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Implementation of Visual Supplements to Strengthen Pedagogical Practices and Enhance the Physical Understanding of Fundamental Concepts in Engineering Mechanics

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Mechanical Engineering is a discipline highly dependent on designing and implementing mechanical, thermal, or energy systems for the improvement of the human environment. Thus, being a proficient engineer involves having a strong mathematical background and a thorough physical understanding on how systems operate in order to apply analytical or numerical schemes during a design process. However, most of the students' academic development is centered on deriving tedious equations and solving textbook problems, which are difficult to visualize and physically understand, and cloud their intuitive nature to comprehend a problem on its entirety. These conventional approaches and methods of disseminating content in the classroom have a tendency to exclude diverse learning styles of students. Thus, teaching schemes solely focused on covering themes verbatim from a textbook or paraphrasing from a slide presentation are hindering the students' ability to understand and apply all the engineering principles in design projects. Such technical concern is observed during their senior year capstone design course, in which the tendency is to solely utilize engineering software to obtain calculations rather than applying rigorous mathematical techniques to validate their results. In this study, such predicament is addressed by strengthening pedagogical practices through the incorporation of physical visual supplements during lectures as early as the students' first Mechanical Engineering course called *Engineering Mechanics,* and thus enhance the physical understanding of fundamental concepts. In particular, three visual sensor-based supplements were created: crane model, Baltimore-bridge model, and a four-cylinder engine model. The uniqueness of such physical models is the incorporation of a real-time monitoring system which allows the students to visualize their behavior and correlate between theoretical concepts and physical applications. As a result, students are acquainted with calculation requirements/procedures, design considerations, potential sources of failure, and cost reduction factors.

I. BACKGROUND AND MOTIVATION

There are various teaching pedagogical approaches that have been identified to enhance student comprehension and scholarship abilities in engineering education. One of the most recurrent is known as Problem-based learning (PBL), which is centralized towards the acquisition of knowledge and primarily focuses on developing learners' self-directed learning capabilities and critical thinking-skills through problem-solving, interpersonal skills, and team skills [1]. As such, intricate real-world problems are integrated and leveraged as a vehicle to tap into students' prior knowledge that enhances scholarship aptitudes and elucidates the usefulness of engineering principles in design applications. Such pedagogical technique has been extensively implemented for professional training in medicine and related health professions, but given its educational versatility, various engineering educators have embraced it as an alternative solution towards alleviating instructional quandaries [1]. Despite its potential to positively impact student learning and transform the learning environment, its utilization is not frequent amongst most engineering educators. The literature reports only a small number of engineering programs such as McMaster University, Pennsylvania State University, Manoah University in Australia, Curtin University in

Australia, and Griffith University in Queensland that implement PBL [17], [18], [19], [20], [21], [22], [23]. Such lack of usage amongst engineering programs may attribute to its unfamiliarity, or the complex nature of real-world problems that may require incorporating knowledge from advanced technical courses.

An alternate pedagogical method adopted in engineering education is known as Project-based learning, and is focalized towards the application of knowledge rather than the acquisition of knowledge. Its primary objective involves enhancing student comprehension by giving a closer perception towards professional development and incorporating project-based instruction [2], [3]. The vast majority of engineering faculty indirectly incorporate Project-based learning practices into their curriculum by assigning a single or multiple projects throughout the semester. The advantage of this pedagogical approach is that real-world engineering problems are in indeed addressed, but not in totality, only in regards to technical content attained in a semester span. As a result, numerous technical assumptions and simplifications are considered when approaching problems of this nature.

However, given the absence, receptivity, and even resistance to pedagogical training in engineering disciplines, many faculty members repeatedly struggle with identifying and incorporating instructional techniques that can positively influence student educational outcomes and retention rates. As such, the retention of certain engineering principles tends to progressively dissipate as students complete their major curriculum. However, the retention and usage of fundamental principles is a critical component to the success of the student, primarily given that engineering related disciplines require the effective utilization of technical and design skills to ensure that designed products are durable, functional, affordable, and safe. This struggling pattern is generally observed as undergraduate seniors are asked to perform analytical calculations in their capstone design project. Most fail to identify and implement certain types of engineering analyses that meet design specifications. Instead, there is a tendency to solely utilize software packages to extract the necessary technical data. Although software packages are employed during the capstone design project, they should serve as a verification tool to the analytical calculations, and not as the primary source of analysis. Such technical distress may attribute to the lack of design experience, loss of consciousness to related topics, or the faculty's inability to implement effective pedagogical techniques that increase the retention rates of certain engineering principles when completing curricular courses. The authors in this study focus on the latter aspect.

Continual exposure to textbook problems during lecture sessions, or homework assignments, may be a cause that hinders retention rates in specific technical areas. Current instructional patterns in most entry-level and upper-level engineering courses are centered on enhancing mathematical skills to solve technical problems. These skills are generally transmitted by covering themes verbatim from a textbook, having summarized lessons on a slide presentation, or deriving tedious equations on the board that generally create technical disorientation rather than a sense of usage to engineering applications. These conventional approaches and methods of disseminating content in the classroom exclude diverse learning styles and tend to obstruct the incorporation of fundamental engineering principles into design projects. Nevertheless, research has consistently attested that people acquire higher retention rates when visual supports are incorporated during instructional settings [4]. Mayer identified that humans have two processing channels, one, which processes verbal information, and the other that processes visual information [4]. Studies additionally reveal that visual cueing is an efficient instructional method to obtain knowledge in less time than uncued visualization [5], [6], [7], [8]. In this context, de Koning *et al.* reported that students elevated their academic performance when visual cueing was implemented as evidenced by increased higher scores on both comprehension and transfer tests [9], [10], [11], [12].

Generally, the only visual support mechanical engineering students have during lecture sessions is graphical images extracted from the textbook content. Nonetheless, visual supplements of this nature are insufficient to fully display engineering principles that are critical in design projects and thus exclude diverse learning styles. A predominant reason attributes to the inability of textbooks to display complete descriptions of structures or mechanisms, which may include various types of connectors, cross-sectional areas, or three-dimensional arrangements. However, exposure to physical visual supplements during lectures and recurrent emphasis on design aspects may alleviate the tendency to forget indispensable technical content.

In the context of engineering education, it is imperative that the instructor considers the nuanced dimensions of the teaching and learning process, while simultaneously cultivating an awareness of different variables that influence the teaching and learning process. In many cases, instructors feel a great deal of stress as their efforts to teach and explain abstract scientific and engineering concepts to their students are not thoroughly comprehended and understood. These experiences may lead to frustration and the formulation of negative perceptions about the learning and intellectual abilities of their students. A reason for this struggle can be attributed to instructors' underdeveloped awareness, competence, and understanding of how the teaching and learning process takes place. Marzano posits that learning is uniquely situated within a complex, dynamic system of interactive processes [13]. This reality requires that instructors be knowledgeable about the material they teach and how they teach it. Moreover, within this interactive process, students' learning styles are a major factor that impact the overall instructors' teaching effectiveness. According to Gardner, all individuals possess a unique combination of abilities and skills that collectively comprise what he termed Multiple Intelligences (MI) [14], [15], [16]. Gardner's theory of multiple intelligences posits that human intelligence is not inherently fixed rather a blend of various forms of cognitive, linguistic, and social abilities. The eight intelligences are: logical-mathematical, verbal-linguistic, interpersonal, body-kinesthetic, musical, visual-spatial, intrapersonal, and naturalist [15].

Informed by Garner's theory of MI, the authors showcase three specific visualization tools that have been implemented to facilitate and enhance student comprehension of engineering related content and concepts. The physical models were assembled during the summer of 2018 with the intention of implementing during the fall semester. Throughout the developmental phase, multiple logistical challenges emerged but were iteratively deciphered based on instructional needs, practicality, commute, and functionality of the models. Additional modifications were instigated during the semester as deemed appropriate. For instance, major challenges consisted of resizing the originally intended Baltimore-bridge and tower crane designs to alleviate the process of mobilizing the models to the lecture hall and the deficiency of parts.

II. PROPOSED WORK

In this study, such predicament is addressed by strengthening pedagogical practices through the incorporation of physical, visual supplements during in-class, instructional sessions. As such, the authors find it imperative for such tools to be integrated on the first mechanical engineering course called *Engineering Mechanics*, which encapsulates two major areas of study, statics and dynamics.

The intent of adopting physical supplements at an early stage is to develop the technical instinct of recognizing existing design applications and the type of analyses involved. In this regard, three physical, small-scale, sensor-based supplements were specifically created with the intention of nurturing fundamental engineering principles in these two areas of study. They include a crane model, Baltimore-bridge model, and a four-cylinder engine model (Figure 1). The uniqueness of these physical models, particularly the crane and Baltimore-bridge models, is the incorporation of a real-time monitoring system (includes load cells, amplifier, interface, and software) that allows students to visualize the loading effects generated on specific structural members. Particularly, load cells are attached within the structural members of the visual supplements and connected to an amplifier, interface, and a Capstone software which collects experimental data and displays it in real-time through a graph, table, digit, meter, oscilloscope, text box, or picture. The interface contains four digital inputs, four analog ports, four-sensor port, a 15 W function generator, and a dual high-speed function generator. The four digital inputs allow direct use of photogates or other digital sensors while the four analog inputs are used to measure voltages at sample rates up to 10 MHz on 1 or 2 channels, or 1 MHz on four channels.

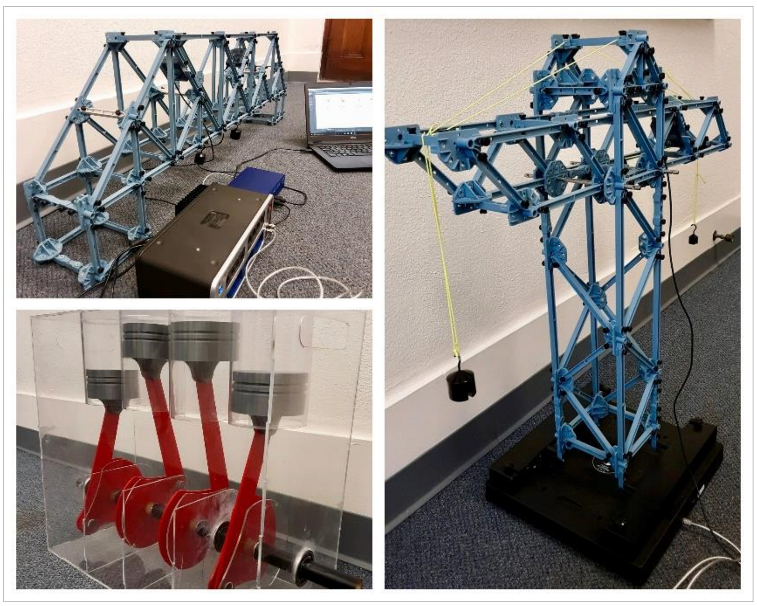

Figure 1. Baltimore-Bridge Model, Crane Model, and Four-cylinder Engine Model

Implementation of Visual Cues during Lecture Sessions

Several fundamental engineering principles were targeted with the incorporation of the physical models and data-collection software. For the statics technical domain, six engineering concepts were highlighted recurrently with the incorporation of the crane and Baltimore-bridge models: free-body diagrams (FBD), centroids and reactions, type of external loads, method of joints/sections, forces generated in real-time, and type of internal loads (Figure 2). For the dynamics technical domain, six engineering concepts were similarly highlighted recurrently with the incorporation of the four-cylinder engine model: free-body diagrams, rigid-body motion, kinematics principles such as linear/angular velocity and acceleration, geometric relationships, equations of motion, and momentum/rotational inertia (Figure 3).

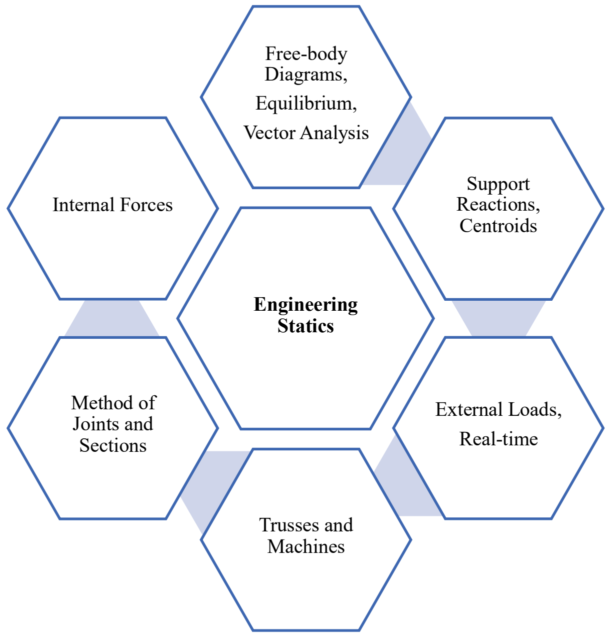

Figure 2. Fundamental Engineering Principles in Statics

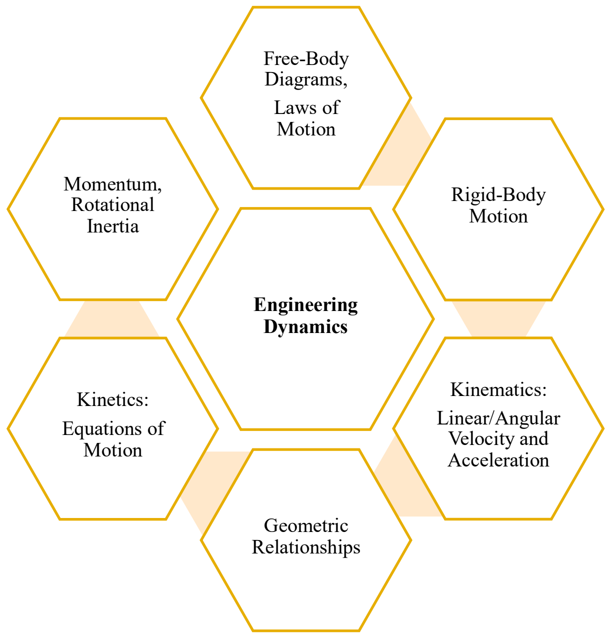

Figure 3. Fundamental Engineering Principles Targeted in Dynamics

Visual models were incorporated and referenced each lecture session by the instructor to stimulate a sense of curiosity regarding themes of study and calculation requirements for specific types of analyses. They were simultaneously utilized to emphasize relevant topics beyond the fundamental *Engineering Mechanics* course such as design considerations, potential sources of failure, cost reduction, and areas of improvement within the structure or mechanism. To encapsulate the significance of real-word engineering applications, students were asked to analyze either the crane model or Baltimore-bridge model as a mid-term project. For such task, students were required to take measurements from the selected model, register the type of loads designated by the instructor, and utilize the mathematical techniques from class to analyze its behavior.

In terms of incorporating such physical models into lesson plans, the instructor arranged the lecture sessions by introduction, inquiry, visual model demonstration, theory, and application (Figure 4). In this regard, the instructor initiated lecture sessions by introducing the respective theme of interest and highlighting real-world applications relevant to the physical visual models. Prior to covering theoretical concepts, however, the instructor would inquire about specific characteristics of the visual tools that correlated to the theme of interest and instigated dialogue between students. Several aspects included orientation of structural members, types of supports, external loads, reactions, and types of motion. These may further be identified through the following list of inquiries posited by the instructor:

1. What type of external loads can be exerted on the structure or mechanism?
2. Where within the structure or mechanism can these external loads generate a reaction?
3. How can these forces be identified and calculated?
4. Will the weight of a member influence support reactions or the motion generated?
5. Can the orientation of the structural members influence the load distribution?
6. In what direction(s) will loads on members or connectors be generated?
7. What is the configuration of the structural members on the bridge or crane? Will they affect the calculations?
8. What assumptions can be made for the given structure or mechanism in order to carry out specific calculations?
9. Is the type of cross-sectional area of structural members important in design? If so, why?
10. How can a free-body diagram (FBD) be created from the given structures or mechanism?
11. Will the type material used in such applications influence the reactions on support members? Can this influence the cost of the structure?
12. Can the configuration of the structure or mechanism allow for geometric relationships to be established?
13. Why are the internal forces of structural members important? What type of analyses can be performed? How can these forces be used in design?
14. What type of motion can be generated from the mechanism as its shaft rotates? Is it linear, rotational, or both?
15. Will the mechanism experience acceleration or deceleration? What factors can influence linear and angular motion?
16. Where within the structure or mechanism will failure mostly occur? How can failure be prevented?

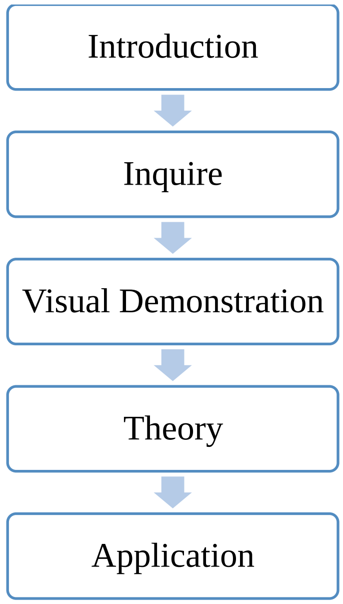

Figure 4. Class Structure when Implementing Physical Visual Supplements

Once these questions were discussed amongst students and instructor for approximately 5-10 minutes, the instructor proceeded by displaying the behavior of a loaded structure or mechanism via a media projector and elaborating on the relevance of engineering principles to enhance the students' physical intuition. As a result, the theoretical concepts were elucidated in detail and exercised through an example problem. Students were additionally granted permission to utilize the physical demonstrations outside lecture sessions classroom to further enhance their physical intuition, recapture lecture material, and experiment as deemed appropriate.

III. METHODS AND ANALYSIS

For this study, three visual sensor-based supplements were created: crane model, Baltimore-bridge model, and a four-cylinder engine model. The uniqueness of such models is the incorporation of a real-time monitoring system, which allows the students to visualize their behavior and correlate between theoretical concepts and physical applications. A mixed method research design was utilized to understand the perspectives of students toward the integration of these visual tools. The context of the study was a small private institution in Texas. The sample selection consisted of 53 students enrolled in an introductory engineering course (Table 1). The classifications of the students ranged from freshman to senior who declared engineering related fields such as Mechanical Engineering, Bioengineering, Civil engineering, and Materials Science prior to enrolling in the *Engineering Mechanics* course.

The primary methods of data collection in the study consisted of a self-developed, small-scale survey instrument that was administered electronically via Qualtrics and focus group student interviews. The survey items were constructed to assess the degree to which students found the visuals useful, relevant and responsive to their learning needs. Recruitment of focus group participants consisted of a class wide email by the instructor inviting the students to participate in the study. In all, a total of six half-hour long focus group interviews were utilized to facilitate collective reflection and dialogue by providing students opportunities to openly discuss their learning experiences with fellow peers. The number of students participating in a given focus group ranged between 6-8 and all focus groups sessions were audio recorded for transcription and analysis purposes. The dynamic nature of the focus group method stimulated conversation among the students and sparked conversations centered on their unique experiences related to the course. The facilitation of the focus group interviews employed a semi-structured approach in which the researchers generated a series of open-ended questions designed guide group conversation. This approach helped create an organic, conversation-oriented environment that encouraged participant autonomy and respected individual and collective experiences and stories.

Table 1. Participant Demographics

Variable	Total	Percentage
Gender		
Females	18	33.96 %
Males	35	66.04 %
Race/Ethnicity		
American Indian or Alaska Native	0	0 %
Asian	19	35.85 %
Black or African Descendant	4	7.55 %
Hispanic/Latina/o	15	28.30 %
Native Hawaiian/Pacific Islander	0	0 %
White	14	26.42 %
Other	1	1.89 %
Classification		
Freshman	1	1.89 %
Sophomore	36	67.92 %
Junior	15	28.30 %
Senior	1	1.89 %

IV. RESULTS

Results (Table 2 & 3) indicate that an overwhelming majority of the students found the visual tools useful and relevant in their understanding of engineering concepts. According to the results, 49 students (92%) indicated that they prefer having visuals when learning new material. Over 85% (46) of the students indicated that the visualization tools provided in the course were useful in understanding specific engineering concepts.

Table 2. Student Responses Mean and Standard Deviation

Question	N	Min	Max	Mean	SD	VAR
I prefer to have visuals when I am learning new material.	53	13	15	13.60	0.62	0.39
The visualization tools provided in this course were helpful in understanding specific engineering concepts.	53	13	15	13.77	0.66	0.40
The visual aid tools helped me correlate between theory and real-world applications.	53	13	15	13.74	0.62	0.38
The instructor utilized the visual tools to emphasize possible design consideration on a structure or mechanism.	53	13	15	13.77	0.66	0.44
I was granted permission by the instructor to use the visual tools outside the classroom.	52	13	16	14.54	0.77	0.59

Table 3. Student Responses Percentages

Question	N	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I prefer to have visuals when learning new material.	53	47.17% (25)	45.28 % (24)	7.55 % (4)	0.00 %	0.00 %
The visualization tools provided in this course were helpful in understanding specific engineering concepts.	53	35.85 % (19)	50.94 % (27)	13.21 % (7)	0.00 %	0.00 %
The visual aid tools helped me correlate between theory and real-world applications.	53	35.85 % (19)	54.72 % (29)	9.43 % (5)	0.00 %	0.00 %
The instructor utilized the visual tools to emphasize possible design consideration on a structure or mechanism.	53	35.85 % (19)	50.94 % (27)	13.21 % (7)	0.00 %	0.00 %
I was granted permission by the instructor to use the visual tools outside the classroom.	52	9.62 % (5)	34.62 % (18)	48.08 % (25)	7.69 % (4)	0.00 %

Concerning the correlation of theory and real-world application, 90% of the students strongly agreed or agreed that the visual tools helped them make the link between theory and practice. Additionally, 46 students (87%) strongly agreed or agreed that the instructor utilized the visual tools to emphasize possible design consideration on a structure or mechanism. Additionally, roughly 44% of the students strongly agreed or agreed that the instructor granted them permission to use the visual tools outside the classroom, whereas nearly 50% of the students stated neither agree nor disagree. Moreover, four students disagreed with this statement.

Student Comments

As part of the survey instrument, students were additionally solicited to allude about the most useful aspects of the *Engineering Mechanics* course. Eight of the participants responded that visuals and/or physical models were most useful in assisting their learning throughout the semester (Table 4). These comments support existing research that posits that the integration of visual tools and physical models is indeed beneficial towards understanding challenging technical concepts and their real-world application.

Table 4. Survey Comments on "What did you find most useful in the class?"

The visual demos were very useful
The real life models
Class demonstrations and examples
Visual demonstrations, group projects
Visual examples
The models helped with understanding how the equations apply to real life concepts
Having physical models to represent examples we were doing made it a lot easier to visualize the problems we were solving
Seeing problems or concepts explained on models/structures brought in during class was very useful and helped clear up confusion

Focus Group Interview Comments

During the focus group interviews, students were presented with opportunities to reflect and share detailed information related to their learning experiences in the engineering course. The focus group sessions followed a semi-structured format in which a list of guiding questions were developed to help inform and to facilitate conversation among the students but not restrict or bound the synergistic potential of group dialogue. This approach allowed for more student-directed conversations that evolved organically and helped to increase levels of student autonomy and engagement. Below are two statements about their perspectives regarding the implementation of physical models during lecture sessions.

> *"It's like a different experience from my background because physics 101 and 102 here is mostly that you learn the concepts in class and then you kind of have to go to discussion or somewhere else to actually how to apply them but it's like really helpful when Dr. Z uses example problems in class and actually shows you how to apply the things he's learning in class. I think that that really helped my confidence level because instead of just trying to figure it out a little bit blindly, it's like everything that we do builds on...like he always says we have the tools and he's not wrong."*

> *"I really like examples like that have some real-world applications, even if it's just a picture. like thing I think of specifically is when you have pliers and it's just a static system and it's gripping something and what I never really thought about is that there is the force of the hand, there's the force of what you're grabbing but there's also a force on the pin. But when you think about it now it's like oh of course there's a force on the pin, it's touching something while something is trying to move against it but just examples like that show you how you like 1. How you can apply it to your life; and 2. It helps you understand how to approach it."*

Additionally, two students shared that the Baltimore-bridge project was useful in developing and applying technical skills required for obtaining solution to the problem:

> *"For me it was with the bridge project cause like at first, I had no idea what to do. It was a group of three and we had no idea where to start but then like we ask the professor and he said to make these assumptions and we made these assumptions and we were able to get it started at least. We had to make a lot of assumptions, but we were able to actually get though it and actually solve the calculations using what he taught us in class, I was like 'wow'."*

> *"I think for me it was also the bridge project cause like even though we made like a bunch of assumptions looking back we ended up like ignoring the z axis and did all the rest of the work and then we plugged our back in and saw that it actually made sense and like the bridge it could work and I think that was nice. Because it took us a really long time to do the project because we were like super lost for a while and then just gratification of just like having a working model situation was really nice."*

Student results further support the benefits of implementing visual tools and models to increase levels of student engagement and understanding. These comments and reflections justify the need and prominence of implementing physical models into engineering lecture sessions. They give students an opportunity to approach real-world problems and understand the intricate process of attaining different types of solution. Moreover, the deliberate integration of physical models through group projects provide students opportunities to engage with peers and help promote technical skills sets and other essential engineering related skills such as leadership, collaborative, and communication skills.

V. CONCLUSION

As evidenced by national statistics and other institutional indicators, such as student retention and completion rates in STEM, there is a growing need to develop effective instructional strategies that help to serve the diverse learning needs of students pursuing engineering degrees. Research has demonstrated that engaging forms of teaching such as project-based learning and the integration of visual tools and other educational resources can significantly enhance student knowledge, problem solving, and critical skills. Yet, despite evidence of the benefits of enacting engaging innovative pedagogical approaches to enhance student learning, there has been limited progress of faculty embracing these instructional practices. Based on the results of this study, it is evident that the integration of visual tools into the engineering classroom are well received and considered to be important in aiding their understanding of engineering concepts and their real-world applications. The results indicated that students greatly value and favor the integration of visual tools to enhance their own learning and acquisition of engineering related concepts and skills. Thus, engineering instructors can greatly benefit from utilizing visual tools as educational resources that meet the learning needs of students.

Ongoing and Future Work

Since the retention and usage of fundamental principles is a critical component to the success of the undergraduate engineering students, particularly their senior year, the authors, in Phase 2 of this long-term project, will track and analyze the performance of the corresponding cohort of undergraduate students pursuing Mechanical Engineering through graduation. The ongoing strategy involves administering surveys after students complete the following courses: *Strength of Materials*, *Fluid Mechanics*, *Machine Design*, and *Capstone Design*, which contain technical overlap. These surveys will target the retention and implementation of fundamental engineering principles. However, the authors are in the process of rapidly developing an assessment scheme for current senior undergraduates enrolled in the *Capstone Design* course who were not exposed to physical models during their *Engineering Mechanics*. The targeted feedback includes the incorporation of engineering software versus analytical techniques, technical difficulties, and areas of improvement during the design time-frame. This information will serve as a medium to evaluate the present cohort of students.

Once the present cohort of students has been evaluated, Phase 3 of the project includes developing a strategy to encourage each faculty member within the Mechanical Engineering department to implement at least one physical model in their course. The primary objective is for undergraduate engineering students to get exposed to a physical model in each of their courses. Assessments through surveys and interviews will then be piloted to determine the academic progression. Resultantly, Phase 4 of the project compromises engaging with faculty members from various departments in the School of Engineering with the intention of presenting the need strengthening pedagogical practices and enhancing the physical understanding of fundamental engineering concepts by incorporating physical models.

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