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Improving Students' Learning through Inquiry-Based Learning Activities as Pre-training for Mechanics of Materials Classes

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Abstract

Pre-training refers to the process of acquiring knowledge or skills before attending a lecture or other format of learning event. It is an important method to reduce students’ cognitive load when learning new concepts during the lecture. In addition, pre-training can also help to increase student engagement and motivation during lectures, thus improving knowledge transfer and retention.

Common pre-training materials include but not limited to textbook reading, flipped lectures, and the use of online modules. However, often these methods are not very successful in engaging students and thus fail to encourage students to complete the pre-training. Hands-on inquiry-based learning activities (IBLAs) have the potential to better engage students in the pre-training and improve students’ knowledge retention and transfer. Hands-on IBLAs provide students an opportunity to explore the concepts through interaction with physical models and devices, thus facilitate better understanding the concepts. IBLAs in Mechanics of Materials courses as pre-training and their impact have not been studied well. Subject matter in the Mechanics of Materials is an important foundational topic for many disciplines, such as mechanical engineering, structural engineering, etc. Conceptual mastery of those content is important for student's academic success in upper-division classes, as well as for their future careers.

This paper investigates the use of IBLAs as pre-training material for a mechanics of materials class and its impact on students’ learning. The purpose of this study is to report the development of 5 new hands-on IBLA models for Mechanics of Materials class used in a large public university in the United States. The impact of the IBLA as pretraining on students' performance is studied through descriptive analysis and statistical hypothesis tests. Through delayed tests (quizzes, midterms, and final exams), it is found that IBLAs have a stronger positive impact on students learning outcomes in the topics using IBLAs than traditional reading assignments.

Effective inquiry-based learning (IBL) in engineering mechanics courses requires a clear and relevant driving question, structured inquiry activities, and opportunities for student reflection and self-assessment. Thus, we will demonstrate the details of the IBLA hands-on models as an open source for other instructors interested in using them.

1. Introduction

Pre-training

Pre-training refers to the process of acquiring knowledge or skills before attending a lecture or other format of learning event. It is an important method to reduce students’ cognitive load when learning new concepts during the lecture [1,2]. In addition, pre-training can also help to increase student engagement in lectures and learning motivation.

Common pre-training materials include but not limited to textbook reading, flipped lectures, and the use of online modules [3-6]. A number of these methods prove to be helpful in better preparing students for classroom learning, as well as aiding students in recalling prerequisite knowledge [1-6]. In particular, the use of online textbooks and modules has become increasingly popular, and students have reported enjoying aspects such as the ability to improve visualization, improve interactions with knowledge, and self-paced learning [3]. There are, however, drawbacks to each pre-training format; for example, Clump et al. noted that students often may not complete pre-class textbook readings, and Long et al. suggested pre-class videos could lack engagement and ability to motivate students to internalize the covered material [5]. Some instructors reflected that often students join class discussions without completing the required pre-requisite reading [7].

Inquiry-Based Learning for Pre-training

Different from traditional methods, Inquiry-Based Learning (IBL) is an active learning format that involves students in a process of discovery and exploration [8]. Prior research has shown Inquiry-Based Learning Activities (IBLA) increase student motivation and engagement, improve critical thinking and problem-solving skills, and promote deep learning and understanding of subject matter. Inquiry-Based Learning is also associated with positive attitudes towards learning, increased self-efficacy, and greater transfer of learning to new situations [9-11]. The potential drawbacks of traditional pre-training methods motivate the development of IBLA and investigate their unique benefits [12-14].

In IBLAs, students engage in a structured process of discovery, exploration, and reflection to develop an understanding of a topic. In the process of IBL, students begin with relevant and meaningful driving questions, then engage in a series of activities including research, experimentation, and reflection, that help them to develop their understanding of the topic [13].

Using IBLAs as pre-training could overcome the challenges of the dependence on reading assignments with which students often do not deeply engage. IBLAs make the pre-training more relevant and engaging for students. Studies have investigated the effectiveness of IBLA in engineering mechanics courses [15]. The results showed that the students who received IBLA instruction performed significantly better on conceptual and problem-solving assessments.

This paper studies the use of hands-on IBLA models as pre-training learning activities for Mechanics of Materials class used in a large public university in the United States. The impact of the IBLA as pretraining on students' performance is studied through descriptive analysis and statistical hypothesis tests. Through delayed tests (delay means the tests - quizzes, midterm and final exams were administered at least a few days after the IBLAs instead of immediate tests), it is found that IBLAs have a stronger positive impact on student learning outcomes on the course concepts than the traditional reading assignments.

2. Method

In this study, we designed and implemented hands-on inquiry-based learning activities as pretraining materials for a Mechanics of Materials class of 99 students in spring 2022. At the same time, traditional reading assignments were also used as pre-training materials. Both pre-trainings used optional learning materials for extra credit. The class met twice a week for 80-minute lectures. The pre-training materials were required to be completed before the upcoming week’s lectures.

Reading Assignment

Students in the class could choose to complete optional reading assignments for extra credit. In the reading assignments, students read through a chapter of the textbook and then answered relevant conceptual questions through an online platform. A sample conceptual question is provided below in Box 1. Students were allowed an unlimited number of tries to complete the conceptual questions. Once a student correctly answered all of the questions for the chapter, the reading assignment is considered complete, and extra credit is awarded to the student.

Hooke's law, $\sigma = E\varepsilon$, models behavior up to the _____ for ductile materials.

a) failure point
b) proportional limit
c) ultimate stress
d) yield point

Box 1: Example conceptual question for reading assignments.

Hands-on Inquiry-Based Learning Activities

Students in the class could also choose to complete optional hands-on learning activities before lectures for extra credit. In hands-on learning activities, students went alone or in groups of up to three students to a classroom reserved for this activity. The classroom had multiple tables, with a few chairs surrounding each table to facilitate these hands-on activities. The IBLA models for each activity were set up on the tables by the instructional team beforehand. At least one Teaching Assistant (TA) was present to answer students' questions and provide assistance to students whenever needed. For each hands-on learning activity, a worksheet with instructions and questions was provided to students to guide them through a series of tasks that help them visualize specific solid mechanics concepts. After each hands-on learning activity, the completed worksheets were collected for each group of students online, and extra credits were given to each student for completion of the worksheet.

Students' performance scores in delayed tests (overall quizzes, midterms and final exam scores, as well as scores on specific questions of interest in quizzes and exams) were used to evaluate the impact of these hands-on learning activities on students' learning outcomes. Comparisons were made between the impact from traditional reading assignments and hands-on IBLAs. In total, eight hands-on learning activities were implemented in the class. Five of the most significant hands-on learning activities will be discussed below.

Activity A. Foam Tower Model for Axial and Torsional Loading

The foam tower model was made to help students visualize the concepts of axial and torsional loadings in solid mechanics. Seeing and manupulating a physical model can be helpful for students to understand these concepts. but no such off-the-shelf models were capable of physically illustrating these models. Therefore, a model consisting of 4 hard acrylic plates and 3 soft polyurethane foam cylinders of different heights and diameters was developed , as shown in Figure 1. Rectangular grids are also drawn on the outside of the soft cylinders to help illustrate deformations due to axial and torsional loading.

To participate the hands-on learning IBLA, students went a classroom before the lecture where several of this model were placed. Worksheets were provided to students guiding them to perform specific tasks utilizing this model. Students applied loadings to this model, such as to pull or twist the model at certain locations. They then recorded the reactions of this model under the specified loading and found correlations between the geometry of this model and its reactions to the loading conditions. Sample prompts from the worksheets are provided in Box 2. This model can also be used in lectures to help instructors explain the concepts of axial and torsional loadings through in class demonstrations.

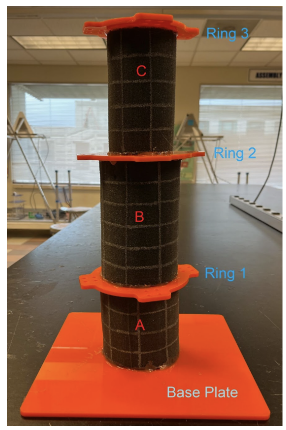


Figure 1: Picture of foam tower model.

With the base plate of the demo sitting on a flat, horizontal surface, apply an upward force on each of the three "rings" separately. We recommend one group member firmly holding the base plate down on the table, while another member **gently** pulls upward on one ring at a time. **Make a hand sketch** for each of the following cases. You may exaggerate the observed deformation for the purpose of illustration clarity.
Address the following prompts based on the activity above:

1. For each applied load, which segment(s) of the foam rod showed deformation?
2. If more than one segment of the rod shows deformation for a given load case, which segment shows the largest elongation, and which segment shows the smallest (nonzero) elongation? What about their strain?
3. What additional questions do you have about this activity and/or topic?

Box 2: Sample worksheet prompts for the foam tower model

Activity B. Foam Beam Model for Statically-Indeterminate Beam Deflection

The foam beam model was developed to help students visualize the concept of statically-indeterminate beam deflection. Students often have difficulty to understand the deflections of statically-indeterminate beams. Being able to vizualize the deflections using a physical model under statically-indeterminate loading conditions can be heplful for improving students understanding of the concepts to solve such problems. This model consists of a beam made from styrofoam supported by three L-shaped aluminum rods, as shown in Figure 2.

The guiding worksheet for the foam beam model tasked students to apply downward forces onto the foam beam model by hand. Students recorded the deformation of the model by drawing and answering questions on the worksheets which introduce the main steps to calculate the deflection of statically indeterminate beams. Sample prompts from this worksheet are provided in Box 3.

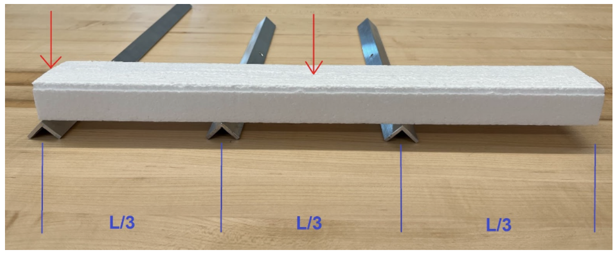


Figure 2: Picture of the foam beam model.

Set up the polystyrene foam beam as shown. Apply two concentrated downward forces. **Make a hand sketch** of the deformed beam. You can exaggerate the deformation to better show the deformed shape.
Address the following prompts based on the activity above:

1. Consider the number of reaction forces acting on the beam (we can neglect horizontal forces), and the number of equilibrium equations that can be formed. Is this beam statically determinate? If not, how are we able to form additional equations?
2. Hopefully you were able to observe that the deformed beam remains continuous and smooth - the beam centerline has no jumps or kinks. How would describe these two conditions using mathematical expressions at the location x = L/2 (halfway along the beam, where one of the two forces is being applied)? You can think about how we describe "smooth" functions in calculus.
3. How would you describe the boundary conditions which the beam is subjected to? Consider how the supports restrict the deflection and/or bending of the beam. How are the boundary conditions for zero deflection and zero slope different from each other? curvature?
4. What is the physical difference between deflection, slope, and curvature? How would you observe each of these? Illustrate these three quantities in a sketch.
5. Try to draw the V-M (shear-moment) diagrams for this beam. Can you observe any connections between the diagrams and the deformed shape of the beam?
6. How do the beam's cross-section moment of inertia and material Young's modulus affect its bending and deflection? Why would the product *EI* often be referred to as the "bending stiffness" of a beam?

Box 3: Sample worksheet prompts for the foam beam model

Activity C. Buckling Models

The buckling column models were developed to help students visualize the concept of buckling of columns under compressive loads. The two-plane buckling model consists of an outer casing made from plastic and aluminum extrusions and two polyurethane foam columns of different cross sections and constraints, as shown in Figure 3. The Euler buckling model consists of a frame made from aluminum extrusions, a plastic back plate, and four thin and long plastic sheets which are constrained to the frame in different ways, as shown in Figure 4.

The two-plane buckling model enables students to visualize in which planes a column will buckle. While demonstrations for Euler buckling already exist in the educational demonstration apparatus market, they are usually expensive. Therefore a low-cost Euler buckling model was developed to help students visualize the effects of different constraints on Euler buckling.

The guiding worksheet first asked students to apply loading to each of the four columns in the Euler buckling model by hand until the column buckles and record the deformation of the buckled columns by drawing. Then students compare the minimum loading needed to make each column buckle and to think about how the different boundary conditions of the columns affect the minimum buckling load. Students also apply loads onto the two columns on the two-plane buckling model and observe in which plane the column buckles first. Sample prompts from this worksheet are shown in Box 4.

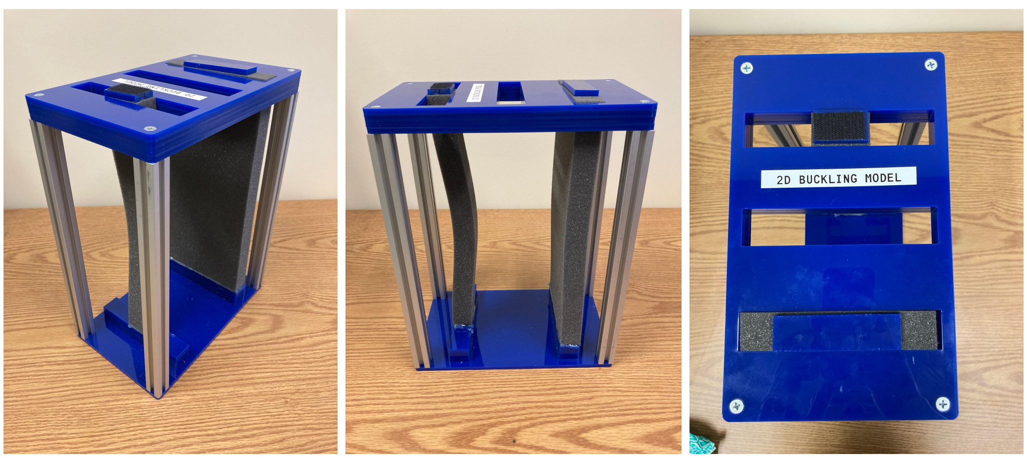


Figure 3: Pictures of the two-plane buckling model
(left: isometric view, middle: front view, right: top view)

Figure 4: Picture of the Euler buckling model
(Constraint conditions from left to right: pin-pin,pin-fixed, fixed-fixed, free end- fixed)

In the buckling demonstration that showcases 4 different combinations of supports, apply a compressive load on each column by hand by pressing down on the top of each column. This demonstration shows how different combinations of supports and constraints affect buckling behavior.
Make a hand-sketch of each deformed column. Try to accurately capture the deflection, slope, and curvature of each.
Address the following prompts based on the activity above:

1. Based purely on hand feel, compare how much force each column can support before buckling (critical buckling load). Try to determine the ratio of critical buckling load between the different columns by hand feel, and then verify this with appropriate equations.
2. How would you describe the boundary conditions each column is subjected to? Consider how the supports restrict the deflection and/or bending of the beam.
3. Consider the deformed shape of each column as a portion of a sinusoidal wave, and the associated "wavelength" of the sinusoids. Using the pinned-pinned column (left most in the picture shown above) as the benchmark, what multiplicative factor would give you the effective length of the other columns?
4. When the compressive load is removed, what happens to the column? Would you consider buckling as a material failure of the column?

Apply a compressive load onto each column and observe its deformation. For the small column on the left, apply the load by placing the provided weight on the top of the column; for the larger column on the right, press down by hand.
Make a hand-sketch of each deformed column. Try to accurately capture the deflection, slope, and curvature of each.

1. How would you describe the constraints/supports for each beam? Explain based on deflection and slope of the deformed shapes. Are these constraints/supports the same regardless of which axis we look at?
2. Would you expect the two columns to buckle the same way even though they have the same supports? Why or why not?
3. What factors influence the critical buckling load of a column? Try to list out all possible contributing factors, and how increasing each would affect the critical buckling load.
4. Given the provided set of constraints/supports on the column and a 1-inch thick block of foam, suppose we wish to make a column with a 1" x L" rectangular cross section. What value of L would you choose to maximize critical buckling load while using the minimum material to achieve this critical buckling load? Back up your result with calculations.

Box 4: Sample worksheet prompts for the buckling models

Activity D. Foam Cylinder Models for Combined Loadings

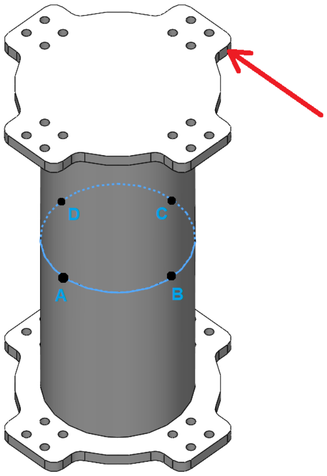
The foam cylinder models were made to show students the concepts of combined loading in solid mechanics. Constructed similarly to the foam tower model A, each short foam cylinder model is made by sandwiching a soft polyurethane foam cylinder between two acrylic plastic plates, as shown in Figure 5. Several foam cylinder models with different diameters were made.

Even though the foam tower model can also be used to show the concept of combined loading, the foam cylinder models were made because they have only one section and can thus reduce students' confusion about where to apply the loading.

The foam cylinder model guiding worksheet would ask students to apply a specific force at a specific location on the foam cylinder model while holding the bottom of the model steady. Student's then observe and record the deformations of the model and think about the stress and strain created by this force on a few different points on the foam cylinder model. After that, the worksheet would ask students to apply a force in another direction at the same location on the foam cylinder model and repeat the process of observation and reflection. Sample prompts from this worksheet are provided in Box 5.

Figure 5: Picture of the foam cylinder model

Hold the bottom disc firmly on a table, and apply a concentrated force as shown below. The force should be horizontal and applied offset from the foam cylinder.



Make a hand-sketch of the deformed cylinder. You can exaggerate the deformation; clearly show the deformed grid lines on the cylinder surface.

Address the following prompts based on the activity above:

1. What type of loading is the cylinder experiencing? Axial, torsional, bending, or some combination?
2. Imagine if we drew small squares at points A, B, C, and D, with their sides initially aligned with the vertical and horizontal directions. As we apply force to the cylinder, try to draw how each "square" would deform. Do they all deform the same way? Pay attention to how spacing and angles change between grid lines on the face of the cylinder.
3. Based on the deformation that you have observed, what types of stress are present at points A, B, C, and D respectively? Are the stresses at each point different from the rest? How is it possible for one force to create different types of stresses?

Box 5: Sample worksheet prompts for the foam cylinder model

Activity E. I -Beam vs Square Beam Demo for Bending and Beam Deflection

The I beam vs square beam demonstration was developed to show students bending the effects of the cross-sectional moment of inertia on the deflection of beams. This demo was made by gluing two styrofoam beams with the same cross-section area but different cross-section shapes to a rigid base, as shown in Figure 6.

While it is quite obvious in calculations that a larger cross-sectional moment of inertia will lead to less beam deflection, not all students intuitively realize that two beams of the same cross-sectional area can have big differences in the moment of inertia and thus have a large difference in deflection when loaded. The I beam vs square beam demo can help students quickly visualize these effects and gain a better understanding of this concept. The guiding worksheet provided to students asked them to apply a tipping load using known weights onto the two beams and compare the observed deformation. Prompts from this worksheet are provided in Box 6.

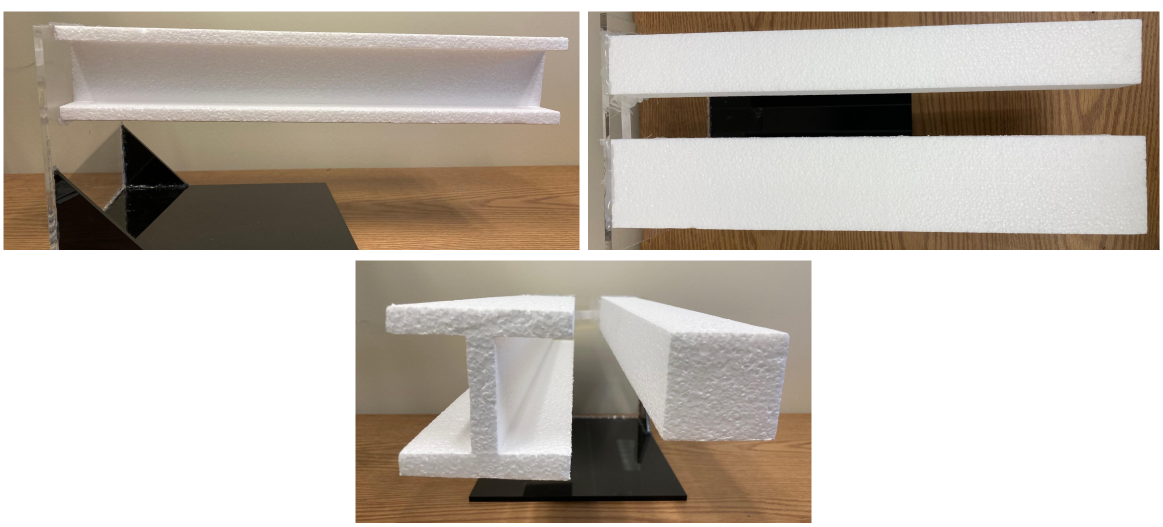
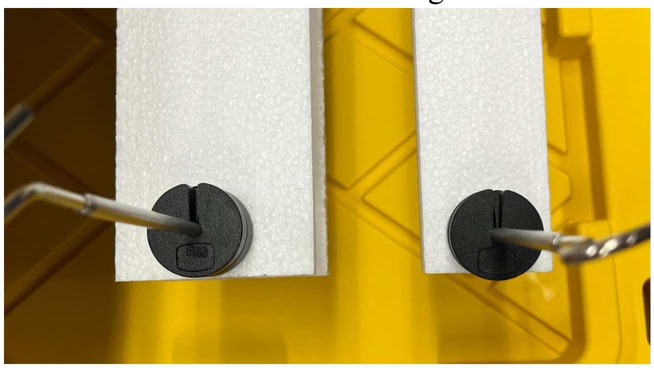


Figure 6: pictures of the I beam vs square beam model
(top -left: side view; top-right: top view; bottom: front view)

Please use the following demonstration tool to investigate the behavior of cantilever beams subjected to a concentrated tip load.
The demonstration tool has two cantilever beams of the same length (17 inches). Each beam also has an equal cross-sectional area (4 in^2), however, one cross-section is square while the other is I-shaped. To apply a tipping load to each of the two beams, place one of the provided weights on the free end of each beam as shown in the figure below.



Observe the deformed shape of the beams and the amount by which the tip of each beam deflects downwards.
Address the following prompts based on the activity above:

1. Which of the two beams exhibits the greatest downward deflection? Why do you think this is the case? Try to list all parameters which will impact the deflection of the beam.
2. Sketch a side view of the deformed square-cross-section beam. Try to describe the displacement and curvature of the beam at each location along its length - in particular, focus on identifying where displacement and curvature are zero, maximum, or minimum. How is tension/compression present in the beam?
3. How does normal stress vary within the cross-section of each of the two beams? Sketch the cross-sectional distributions of normal stress for both beams. Be sure to indicate the location(s) of zero stress, maximum stress, and minimum stress. Which of the two beams will experience larger maximum normal stress?
4. Now place the provided weights in the middle of each beam. Observe the difference in the beams' deflection and curvature (along the entire length of each beam) in comparison to when loading was applied to the tip. Which placement of the weight produced greater deflection? Why is it so?

Box 6: Worksheet prompts for I beam vs square beam demonstration

3. Result and Discussion

Impact of the reading assignment on students' learning outcomes

Data used for the study were the completion of each reading assignment and the hands-on learning IBLA for each student, students' scores on major exams (quizzes, midterm and final exams), and their score on questions about specific concepts. Out of the 99 students in the class, 51 completed at least one hands-on learning activity, while 26 students completed all of these activities; and there were 75 students who completed at least one reading assignment, while 17 completed all reading assignments. T-tests were performed to assess the impact of reading assignment completion on students' scores on quizzes and exams. Results from t-tests are shown in Table 1. The p values gained for T-tests suggest that students achieved significantly higher average scores on some exams after completing reading assignments of chapter 1, 2, 3, 4, 7, 9, and 10, compared to those who did not do the reading assignment. Whereas for the other 3 reading assignments, there was no significant difference between the average scores of students who completed and that of students who did not complete the reading assignments. Also, the p values gained from t-tests suggest that, for the concepts that were tested in specific questions, students did not achieve significantly higher scores on questions testing the specific concepts covered in each reading assignment.

Reading Assignment	Concept Involved	Exam/Question Used to Evaluate of Students' Learning	Average Score of Students who Completed the Reading	Average Score of Students who Did Not Complete the Reading	T-test p value
Chapter 1 Reading	**Stress**	**Final Exam**	**66.6% (n=66, SD=21.9%)**	**57.3% (n=33, SD=24.9%)**	**0.038**
Chapter 2 Reading	**Axial Loadings**	Questions in Quiz 1 and Midterm Exam on the Specific Topic of Axial Loading	58.1% (n=62, SD=25.5%)	49.6% (n=37, SD=29.5%)	0.074
		Quiz 1	80.1% (n=62, SD=19.4%)	78.2% (n=37, SD=17.7%)	0.32
		Midterm Exam	**61.2% (n=62, SD=22.2%)**	**53.9% (n=37, SD=19.7%)**	**0.046**
Chapter 3 Reading	**Torsional Loadings**	Questions in Midterm Exam on the Specific Topic of Torsional Loadings	70.8% (n=50, SD=21.4%)	65.8% (n=49, SD=19.3%)	0.11
		Midterm Exam	**62.2% (n=50, SD=21.0%)**	**54.5% (n=49, SD=21.5%)**	**0.037**
Chapter 4 Reading	**Pure Bending**	**Final Exam**	**70.1% (n=37, SD=19.6%)**	**59.5% (n=62, SD=24.5%)**	**0.01**
Chapter 5 Reading	Bending and Deflection of Beams	Questions in Final Exam on the Specific Topic of Bending and Deflection of Beams	62.9% (n=35, SD=21.1%)	56.0% (n=64, SD=21.1%)	0.065
	Bending in Beams	Final Exam	62.9% (n=35, SD=21.1%)	56.0% (n=64, SD=21.5%)	0.065
Chapter 6 Reading	Transverse Shear	Questions in Final Exam on the Specific Topic of Shear in Beams	73.2% (n=40, SD=28.2%)	67.5% (n=59, SD=30.5%)	0.172
		Final Exam	67.6% (n=40, SD=20.8%)	60.64% (n=59, SD=18.8%)	0.28

Chapter 7 Reading	**Stress Transformation**	**Final Exam**	**69.3% (n=36, SD=21.3%)**	**60.1% (n=62, SD=24.0%)**	**0.027**
Chapter 8 Reading	Combined loadings	Final Exam	66.6% (n=41, SD=22.1%)	61.3% (n=58, SD=23.9%)	0.13
		Questions in Quiz 2 and Final Exam on the Specific Topic of Combined Loadings	57.1% (n=41, SD=28.8%)	50% (n=58, SD=31.7%)	0.13
Chapter 9 Reading	**Deflection of Beams**	Final Exam	68.7% (n=42, SD=22.3%)	59.7% (n=57, SD=23.4%)	**0.027**
Chapter 10 Reading	**Buckling of Column**	Questions in Final Exam on the Specific Topic of Buckling	80.4% (n=43, SD=21.6%)	72.3% (n=56, SD=32.3%)	0.07
		Final Exam	**69.9% (n=43, SD=19.4%)**	**58.6% (n=56, SD=24.9%)**	**0.006**

Table 1: Comparison of Exam Performance between Students who Completed/Did Not Complete Specific Reading Assignments (Bolded rows are the ones has significant difference)

Impact of the IBLAs on students' learning outcomes

Overall, students who completed the IBL activities have performed significantly better on the exams and quizzes than students who did not do the IBL activities. This positive impact is also stronger than the reading assignments completion. In this section, we will discuss students' academic performance on the corresponding questions and exams. A summary of students' performance on quizzes and exams and t-test results are shown in Table 2, and we discuss the details as follows.

Activity A: Foam Tower for Axial and Torsional Loadings

Analysis of students' scores on questions specifically about axial loading in quiz 1 and the midterm exam shows that students who used the foam tower model scored better on axial loading questions at an average of 60.6% with a standard deviation of 25.3%, in comparison to students who did not complete this IBLA and scored 50.4% on these questions with a standard deviation of 28.1%. T-test comparing the means of students' scores on these axial loading questions with a 95% confidence interval gives a p-value of 0.031, indicating that there is a significant difference between students' performance on questions about axial loading depending on whether they have done this IBLA. However, data on students' scores on Quiz 1, which was mainly about axial loading, shows that students who used the foam tower model performed only slightly better at an average score of 79.6% with a standard deviation of 19.4%. In comparison, students who did not complete this IBLA scored an average of 79.3% on Quiz 1 with a standard deviation of 18.3%. T-test comparing the means of students' scores on quiz 1 with a 95% confidence interval gives a p-value of 0.47, indicating that there is no significant difference between students' performance on quiz 1 depending on whether they have used the foam tower model or not. Analysis of student's scores on the midterm exam shows that students who used the foam tower model performed better at an average score of 64.4% with a standard deviation of

21.0%. In comparison, students who did not complete this IBLA scored an average of 53.7% with a standard deviation of 20.9%. T-test comparing the means of students' scores on the midterm exam with a 95% confidence interval gives a p-value of 0.007, indicating that there is a significant difference between students' performance on the midterm exam depending on whether they have used the foam tower model or not.

Activity B: Foam Beam Model for Statically-Indeterminate Beam Deflection

Students' understanding of the concept of statically-indeterminate beam deflections was tested in the final exam. Analysis of students' final exam scores shows that students who used the foam beam model for statically-indeterminate beam deflection performed significantly better on the questions regarding this topic in the final exam at an average score of 67.9% with a standard deviation of 21.0%. In comparison, students who did not complete this IBLA scored an average of 52.3% on these questions with a standard deviation of 26.6%. T-test comparing the means of students' scores on these questions about statically-indeterminate beams with a 95% confidence interval gives a p-value of less than 0.001, indicating that there is a significant difference between students' performance on the questions about statically-indeterminate beams depending on whether they have used the foam beam model or not. The analysis also shows that students who used the foam beam model for statically-indeterminate beams performed significantly better on the final exam at an average score of 74.5% with a standard deviation of 18.8%. In comparison, students who did not complete this IBLA scored an average of 56.6% on the final exam with a standard deviation of 23.2%. T-test comparing the means of students' final exam scores with a 95% confidence interval gives a p-value of less than 0.001, indicating that there is a significant difference between students' performance on the final exam depending on whether they have used the foam beam model or not.

Activity C. Buckling Models

Students' understanding of the concept of buckling was tested in the final exam. Analysis of students' performance on the final exam shows that students who used the buckling models performed significantly better on these questions about buckling in the final exam at an average score of 86.8% with a standard deviation of 15.8%. In comparison, students who did not use this IBLA scored an average of 69.1% on these questions with a standard deviation of 32.2%. T-test comparing the means of students' scores on these questions with a 95% confidence interval gives a p-value of less than 0.001, indicating that there is a significant difference between students' performance on questions about buckling depending on whether they have used the buckling models or not. Data analysis also shows that students who used the buckling models performed significantly better on the final exam overall with an average score of 74.7% with a standard deviation of 18.9%. In comparison, students who did not use this IBLA scored an average of 56.5% on the final exam with a standard deviation of 23.1%. T-test comparing the means of students' overall final exam scores with a 95% confidence interval gives a p-value of less than 0.001, indicating that there is a significant difference between students' performance on the final exam depending on whether they have used the buckling models or not.

Activity D. Foam Cylinder Models for Combined Loadings

Students' understanding of the concept of combined loadings was tested in quiz 2 and the final exam. Analysis of students' scores on questions about combined loadings in quiz 2 and the final exam shows that students who used the foam cylinder model scored significantly better at an average of 63.5% with a standard deviation of 27.2% in comparison to students who did not use this IBLA that scored 44.2% on average with a standard deviation of 30.8%. T-test comparing the means of students' scores on these questions with a 95% confidence interval gives a p-value of less than 0.001, indicating that there is a significant difference between students' performance on questions about combined loadings depending on whether they have used the foam cylinder models or not.

Activity E. I -Beam vs Square Beam Model for Bending and Beam Deflection

Students' understanding of the concept of bending and deflection of beams was tested in the final exam. Analysis of students' scores on questions about bending and beam deflection in the final exam shows that students who used the I-beam vs square beam model performed slightly better at an average score of 76.7% with a standard deviation of 27.3%. In comparison, students who did not complete this IBLA scored an average of 66.8% with a standard deviation of 30.2%. T-test comparing the means of students' scores on these questions with a 95% confidence interval gives a p-value of 0.056, indicating that there is not a sufficiently large difference between students' performance on these questions depending on whether they have used the I-beam vs square beam model or not. Data analysis also shows that students who used the I beam vs square beam demo performed significantly better on the final exam overall at an average score of 73.2% with a standard deviation of 19.5%. In comparison, students who did not complete this IBLA scored an average of 59.2% on the final exam with a standard deviation of 23.6%. T-test comparing the means of students' scores on the final exam with a 95% confidence interval gives a p-value of 0.002, indicating that there is a significant difference between students' performance on the final exam depending on whether they have used the I-beam vs square beam model or not.

Hands-on Learning Activity	Concept Involved	Exam/Question Used to Evaluate of Students' Learning	Average Score of Students who Completed the Activity	Average Score of Students who Did Not Complete the Activity	T-test p value
Activity A	**Axial Loadings**	**Questions in Quiz 1 and Midterm Exam on the Specific Topic of Axial Loading**	**60.6% (n=44, SD=25.3%)**	**50.4% (n=55, SD=28.1%)**	**0.031**
		Quiz 1	79.6% (n=44, SD=19.4%)	79.3% (n=55, SD=18.3%)	0.47
		Midterm Exam	**64.4% (n=44, SD=21.0%)**	**53.7% (n=55, SD=20.9%)**	**0.007**

Activity B	**Statically-indeterminate Beams**	**Questions in Final Exam on the specific topic of Statically-indeterminate Beams**	**67.9% (n=38, SD=21.0%)**	**52.3% (n=61, SD=26.6%)**	**<0.001**
		Final Exam	**74.5% (n=38, SD=18.8%)**	**56.6% (n=61, SD=23.2%)**	**<0.001**
Activity C	**Buckling**	**Questions in Final Exam on the Specific Topic of Buckling**	**86.6% (n=38, SD=15.8%)**	**69.1% (n=61, SD=32.2%)**	**<0.001**
		Final Exam	**74.7% (n=38, SD=18.9%)**	**56.5% (n=61, SD=23.1%)**	**<0.001**
Activity D	**Combined Loadings**	**Questions in Quiz 2 and Final Exam on the Specific Topic of Combined Loadings**	**63.5% (n=45, SD=27.2%)**	**44.2% (n=54, SD=30.8%)**	**<0.001**
		Final Exam	**72.9% (n=45, SD=17.9%)**	**55.6% (n=54, SD=24.3)**	**<0.001**
Activity E	**Bending and Deflection of Beams**	Questions in Final Exam on the Specific Topic of Bending and Deflection of Beams	76.7% (n=30, SD=27.3%)	66.8 (n=69, SD=30.2%)	0.056
		Final Exam	**73.2% (n=30, SD=19.5%)**	**59.2% (n=69, SD=23.6%)**	**0.002**

Table 2: Comparison of Exam Performance between Students who Completed/Did Not Complete Specific Hands-on Learning Activities (Bolded rows are the ones has significant difference)

Discussion

From the analysis, students' learning outcome performance (grades on both overall assessment and topic-specific questions in exams) is highly correlated to whether they have completed the hands-on IBLAs. Students who completed hands-on learning activities performed much better than those who did not. This suggests that hands-on learning activities are beneficial for students' understanding of solid mechanics concepts. Compared to the smaller correlation between reading assignments and students' performance, hands-on learning IBLAs are more effective than reading assignments in facilitating students' learning.

There is a range of different levels of impact of the hands-on IBLAs on students' learning outcomes. Multiple factors could contribute to this result: First, the hands-on IBLAs were graded based on completion not the quality of students' work. This was the case because of the limited availability of TA and graders to grade the extra hands-on learning worksheets. As a result of this limitation, some students may have chosen to quickly complete the hands-on learning activities to get the extra credit awarded for its completion, and did not try to fully understand the concept and objective behind the activities. To reduce the impacts of this limitation, it would be beneficial in future studies to grade the students' completed hands-on activity worksheets in detail.

Second, the fact that the hands-on learning activities are optional extra-credit assignments does not set a good baseline to compare the impact of IBLAs on students learning. Factors such as motivation, and perception of the utility of the IBLAs assignments contribute to their class performance, as well as their decision of doing the extra credits assignments or not. There may be students who were confident about their ability to excel in the class choose not to participate in the hands-on learning activities. Thus some of the students who did not complete any hands-on learning activities still performed very well in exams. In future studies, it will be beneficial to compare cohorts of students that the entire class to be required to complete hands-on IBLAs, to the cohorts that the entire class did not complete the IBLAs.

4. Conclusion

This study has shown that compared to textbook reading, hands-on Inquiry-Based Learning Activities (IBLA) promises a stronger positive impact on student's academic performance on the corresponding topics as a pre-training tool. The hands-on IBLA were given as an optional extra credit opportunity, which posed some limitations on the impact of the study. First, students who have choose to do the optional reading assignments and hands-on IBLA might be students who have higher motivation and/or are able to manage their time well. These students are more likely to perform better than students with lower motivation and/or weaker time management skills. However, on the other hand, some of the students who took the extra credits reading assignments and hands-on learning IBLA were motivated by the extra credits opportunities themselves. Due to limited Teaching Assistants' resources, the grading of the hands-on IBLA is completion-based instead of performance-based. Thus, the quality of the IBLA completion was not differentiated. Secondly, the impact of the IBLA is studied in delayed tests (quizzes, midterm, and final exams) a few days to a few weeks after they completed the IBLAs. There are many other factors that can compensate for the impact of IBLAs, such as longer studying time and more study efforts. Our future research efforts will attempt to minimize such limitations by establishing baseline performance by giving prerequisite exams at the beginning of the quarter, as well as use more immediate tests after the IBLA competition, rather than relying on the delayed tests.

A note for for instructors is that the successful implementation of IBLAs can be labor intensive and time consuming. In our pilot study, students often have questions on the IBLA itself or the worksheet questions. Thus, having instructors and TA present to clarify those questions is important.

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