The Effect of an Open-Ended Design Experience on Student Achievement in an Engineering Laboratory Course

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Abstract—This study explores the effect of incorporating an Open-Ended Design Experience (OEDE) into an undergraduate materials science laboratory taken by third-year mechanical engineering students. The focus of the OEDE was carbon fiber reinforced plastics and sandwich structures. The results indicate that the incorporation of OEDEs in laboratory courses produces significant benefits in terms of student engagement, participation, and perception of competence. In addition, the OEDE was found to enhance students' ability to apply related concepts as compared to non-OEDE lab activities. The authors conclude that the incorporation of OEDEs can increase the effectiveness of engineering laboratory courses.

Keywords—project based learning, design challenge, mechanical engineering, laboratory

1 Introduction

Through the years, many definitions of engineering have been proposed. The focus of these definitions differ significantly and often reflect the specialization of the individual author. In a broad sense, a successful engineer must possess: (1) an understanding of fundamental engineering principles, (2) an ability to apply knowledge of fundamental principles to solve open-ended problems, and (3) the interpersonal skill required to function effectively as part of a team. The Accreditation Board for Engineering and Technology (ABET) expands on these simplistic requirements, defining 11 student outcomes for engineering programs in Criterion 3 (a)-(k). ABET further requires that accredited programs engage in a process of continuous improvement, wherein programs regularly evaluate attainment of student outcomes (a) through (k) and take action to continually improve student performance [1]. This requirement has certainly played a part in the recent surge in engineering educational research and the introduction of many innovative, high-impact teaching practices in engineering classrooms. More than ever before, engineering educators are focused on determining *how* engineering students learn, ostensibly for the purpose of increasing the efficiency of the educational process and the quality of their product. High-impact teaching practices including project-based learning, problem-based learning, and open-ended design experiences are increasingly utilized in engineering programs, and are the focus of this paper.

1.1 Project-based learning (PBL)

In 1995, the National Science Foundation Engineering directorate convened a workshop to produce an action agenda for the reformation of engineering education. The workshop participants concluded that traditional, lecture-based instruction is unlikely to produce engineering graduates who possess the communication, teaming, and other non-technical abilities required for modern engineering practice [2]. The associated solicitation called for engineering educators to, among other things, incorporate active, project-based learning (PBL) activities into their curriculum [3]. PBL builds on Kolb's model of experiential learning and is, in practice, often carried out by teams of students [4]. An international review panel found that graduates from Aalborg University's experimental PBL engineering program were comparable to those from traditional, non-PBL programs, with the exception that they tended to be more adaptable and possessed superior interpersonal abilities [5]. Other PBL studies in science and engineering document increased student interest, engagement, and self-learning, as well as, gains in critical thinking, problem solving, teaming skills, communication abilities, and project management techniques [6]–[11]. The results of these studies suggest that PBL is a particularly effective pedagogical tool in building the so-called "soft skills" which engineering employers' desire. Additionally, there is evidence to suggest that PBL produces a significant increase in technical abilities over a traditional, lecture-based format [12].

While some investigators have used standardized tests to evaluate student understanding, other modes of assessment including interviews and writing samples are suggested as better tools for assessing higher-order understanding [13]. These assessment methods can, however, be time consuming and are somewhat subjective. Assessment of student perception of the PBL experience is also an important tool in quantifying the efficacy of such endeavors. Students' perception of their own competence greatly influences their ability to engage and learn [14]. As such, an effective PBL activity will contain one or more elements which have been shown to increase students' perception of competence, namely, an authentic and clearly-defined focus, the generation of artifacts, and a retrospective evaluation of the project [15], [16]. With respect to engineering education, an effective PBL activity should: (1) be focused on a realistic problem which students perceive as having value, (2) result in the generation of a report or product which serves as a record of student achievement of the project goals, and (3) make an effort to "close the loop" and illustrate to the students the validity of their analysis and final solution. While not a prerequisite for PBL, the addition of a design element to PBL activities has been shown to offer additional benefits.

1.2 Design Experiences

Design has been cited as a defining element of engineering practice. The open-ended nature of the design process changes the way that engineering students think; helping develop the divergent and convergent questioning strategies that are central to engineering practice [17]. Indeed, a revision of Bloom's taxonomy identifies the ability to create as the highest-order cognitive process [18]. Design experiences provide participants with additional choice and control, both of which are critical to enhancing student motivation and encouraging a sense of ownership [19], [20]. The level of complexity inherent in the design process can be tailored to the level of the course, allowing it to be deployed throughout the engineering curricula. Historically, design experiences have been reserved for capstone courses taken by undergraduates in their final semester [17]. More recently, design experiences have been incorporated into the first year of engineering study (cornerstone). Cornerstone design experiences have addressed the disconnect between first-year preparatory courses and engineering, and have been shown to increase retention and graduation rates [21]–[23]. Other programs have made a more concerted effort to incorporate meaningful design experiences throughout their engineering curricula [24], [25]. While design experiences appear to have a positive impact on the cognitive development of engineering students, they also tend to be more resource intensive in terms to faculty time, space, and equipment (as compared to a traditional lecture format). As such, it is important to quantify the positive impact of design experiences and determine the point of diminishing returns. Should design be central to engineering instruction, or, can a few, meaningful design experiences provide similar benefit? For programs that do not have the resources to implement a large-scale, design-centric restructuring, smaller-scale design experiences may be an effective alternative. Within the traditional engineering curriculum, laboratory classes have a tremendous potential to be enhanced by the addition of design experiences.

1.3 Engineering laboratory courses

Laboratory experiences play a central role in engineering education, developing hands-on skills, and bridging the gap between theory and practice. One study suggests that engineering students view themselves as innately practical individuals [26]. It follows that engineering laboratory experiences should be both natural and formative for engineering students. Despite a general consensus on the value of laboratory experiences in engineering education, others have suggested that a lack of clearly defined learning objectives hampers their effectiveness [27]. Many engineering laboratory courses make use of the "lab-in-a-box" model. This approach is characterized by a reliance on heavily-structured experiments and a distinct lack of higher-order synthesis of knowledge. Students typically perform a pre-lab reading, arrive to find a prepared experimental apparatus, follow a detailed procedure, and collect data for analysis. A heavily-structured laboratory format is often justified by safety and cost. Meaningful laboratory experiences tend to be time consuming to plan and execute. Furthermore, the graduate teaching assistants that lead engineering laboratories at many universities often lack the topical understanding to effectively guide undergraduate students through a less structured activity.

Despite these challenges, several investigators have shown that PBL can be used to enhance student interest and engagement in engineering laboratories [8], [9]. The authors of this paper hypothesize that the incorporation of open-ended design experiences (OEDE) in engineering laboratory courses will produce similar benefits.

The authors of the study propose two hypotheses: the incorporation of an OEDE in a laboratory course will (1) improve student attainment of relevant learning outcomes and (2) increase student interest and engagement. The materials testing laboratory environment is particularly well-suited for design-build-test activities. As such, the authors deployed an OEDE in a materials science laboratory course to test the aforementioned hypotheses. The theme of the OEDE is carbon fiber reinforced plastic (CFRP) materials and composite sandwich structures.

The remaining part of the paper is organized as follows. Section 2 provides the approach and methodology used in this study. Section 3 describes the experimental procedures and the metrics used to evaluate the outcomes. In Section 4 results are provided and discussed. In the final Section, conclusions and further directions are presented.

2 Methodology

It is the authors' intent to provide a description of the OEDE such that it may be replicated elsewhere. To facilitate this description a brief review of concepts related to composite sandwich structures is necessary.

2.1 Background on sandwich structures

The driving force behind composite sandwich structures is to achieve a stiffness-to-weight ratio that is superior to a structure made of a single material. Sandwich structures are used extensively in applications where a high stiffness-to-weight ratio is advantageous (i.e., aerospace). The stiffness, k, of a structure acted on by a force, F, is defined by Eq. 1

$$k = \frac{F}{\delta} \tag{1}$$

where δ is the displacement of the structure at the point of load application along the line of action of the force. The flexibility, or compliance, of the structure is the reciprocal of the stiffness.

In order to maximize the stiffness-to-weight ratio, a sandwich structure uses relatively thin, stiff face sheets which carry the vast majority of the axial stresses induced during bending. A lightweight core material is sandwiched in between the face sheets and shifts the faces away from the bending axis, increasing the area moment of inertia and stiffness of the beam. Because the face sheet thickness is small compared to the core, and the core is generally made of a much more compliant material, Euler-Bernoulli beam theory does not accurately predict the behavior of the beam. As such, Timoshenko beam theory, which accounts for the deformation of the beam due to transverse shear (allowing rotation between the cross section and the bending line), is used to predict the behavior of the sandwich beam [28]–[30]. For a sandwich beam of the general dimensions shown in Fig. 1, loaded in central, three-point bending the compliance may be approximated by Eq. 2.

$$\frac{\delta}{F}=\frac{1}{k}=\frac{2L^3}{48E_{face}BtH_c^2}+\frac{L}{4BH_cG_{core}} \tag{2}$$

where G_{core} is the shear modulus of the core material and E_{face} is the elastic modulus of the face material in the lateral direction, L is the distance between the outer supports, B is the width of the sandwich beam, H_c is the height of the core, and t is the thickness of the face sheets.

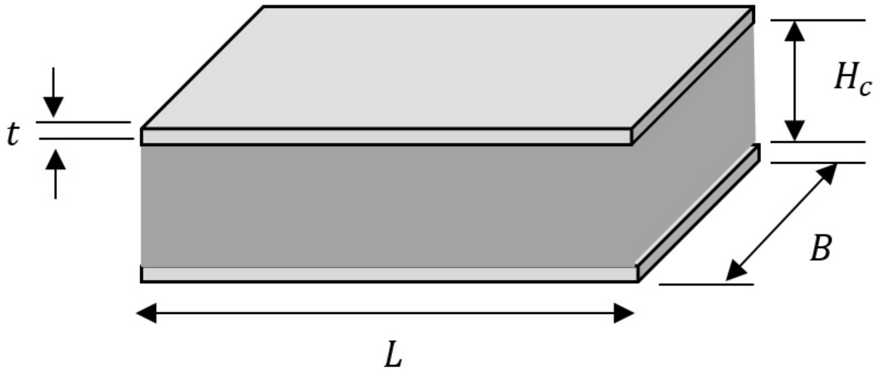

Fig. 1. Schematic representation of sandwich structure with relevant dimensions shown

Sandwich beam failure modes vary significantly depending on the materials used and the beam dimensions. Some common failure modes include: tensile and compressive failure of the face sheets, delamination at the core/face interface, indentation failure at the load point, core failure (usually by shear), wrinkling of the face sheets, and global buckling [28], [31].

2.2 Experimental design

The study was carried out in an introductory materials science course. This course is required for undergraduates majoring in mechanical engineering and it is typically taken in the third year of the four-year program. The course consists of a three-credit lecture accompanied by a one-credit laboratory. The goal of the laboratory is to enhance student understanding of the theoretical topics covered in lecture and to provide students with practical material testing experience. Students learn about CFRP and sandwich structures in the lecture, prior to completion of the OEDE in laboratory.

The students' ability to analyze and design structures using composite materials was assessed after the composite material lecture unit (via a quiz) and again at the end of the semester (via questions on the final examination). In addition, students were asked to complete an anonymous survey at the end of the OEDE which focused on their perception of the OEDEs contribution to the attainment of relevant learning outcomes, as well as, the perceived impact of particular aspects (i.e., team-based, open-ended, etc.) of the OEDE on their learning experience.

2.3 OEDE description

Students are divided into design teams (ideally 3-4 members per team) at the start of the OEDE. These teams are asked to design, analyze, build, and test a sandwich structure consisting of carbon fiber laminate face sheets and a lightweight core. The OEDE is divided into five modules:

1. **Layup:** fabricate carbon fiber laminate
2. **Preliminary testing:** determine fiber fraction and Elastic modulus
3. **Design and Analysis:** use Finite Element Analysis (FEA) and Timoshenko beam theory to predict the relevant performance metrics for various designs
4. **Construction:** fabricate sandwich beam by laminating a core and face sheets
5. **Final testing:** conduct three-point bend test of the sandwich beam and calculate specified design metrics

A description of each module is provided in the following sections.

2.4 Layup

During this module, student groups layup a 12 in. x 24 in. carbon fiber laminate. The laminate consists of four plies of a plain weave, standard modulus, 3k carbon fiber fabric in a polyester resin matrix. A vacuum-assisted, hand layup process is used. Students are given a detailed description at the beginning of the module on the details of the process including mold preparation, release agent application, resin application, resin polymerization, and vacuum bag construction. The teams are supervised and advised throughout the layup process by the course instructor (or laboratory assistant). Students are allowed to work through the various challenges associated with the technique with minimal instructor guidance. Here, the intent is not to frustrate, but rather to encourage students to use their fundamental knowledge of composite materials to solve the practical problems associated with the manufacturing of said materials. As a result of this instructional technique, the exact fabrication method and quality of the laminates varies from group to group. These differences are an excellent subject for an instructor-led discussion as the laminates cure under vacuum.

2.5 Preliminary testing

Once the carbon fiber laminates are cured, tensile specimens (1 in. x 10 in.) and uniformly-sized face sheets (2.5 in. x 12 in.) are cut using a water jet cutter. Students complete a tensile test of the tensile specimens and determine the experimental Elastic modulus of their laminate. Dimensional measurements of the laminate are taken with calipers and a micrometer, and the fiber fraction of the laminate is calculated. The rule-of-mixtures is used to predict the theoretical value of the Elastic modulus from the fiber fraction [32]. The theoretical and experimental values of the Elastic modulus are compared. Students are asked to consider possible sources of uncertainty in the measurement procedure and steps that could be taken to reduce said uncertainty. These higher-order discussions of the experimental procedure challenge students to think critically about uncertainty and help expose lingering (and often subtle) misunderstandings related to composite materials.

2.6 Design and analysis

The design criterion for the composite sandwich beam is a stiffness greater than 200 N/mm as determined from the deflection of the beam at the central load point during a three-point bend test (8 in. span). The plan dimension (top view) of the beam is fixed at 2.5 in. x 12 in. and the overall height is not to exceed 1.1 in. Design teams are permitted to use any core material and configuration they can acquire and fabricate, with the caveat that solid metal cores may not be used. While students are reimbursed for purchased materials, they are provided with two commonly-used core materials: $3\,lb/ft^3$ Polyvinyl chloride (PVC) foam (tradename Divinycell) and end grain balsa wood.

The design metrics for the competition are (assuming minimum design stiffness achieved):

- Lowest weight
- Closest match, stiffness (predicted vs. experimental)
- Highest, stiffness-to-weight ratio
- Highest, failure load-to-weight ratio

In addition, the overall performance of each design is determined using an amalgamation of the team's ranking in each of the four categories listed above.

Students are asked to analyze each of their designs using Timoshenko beam theory, as well as, FEA. Using these tools, the stiffness of each design and weight are estimated. Relevant design metrics are then calculated. Teams formulate a competitive strategy, and choose their best design for construction. While the ultimate failure mode is not explicitly predicted, students are encouraged to research best practices related to sandwich structure design and fabrication, and incorporate their findings into the design.

2.7 Construction

In this module, students cut and assemble their core structures and then bond the core to the face sheets. Face sheets may be stacked to produce multiples of the original four-ply laminate (i.e., 8-ply, 12-ply). Students are given the option of using epoxy or polyester resin to bond the sandwich structure. In addition, students are permitted to vacuum bag the sandwich beam, or, to use evenly distributed weights during curing. Students are encouraged to research the advantages and disadvantages of the resin and fabrication options before arriving to the module. Specifically, they are asked to consider the bond strength of the available resin-core combinations and to identify common problems which arise during sandwich structure fabrication. One example is the tendency of relatively porous balsa wood to absorb resin and cause incomplete adhesion between layers. This problem is well documented in the literature and some light research reveals that balsa layers should be pre-sealed with a polyurethane sealant or a thin coat of resin. The assembled sandwich structures are allowed to cure before final testing.

2.8 Final testing

The final testing module consists of a weigh-in and a three-point bend test. Each group's beam is tested to failure. The linear portion of the load-displacement curve is used to determine the beam stiffness. The bend test can be run in displacement- or load-control, however, the latter tends to produce a more distinct (and entertaining) failure. The peak load before failure is recorded and used to calculate the failure load-to-weight ratio. The mode of failure is documented and discussed. Students are asked to consider the implications of the failure mode. Does the failure mode suggest a defect in the materials or fabrication processes? How could future designs address this mode and increase the failure load? Once the individual team results have been compiled, the rankings are tabulated and announced to the group. This announcement gives the groups perspective on the relative strengths and weaknesses of their designs. In addition, this process "closes the loop" and reinforces the practical utility of the analysis methods (Timoshenko and FEA) in predicting the behavior of structures.

3 Experimental design

Both quantitative and qualitative metrics were employed to obtain a more complete view of the overall impact of the OEDE.

3.1 Quantitative metrics

Quiz and exam results from the lecture section of the course are used to test the hypothesis that an OEDE produces a more complete topical understanding. The structure of the lecture and lab is such that topics are covered in lecture, reinforced with a homework assignment, and student comprehension is assessed with a focused quiz. The laboratory exercise is executed after students have taken the quiz. A comprehensive final examination is given at the end of the semester. Given this structure, the authors assess the efficacy of the OEDE by comparing changes in the achievement of individual students between the quiz (pre-OEDE) and the final exam (post-OEDE). For comparison, two other topics, one with a non-OEDE laboratory exercise, and one without an associated laboratory exercise, are also investigated. Student scores for each assessment are calculated as a percentage of points earned.

3.2 Qualitative metrics

Qualitative metrics are assessed using an anonymous survey administered at the completion of the OEDE. The first section of the survey asks students to evaluate the impact of the OEDE on their attainment of topic-specific learning outcomes. These questions are of the form:

How well did this project affect your _______________ fiber-reinforced plastics and sandwich structures?

Where the blank is filled with:

1. *understanding of the mechanical behavior of*
2. *ability to analyze and design structures containing*
3. *understanding of the fabrication techniques used to manufacture*
4. *understanding of the technical advantages/limitations of*
5. *understanding of the potential applications of*

Students are asked to select one of the following four answers for each of these questions:

1. ***No impact:*** *I understood the concepts after lecture. The project did not enhance my understanding. I did not gain any new knowledge.*
2. ***Limited impact:*** *The project helped clear up a few misunderstandings and/or provided me with marginal new knowledge.*
3. ***Moderate impact:*** *The project contributed significantly to my understanding of the material and/or provided me a moderate amount of new knowledge.*
4. ***Major impact:*** *The project was essential to my understanding of the material and/or provided me with substantial new knowledge.*

The second section of the survey asks students to assess the impact of various aspects of the OEDE on their learning experience. The questions are of the form:

What effect did the _______________ of the project have on your learning experience?

Where the blank is filled with:

1. *team-based format*
2. *open-ended design aspect*
3. *competitive aspect*

Students are asked to select one of the following five answers for each of these questions: very negative, slightly negative, no effect, slightly positive, very positive.

The results of the survey represent an assessment of the students' perception of the impact of the project. The level of engagement of engineering students is often tied to their perception of a particular activity's value. In this sense, the students' perception of the project is as important as the quantitative assessment of their progress towards relevant educational outcomes.

In addition to the survey, the instructors took notes throughout the OEDE concerning student participation and engagement in the individual modules. These observations are summarized in the results section.

4 Results

4.1 Quantitative results

Quantitative results were obtained for 37 students who were concurrently enrolled in the lecture and laboratory portions of the course. The mean values and standard deviations of the pre-lab (quiz) and post-lab (final exam) scores are listed in Table 1 for three topics: one with an OEDE laboratory exercise (composite material), one with a non-OEDE laboratory exercise (tensile behavior), and one without a laboratory exercise (corrosion).

A matched-pair t-test was used to investigate the statistical significance of the positive impact of the laboratory exercises. This analysis considered the improvement of each student from the quiz (pre-laboratory exercise) to the final exam (post-laboratory exercise). An Individual Student Improvement (ISI) value was calculated for each student according to Eq. 3:

$$ISI = (Post - lab\ exam\ score, \%) - (Pre - lab\ quiz\ score, \%) \tag{3}$$

The results are summarized in Table 2.

Table 1. Summary of scores (percentage of points earned) on assessments completed before (quiz) and after (final exam) a laboratory exercise

Topic		Quiz result (%)	Score on relevant final exam questions (%)
Composite materials (OEDE lab)	Mean	60.3%	76.1%
	SD	22.9%	31.3%
Tensile behavior (non-OEDE lab)	Mean	63.2%	72.5%
	SD	28.2%	26.7%
Corrosion (no lab)	Mean	49.3%	53.5%
	SD	27.5%	44.1%

Table 2. Summary of Individual Student Improvement (negative values indicate a decline)

Topic	Individual Student Improvement (ISI)	
Composite materials (OEDE lab)	Mean	15.4%
	SD	27.3%
Tensile behavior (non-OEDE lab)	Mean	8.9%
	SD	30.2%
Corrosion (no lab)	Mean	3.0%
	SD	51.0%

The null hypothesis for the t-tests is $ISI \leq 0$, and the alternative hypothesis is $ISI > 0$. The results for the composite materials topic indicate a very high likelihood of an improvement in student understanding from before the OEDE laboratory exercise to after (p = 7.7E-4). The results for the tensile behavior topic also indicate a strong likelihood of an improvement in student understanding from before the non-OEDE laboratory exercise to after (p = .04).

Of the 37 students that participated, 29 (78%) showed an improvement in understanding of composite material topics between pre-laboratory to post-laboratory assessments. For the non-OEDE (tensile behavior) topic, 25 of 37 students (68%) showed an improvement between pre-laboratory to post-laboratory assessments. For the corrosion topic (no lab), only 18 of 37 students (49%) showed an improvement between the quiz and final exam assessments.

The authors also investigated whether a particular instructional strategy had a greater impact than another by comparing ISI values. The Student Improvement Advantage (SIA) was calculated for each student by Eq. 4.

$$SIA_{x,y} = ISI_x - ISI_y \tag{4}$$

where the subscripts x and y denote the instructional technique used for the lab (i.e., OEDE, non-OEDE, non-laboratory). On average, the OEDE laboratory exercise had a greater positive impact on student understanding than the non-OEDE exercise ($\overline{SIA}_{OEDE,\ non-OEDE}$ = 6.52%, p = 0.15) or the non-laboratory approach ($\overline{SIA}_{OEDE,\ non-lab}$ = 12.4%, p = 0.10). The results also suggest that, on average, the non-OEDE laboratory exercise had a greater positive impact over the non-laboratory approach, although the statistical significance of this hypothesis is considerably lower ($\overline{SIA}_{non-OEDE,\ non-lab}$ = 5.86%, p = 0.28).

These results are promising and suggest that laboratory exercises are effective at increasing student understanding of engineering topics. OEDE laboratory exercises have an advantage over non-OEDE exercises in terms of student understanding (as assessed by examinations). The data also supports the widely-held belief that laboratory exercises help increase student comprehension of engineering concepts.

While the results of this experiment are encouraging, there are several potential sources of bias that exist. The first, is the increased duration of the OEDE exercise. Students spent three weeks on the sandwich beam project, but devoted only one week to tensile behavior (2.5 hours of lab time hours per week). It is also acknowledged that student interest in a topic plays a role in their level of engagement in learning activities. Carbon fiber-reinforced plastic materials and lightweight sandwich structures are more likely to peak student interest than the tensile behavior and corrosion properties of materials.

4.2 Qualitative results

The results of the anonymous student survey indicate a positive student perception of the OEDE laboratory exercise. The results are summarized for the 38 respondents in the Tables 3 and 4.

The results of the survey indicate a positive perception amongst students concerning the effectiveness of the OEDE exercise and further support the conclusion that the OEDE exercise improved student attainment of topic-specific learning outcomes. While all respondents reported the OEDE exercise having some impact on relevant learning outcomes, students perceived the greatest impact was to their understanding of the mechanical behavior of composites. Students reported that their knowledge of potential applications of composite materials was least impacted by the activity. These results mirror the focus of the OEDE activities and discussion topics.

The results of the student learning experience portion of the survey indicate a lukewarm student response to the competitive aspect of the project. Only 66% of respondents reported that the competitive aspect had a positive effect on their learning experience, while two (5.3%) of respondents reported it having a negative effect. This result suggests that the competitive aspect of the OEDE is the least-effective feature of the activity. To maintain anonymity on the handwritten survey, additional comments were not requested from the students. Without further details, it is difficult to assess the specific mechanisms at play for students that were negatively affected (i.e., a bad group member, unclear design expectations, a low final ranking, etc.).

Table 3. Student learning outcomes survey results (post-OEDE laboratory exercise).

Question	No Impact	Limited Impact	Moderate Impact	Major Impact
1. Understanding mechanical behavior	0 (0%)	1 (2.6%)	14 (36.8%)	23 (60.5%)
2. Ability to analyze and design structures	0 (0%)	3 (7.9%)	15 (39.5%)	20 (52.6%)
3. Fabrication techniques	0 (0%)	2 (5.3%)	17 (44.7%)	19 (50.0%)
4. Technical advantages/limitations	0 (0%)	2 (5.3%)	16 (42.1%)	20 (52.6%)
5. Potential applications	0 (0%)	6 (15.8%)	14 (36.8%)	18 (47.4%)

Table 4. Student learning experience survey results (post-OEDE laboratory exercise).

Question	Very Negative	Slightly Negative	No Effect	Slightly Positive	Very Positive
1. Team-based format	0 (0%)	1 (2.6%)	3 (7.9%)	12 (31.6%)	22 (57.9%)
2. Open-ended design aspect	1 (2.6%)	1 (2.6%)	2 (5.3%)	14 (36.8%)	20 (52.6%)
3. Competitive aspect	2 (5.3%)	0 (0%)	11 (29.0%)	5 (13.2%)	20 (52.6%)

4.3 Instructor's observations

The laboratory instructors for this course observed significant differences in student behavior between the OEDE and non-OEDE laboratory exercises. On average, students were more engaged in the OEDE activities. The open-ended and competitive nature of the activity yielded ten different designs from the ten teams that participated. Student laboratory attendance was considerably higher than the semester average (for the non-OEDE activities). The group discussions which occurred during the OEDE modules indicated a high degree of critical thinking and showed evidence of a strong student desire to understand the fundamental principles of composite material analysis. Student behavior during the non-OEDE laboratory exercises was more subdued. Student engagement was inconsistent and fewer students seemed motivated to ask questions and think critically. Instead, most questions focused on the requirements of the week's assignment. While not evaluated quantitatively, the instructors felt that the contrast in student behavior was extremely pronounced and worth noting.

5 Conclusions and future work

The results of this study indicate that Open-Ended Design Experiences (OEDE) are an effective pedagogical tool in increasing student attainment of learning outcomes. Student perception of the impact of said experiences is overwhelmingly positive. On average, the OEDE activity had a larger impact on student understanding than non-OEDE activities. The addition of a team-based element to the OEDE had a positive effect on the student learning experience of a majority of participants. The competitive aspect of the OEDE appears to have had the weakest positive effect on the student learning experience. Overall, the incorporation of an OEDE appears to have produced a significant positive impact on student engagement, attitude, and achievement.

The authors conclude that not all laboratory experiences are created equal. While the general trend is to increase hands-on laboratory experiences for undergraduate engineering students, the results suggest that a greater focus should be placed on increasing the quality of these experiences. Specifically, the findings of this study suggest that team-based, open-ended design experiences are particularly effective at increasing student attainment of learning outcomes. Such activities can be carried out in lecture, but are particularly well-suited for implementation in the laboratory environment. Additional work is required to assess whether there is an advantage to a hands-on implementation (design, analyze, build, test) of OEDEs, over a non-hands-on implementation (design, analyze).

In the future, additional OEDEs should be designed and incorporated into both lecture and laboratory courses to further assess their effect on student engagement and achievement. Ideally, these OEDE activities will have a non-OEDE equivalent such that instructors can easily alternate between the OEDE and non-OEDE formats. This ability would help reduce the likelihood of systematic bias in the experiment. Another interesting activity would be to replicate the study across an array of institutions (i.e., public, private, open-access, selective) and to track student demographics to determine what, if any, differences are observed.

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