chosen career, leading to more career opportunities upon graduation. Additionally, they allow students to work in different roles and fields helping students choose a career direction, while also building and expanding their professional networks. However, at most US universities, internships and coops are only highly encouraged but are not required. Consequently, learning outcomes from these two opportunities working with industry are only limited to students who participated in these two opportunities.

2.3 Introduction to the Intervention

Instilling the entrepreneurial mindset (EM) into Engineering students is the mission of KEEN. EM formally is defined as "the inclination to discover, evaluate, and exploit opportunities" and it includes what are referred to as the 3Cs (curiosity, connections, and creating values). EM learning (EML) engages engineering students substantially because it enables them to see the value of learning engineering knowledge and technical skills. Challenges of EML include creating comprehensive projects that mirror real-world engineering problems and responding to resistance and complaints from engineering students [23].

Bio-inspired design, which is also known as biomimetics or biomimicry, uses the knowledge of any biological systems (including our humans) to tackle any engineering and scientific technical problems for sustainability, security, and/or biomedicine and health outcomes [24][25]. Due to the nature of bio-inspired design, transdisciplinary problem-solving is encouraged, and connections between engineering disciplines are promoted. This transdisciplinarity usually engages students who are consequentially motivated in learning engineering subjects. The biggest challenge for bio-inspired design is that it demands knowledge and expertise in both biological system(s) that are mimicked and engineering discipline(s) that bio-inspired design is used and applied to.

STEAM stands for science, technology, engineering, art, and math. It is an innovative expansion from STEM (science, technology, engineering, and math) that incorporates artistic elements (the study of the humanities, language arts, dance, drama, music, visual arts, design, new media and more) into STEM education [26][27]. Due to artistic elements, engineering students are engaged and motivated when learning engineering subjects. The challenge of STEAM is how to effectively relate engineering subjects to art.

2.4 Contribution to Literature

This research demonstrates how bioengineering and bio-inspired design can be used to engage students by connecting theory, practice, and application when teaching mathematically intensive engineering subjects, while also instilling an entrepreneurial mindset among students, enhancing their creativity by combining art and STEM, and sharpening their professional skills.

3. Methods

3.1 Study Design

In the Department of Aerospace and Mechanical Engineering at Saint Louis University, linear elasticity of engineering materials is the first topic/module in Computer Aided Engineering (CAE) course. Important module information is provided in Exhibit 1.

Exhibit 1. Key Module Components and Module Design

Module Components:

- Part 1: Students are asked to investigate several construction biomaterials that have superior strength and/or hardness.
- Part 2: Students are asked to investigate the possibility of applying these biomaterials into constructions that people can use, e.g. buildings, sculptures and statues, monuments, etc. for superior durability without plastic deformation.
- Part 3: The students are asked to design/analyze constructions built from the investigated biomaterials via analytical tools (equations) and numerical tool (ABAQUS FEM software). The students will also predict the artistic values of the constructions.

Module Learning Objectives:

- Describe several applications of bio-inspired architecture materials.
- Describe current development of bio-inspired architecture materials, challenges of these materials, and how the development of bio-inspired architecture materials was influenced by biological inspiration.
- Design and analyze a structure both analytically using equations and numerically using Abaqus to predict the soundness of this structure professionally and artistically.
- Evaluate the models by comparing and contrasting to students own (either individual or group's collective) aesthetics.

Module Learning Activities:

- Learn stress and strain concepts
- Learning equilibrium equations in terms of stress components
- Learn kinematic equations
- Learn constitutive equations
- Learn compatibility equations
- Learn Abaqus modeling of elastic deformation of structures.

Module Assessment of Learning:

- Two summaries (three weeks)
- Reports and presentations about designed construction/structure made of bio-materials using equations and/or using Abaqus modeling software, marker analysis, and cost analysis of the constructure/structure (one week)
- Exam about the fundamentals of elasticity of materials (2 days)
- Finish photovoice reflection of student assessment of learning (one week)

3.2 Participants

Participating students were junior Aerospace and Mechanical Engineering students. This topic/module is the first topic in the course of Computer Aided Engineering and its course number is AENG/MENG 3100. This is a required course for all Aerospace and Mechanical Engineering students. In Fall 2022, there were 21 students including 4 female students and 17 male students. In addition, one student is from Aerospace engineering and 20 students are from Mechanical Engineering.

In this course, students are taught the fundamentals of linear elasticity (covered in this project), energy methods, theories of failure prediction, introduction to Numerical method, and introduction to optimization. This course prepares Aerospace and Mechanical Engineering students for their subsequent courses, e.g. machine design, senior design.

3.3 Data Collection Instrument(s)

As part of the project, students were asked to write two summaries (for each summary, 10 journal articles obtained via Engineering database Scopus are required): the first is used to describe several applications of bio-inspired architecture materials; the second is used describe current development of bio-inspired architecture materials and challenges of these materials and how the development of bio-inspired architecture materials was influenced by biological inspiration. The students are also required to respond to reflection prompts linked to *Entrepreneurial Mindset, STEAM, bio-inspired design, and several open-ended questions about interdisciplinarity, how the project went on, and connection of the project to the world.* Reflection prompts are shown in Exhibit 2.

Exhibit 2. Photovoice Reflection Prompts

1. Entrepreneurial Mindset: The entrepreneurial mindset is defined as "the inclination to discover, evaluate, and exploit opportunities." Explain how participating in the newly developed curriculum incorporated the entrepreneurial mindset, and lessons learned relevant to the entrepreneurial mindset.

2. STEAM: STEAM (science, technology, engineering, arts, math) goes one step beyond the well-known STEM to acknowledge the importance of integrating the arts and humanities into more analytical coursework such as that found within engineering. Art can be incorporated through pieces, process, and movements. Explain how participating in the newly developed curriculum incorporated STEAM (specifically, the arts), and lessons learned relevant to STEAM (specifically, the arts).

3. Bio-Inspired Design: Bio-inspired design uses the nature-focused context of sustainability, security, and/or biomedicine and health outcomes to motivate analogical thinking and improve the engineering design process. Explain how participating in the newly developed curriculum incorporated bio-inspired design and lessons learned relevant to bio-inspired design.

4. Interdisciplinary Approach: The interdisciplinary approach of integrating the entrepreneurial mindset, STEAM (specifically, the arts), and bio-inspired design has been shown to improve student engagement, motivation and learning outcomes. How did this interdisciplinary learning experience affect your ability to engage with the newly developed curriculum?

5. Debrief: (in this project) What went well? What didn't go so well? What will you do differently next time?

6. Real-World Connections: What skills did you learn? Please consider both professional skills (e.g., communication, collaboration, etc…) and context specific skills (e.g., topic area). Why are these skills important for engineers in the real world?

3.4 Data Analysis Procedure(s)

In this study, thematic analysis was conducted to qualitatively analyze the obtained data. Braun and Clarke explained that thematic analysis is a foundational qualitative approach to identify certain patterns within the obtained research data [28], which should be conducted using a step-by-step process. The authors first read and familiarize themselves with what student participants have written for all these prompted questions, then the authors summarize the data and identify the patterns and themes. Finally, the authors write the report. The authors discuss the strengths and weaknesses between two presenting styles, one is strictly conceptualizing and summarizing themes without using any quotes and the other one is presenting themes using quotes verbatim in order to show readers direct evidences. Finally, the authors decide to combine these presenting styles so that the reader will be able to judge credibility, fairness, and accuracy of the data with quotes being presented verbatim [29].

4. Results

Three themes emerged from the analysis of photovoice reflection data obtained from students: (1) Perspective making/taking, (1) Bio-inspired design, (3) sharpening of professional skills. These three themes show that this bio-inspired design project could engage engineering students by connecting theories in linear elasticity of engineering materials to applications of biomaterials, instill entrepreneurial mindset among students, enhance students' creativity by combining art and STEM, sharpen students' professional skills.

(1). Perspective making/taking. Student participants acknowledge that the bio-inspired project helped them approach problems from different perspectives. Example quotes are the following:
"**Research adds diversity to our ideas,** as its inherent nature is to learn more to solve the central problem of the project. Once we know what exists we can look at what works and if we can further other people's research or incorporate their ideas."

"The newly developed curriculum incorporated the entrepreneurial mindset by **making us think about new ways to approach already-existing ideas**. The main lessons learned relevant to the entrepreneurial mindset included collaboration, problem-solving, and the power of initiative"

"It takes a lot of creativity and **different ways of thinking** (Photo 1) to come up with ideas like that, which we are then able to build off of. It also takes entrepreneurs who are willing to come up with and **try out these new ideas** until they work properly"

"For me, if engineering had no art it would be quite boring. Most people, including me at first, question how art could be connected with science. They seem like polar opposites, **one is very creative and open-ended while the other involves strict calculations** within certain boundaries. However, after looking at what makes an entrepreneur, **it is clear to me that art and science have an overlap in creativity however hard it may seem to see."**

"Art allows a creative window to be opened in your mind. Engineering is not only about solving problems analytically. Some of the best solutions to problems come from crazy, out of the box ideas. Art can be seen in many more buildings around the world. ... Art is a fundamental part of creation, and to be an engineer is to be able to create things that are needed. I am glad that art is taking a more forefront seat in the lives of new engineers."

"The integration of the entrepreneurial mindset, STEAM, as well as the bio-inspired design allowed me to **tackle the curriculum from several different angles**."

"As I work to become an engineer with the goal of creating many new technologies, I must be **open to new ideas and ways of thinking."**

(2). Bio-inspired design can help improve all fields of engineering
"Robotics has been researching the cheetah to develop more effective four legged robots (figure 2). When **designing a robot meant to mimic the way animals walk and run**, it is important to have a model to study"-

"In swimming, the suits of the swimmers have been **modeled after shark skin's ability to create less drag in water** (figure 3) due to an oily layer."

"Gecko feet have been **analyzed to help create arms that can pick up objects, and the aerodynamics of a penguin have been explored** too"

"Other than humanitarian solutions, we can also find practical solutions in nature. **The bullet train was inspired by the Kingfisher** bird (Figure 2) and its long beak. The inspiration of the beak allowed the train to safely pass out of a tunnel going at high speeds and avoiding a dramatic 'tunnel boom'. Humans can also look **to our own anatomy to find solutions** to our problems, such as designs for prosthetics."

(3). Professional skills. Student participants acknowledge several essential professional skills have been built and/or sharpened. Example quotes are provided here:

"I learned, especially, **the importance of communication and planning with my peers**. The collaboration and participation among my group had to be structured, planned, and dynamic when we researched about bio-inspired professional reports. I learned the importance of proactive planning ahead of deadlines and consistently communicating what my progress was on my research."

"Another **skilled learned was teamwork**. Teamwork in the project was needed to collaborate all of ones ideas to make the best possible outcome. Overall this class taught us all the skills needed to perform best as an engineer in the field."

"It helped me engage in critical thinking and learn more about how to **effectively write summaries after reading various articles**. My approach to problems have changed because now I will start with a linear way of thinking starting with what are solutions that have been invented, what purpose do we need to modify the product, and then how can we achieve our intended goal."

"I believe that this project helped me learn how to **conduct more effective research, how to read research articles, and work with others in order to complete tasks.** The ability to be able to do things more efficiently kept me motivated to take my time in reading over the instructions as well as the research articles."

5. Discussion

This study examined how we can engage students by connecting theories to practice using bio-inspired projects when we teach mathematically-intensive engineering subjects.

5.1 Theoretical Interpretation

It is shown that students' learning outcomes for mathematically-intensive courses can be better if the students have chances to connect the theories/equations with real-life activities (practice), especially using bio-inspired projects. The students are more engaged when they can see the values of learning traditionally boring subjects (e.g. mathematically intensive courses).

5.2 Compare and Contrast

Bio-inspired projects can engage students for learning mathematically intensive subjects because bio-inspired projects are much closer to us. We (both students and teachers) can be easily motivated when we are introduced to bio-inspired projects or other biomimicry. Because of this, this research opens a new channel to engage students by connecting theories/equations with real-life bio-inspired projects.

5.3 Implications for Practitioners

Involving students in bio-inspired design could take more time for both professors and students. Time allocation is very important for successfully implementing the bio-inspired projects. In addition, students did get an appreciation for interdisciplinarity and applied learning. Students have the chance to develop their entrepreneurial mindset by relating what they have learned in the classroom to potential application and conducting cost analysis.

As an engineering professor, who teaches mechanics courses, I would like to include other bio-inspired projects in the courses I teach to connect theories, practice, and application to engage students to learn mechanics courses better.

6. Conclusion

6.1 Response to Research Question/Objective

The photovoice reflections from students show that we can enhance the engagement of engineering students when we use bio-inspired design project to instill EM via integrated STEAM when we teach mathematically-intensive engineering subjects. Students' ways of thinking can be positively changed, and they can learn soft skills (e.g. interpersonal skills and teamwork) much better. The results suggest that it is promising for student learning outcomes might be better since students' engagement is high and they had a positive experience when we use bio-inspired projects to connect theory, practice, and application.

6.2 Summary of Main Takeaway

Mathematically intensive engineering subjects can be taught well if we use bio-inspired projects to engage students by connecting theories, practice, and application. In the meantime, using bio-inspired projects, we can also instill an entrepreneurial mindset among students, enhance their creativity by combining art and STEM, and sharpen their professional skills.

6.3 Limitations and Future Research

Based on the observations from the instructor, the common limitations include: (1) only one engineering course at Saint Louis University; (2) only one institution (e.g., Saint Louis University); (3) only one subset of students (21 junior students-4 female student and 17 male students); (4) qualitative exploratory approach. To address these limitations, the following will be future research directions: (1) repeat in other engineering courses; (2) repeat at other institutions; (3) repeat again with same class and different students; (4) should implement quantitative explanatory findings and/or offer mixed methods data collection approach.

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