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Implementing Interactive 3-D Models in an Entry Level Engineering Course to Enhance Students' Visualization

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Abstract

The ability to evaluate engineering elements, identify expected deformations, and predict possible failure mechanisms are critical skills for engineers. However, it has been observed that many undergraduate engineering students in applied mechanics courses struggle with applying these skills in engineering problems. Previous studies have shown that three-dimensional (3D) visualization can help students to improve spatial understanding, learn material more permanently and improve their creativity. In an attempt to build on this phenomenon, interactive 3D models using Augmented Reality (AR) were incorporated in a Mechanics of Materials course. This course is an entry level course and a major requirement for different engineering disciplines such as Civil, Mechanical, Biomedical, Materials Science, and Manufacturing Engineering. Two levels of learning were targeted in this study; applying and creating. For applying, 3D models were made available that could be viewed on a smartphone using an AR application or on a computer. The models were generated for problems that students in previous years found challenging or expressed difficulty in visualizing. Students were then encouraged to use this model to inform their problem solving. For creating, students were given the opportunity to generate 3D models based on textbook examples, indicate types of stresses and display deformed shapes. For both activities, student perceptions, best practices, and lessons learned are noted. Students were also asked to provide feedback about their experience and the effectiveness of AR models in their learning in class evaluation surveys. To evaluate the effect of using 3D models on students' performance, an independent study was conducted with students in the Mechanics of Materials course. In this two-problem study, one group only had access to a traditional two-dimensional (2D) schematic, while the other group had access to a 3D model. The experimental and control groups were then swapped for the second problem. The results of this initial study revealed that 3D models can significantly improve students' performance. It is anticipated that discussing the benefits and challenges associated with incorporating such activities, along with providing suggestions for incorporation, will help other institutions add similar activities to their engineering courses in an effort to improve student learning.

Introduction

It is critical for engineers to recognize the actual shape of elements from 2D drawings, identify potential applied loadings scenarios on structural elements, and predict the expected deformation and possible failure mechanisms. The ability to visualize and manipulate objects in one's mind is a vital skill in engineering [1]. Previous studies have shown that accurately visualizing objects in 3D improves spatial understanding [2], which has been associated with success in engineering programs. However, students often tend to struggle with 3D visualization due to a lack of training [3]. One option for improving visualization and spatial skills is providing opportunities for students to interact with handheld models. However, there is often not sufficient time or resources available to allow students to interact with handheld models in large classes [4]. In recent years, virtual reality (VR) and augmented reality (AR) have emerged as promising methods to incorporate 3D visualization in the classroom [5]. This visualization can help students learn the material permanently and improve their creativity [6]. The rapid advancement of new technologies—combined with the exponential increase in the computation power of personal computers and devices—has presented our education system with a unique opportunity to incorporate such creative educational methods on a broad scale, which was out-of-reach less than a decade ago.

Experiences such as AR/VR have significant potential to transform undergraduate engineering education by providing learning experiences in which students interact with complex engineering problems in an immersive, low-risk environment [7]. Using AR/VR in education is an alternative option to improve learning through increased engagement and immersion [8]. Interacting with 3D models that simulate the real-world is an exceptionally powerful educational tool because it is how the human perceptual system is accustomed to processing real-world environments [9]. While both technologies have a multitude of applications within higher education, AR is particularly attractive at an undergraduate level due to the low cost required for implementation. VR completely immerses users in a virtual world, which requires the use of a headset. Not only does this add cost, but it can be prohibitive in large class sizes with short class times and limited space. AR technology superimposes virtual objects upon the physical world [10], often using a computing device with both a camera and a viewing screen. Today, most cellphones have the hardware and operating systems required for supporting AR applications. Using technology readily available to students enables the widespread application of this technology in the classroom.

To build on this phenomenon, interactive 3D models using AR were incorporated in a flipped style Mechanics of Materials course. This entry level undergraduate course is taken by most engineering majors (Civil, Mechanical, Biomedical, Material Science and Management and Manufacturing Engineering). There were two levels of learning targeted; applying and creating. For creating, students were given the opportunity to generate 3D models based on textbook examples, indicate types of stresses, and display deformed shapes. The generation component of the course was optional and was evaluated qualitatively by student perceptions of the activities. For applying, AR models viewable on a smartphone as well as 3D models viewable on a computer were generated for problems that students found challenging or expressed difficulty in visualizing in previous years. Students were then encouraged to use these models to inform their problem solving. The implementation of both the applying and creating components occurred throughout the semester and were evaluated in an initial and end of semester survey.

To evaluate the impact of using AR models on student performance, a separate IRB reviewed study was conducted with students enrolled in the course. The study compared the performance of two groups solving two engineering problems. For the first problem, one group was given a 3D AR model (experimental group) showing the geometry of the subject of the problem while the other group received a 2D representation of the same problem (control group). For the second question, the experimental and control groups were swapped. A series of analytical and conceptual questions were answered by students. They also responded to survey questions at the end of each problem related to their confidence level in solving the different aspects of the problems. Statistical analysis was used to interpret the results of the study.

This paper reviews the motivation for incorporating interactive 3D modeling in the course, an overview of how modeling was incorporated, and student perceptions of the activities as well as the design, results, and major findings from the study on the effectiveness of AR. It is anticipated that discussing the benefits and challenges associated with incorporating interactive 3D models in the classroom, along with providing suggestions for incorporation, will help other institutions add similar activities to their engineering courses in an effort to improve student learning.

Background & Motivation

The course targeted for implementation of AR was Mechanics of Materials, which was selected for numerous reasons including: 1) high enrollment, 2) diverse engineering disciplines, and 3) the flipped nature of the course. The flipped class offers the opportunity to target higher learning objectives such as analyzing, evaluation and creation based on Bloom's taxonomy [11, 12]. The flipped version of the Mechanics of Materials course was developed in 2013. The traditional course contents are presented via online, pre-recorded videos. The class time is assigned to a short review of the contents followed by discussion and problem-solving activities by the students and instructor.

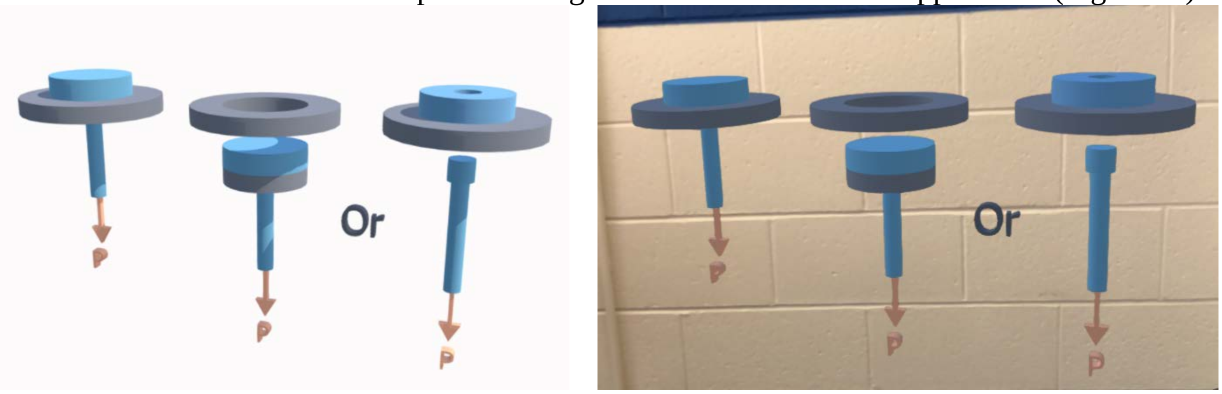
It was noticed by the instructor that students may judge an engineering problem poorly due to a lack of 3D visualizations skills. Therefore, in previous years, different methods were employed to strengthen this skill. Some simple models were built out of foam and colored properly for topics such as elements under axial loading, twisting, and bending. The instructor uses these models to display the loading, deformation, and potential failures. Most students expressed in the class evaluation that these models are helpful to grasp the materials better. Due to the large class size and the classroom setup, students do not have the opportunity to interact with the models first-hand. Another strategy employed to improve students' visualization is displaying pictures of real-life applications of engineering topics or catastrophic designs. These pictures are presented during the class discussion and students are asked to identify types of loading, stresses, and causes of failures. However, it is still challenging for some students to participate in the discussion due to lacking visualization skills.

As an alternative method to enhance student's visualization skill, 3D computer models along with AR were employed to display basic engineering concepts, real-life examples, and complicated structures. AR is a technology that overlays a digital representation over a view of the physical environment. This is accomplished by using a computing device, such as a smartphone, that has both a camera and a viewing screen, and an app with the AR technology built in. In the application, the user points the camera at the area of interest in the physical world, and then virtual elements are overlaid in the display [13]. AR offers the opportunity to look at the models from different views, zoom in on parts of the structure and interact with the models. This allows for students to interact with realistic digital objects when the bounds of the traditional classroom environment may not allow for this exploration [14].

Implementation of 3D modeling

For implementation, a few challenging problems that former students had difficulty in visualizing from each chapter of the textbook were selected. SketchUp 3D modeling software was used to build the corresponding models. There were three possible methods to make these models accessible to students including 1) a VR headset, 2) Sketchfab applications on a smart device, or 3) models displayed on the class projector. VR headsets were not used due to the large class enrollments, which would require additional coordination to be able to provide and collect 100 headsets in each lecture. In addition, class times may not be used efficiently while asking students to wear headsets.

The Sketchfab application was a practical option to share 3D models with students and offer them the opportunity to interact with models in AR. Students were asked to install this application on their cellphones or tablets. All available 3D models were launched and stored in this application. The instructor guided students to locate these models, interact with them, and discuss the engineering solution during lecture. The 3D models had magnified displacements to allow students to easily visualize the deformation. While magnifying the displacements makes the models less "real", it helps students to understand how deformation occurs in the object, similar to the method of using physical foam models. A sample view of an AR model from the course being viewed on a computer and in AR is shown in Figure 1a and b, respectively. There were minimal technical challenges when using the Sketchfab application in class. One such challenge was that students with older cell phones, approximately 5 students out of over 100, were unable to use the AR feature (Figure 1b). However, these students were still able to view and rotate the model on their cell phones using the online viewer in the application (Figure 1a).



(a) (b)

Figure 1. Sample visualization of viewing 3D model in Sketchfab using a) the online viewer and b) the AR phone application.

Students' Feedback

Students were asked in the class initial survey to express their opinion on the following statement of "The 3D models available in Sketchfab application (Augmented Reality) are beneficial for my learning and help with my visualization". Total of 111 students responded to this question. Figure 2 below shows the results.

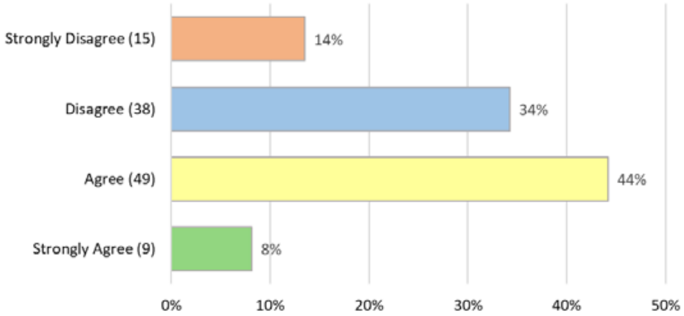


Figure 2. Responses from initial class survey on if AR models are beneficial to learning and help with visualization.

Approximately 52% of students agreed or strongly agreed that using AR is helpful. However, as 48% of students did not find the activity helpful, student suggestions were incorporated to improve the effectiveness of this tool. For example, students expressed that they do not prefer using their cellphone during class to get access to the models via the application. They suggested that it is more efficient if instructor displays the 3D models using the projector and explains relevant concepts during the demonstration. It was also found that providing QR (Quick Response) code of available 3D models (stored on the Sketchfab website) makes it easier for students to navigate and interact with the models.

Per the students' suggestions, in the second half of the semester the class projector was used to interact with the 3D models relevant to each topic (Figure 3). The instructor displayed models, showed different views, and used them as part of the lecture. It is anticipated that using the projector was beneficial due to the size of the display. This allowed students to more easily view complex details on the models compared to trying to see the details on smaller cell phone displays. The students still had access to the models in Sketchfab and had the opportunity to view the models after class either in AR or on a computer.

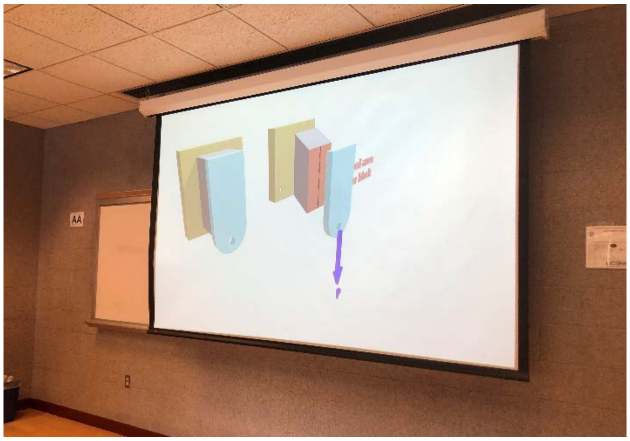


Figure 3. Demonstration of 3D models in Augmented Reality using Computer and Projector

In the final Student Evaluation of Teaching, students were asked again about the effectiveness of AR and 3D modeling in their learning. After the changes in presentation were made, more than 70% of responders found the activity helpful compared to the 52% in the initial survey. Students were asked to suggest other activities to enhance their visualization and share methods to improve the implementation of the AR (or 3D modeling) activity in the class. They expressed adding animation features to 3D models to show deformations or potential failures could improve their experience. They also expressed that physical 3D models (foam models or 3D printed models) would enhance their visualization skills.

Students experience in creating models

An optional activity was offered to students to either create 3D models of textbook problems, display loads and deformations, or conduct a comprehensive analysis a real-life example for an available 3D model. The purpose of this bonus activity was to encourage students to learn how to draft objects in SketchUp (or other drafting software), enable them to expand a 2D view of a structure to its 3D version, contribute to the expansion of available 3D models from the textbook to form a library of models, and evaluate an actual designed object by implementing their knowledge from the Mechanics of Materials course. The class time did not allow the instructor to provide training on 3D modeling to students. However, training videos were provided on the course website and a teaching assistant (10 hours per week) was assigned to assist students.

Approximately 31% of the class population participated in this activity. Low participation in this activity could be attributed to the bonus nature of it and the fact that students were asked to learn this skill on their own.

Effect of AR models on student performance

Overview of study

To evaluate the effectiveness of AR models in improving student understanding of problem geometry and potential failure modes, a study was developed and was conducted midway through the course offering. The optional study took place during one 50-minute class period and involved solving two multi-step engineering problems. Participants were split into two groups (Group A and B) to balance for major, academic year, and their existing level of performance in the class (based on self-reported Exam 1 grade). The two groups were asked to solve the same engineering problem with the same problem description. One group was given only a 3D AR model showing the geometry of the subject of the problem while the other received only a 2D drawing. For the second problem, the visualization tool (AR vs 2D) was switched between the groups to swap the experimental and control groups. The engineering problems were multi-part to evaluate if students were able to 1) identify the engineering concept, 2) recognize key parameters in the problem and their corresponding values from the problem statement, 3) predict the failure point based on the location of maximum stress/strain, and 4) obtain the final correct answer for the problem. For brevity, only a subset of the questions and survey responses directly related to visualization will be presented.

The demographics of the participants in each group are shown below in Tables 1-3. While an effort was made to balance for GPA, major, and performance on Exam 1, some students who filled out consent forms did not show up for the study. In addition, four participants were excluded from the results. The exclusion criteria were if a participant did not attempt either question 1 or 2 and did not provide any survey responses for the corresponding question. The total number of participants in Group A and B were 60 and 64, respectively.

Table 1. Breakdown of participants in groups by major.

Group	Mechanical	MEM	Materials Science	Biomedical	Civil	Other
A	43	3	2	3	6	3
B	41	5	3	4	9	2

Table 2. Breakdown of participants in groups by academic level.

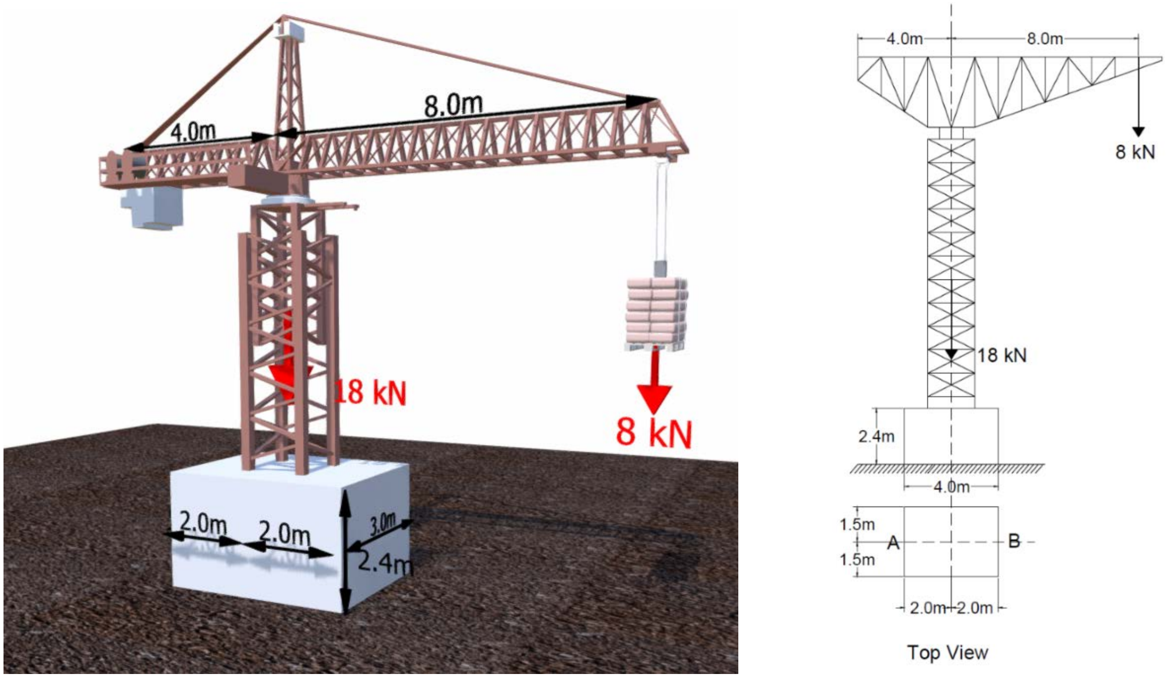
Group	Sophomore	Junior	Senior
A	4	51	5
B	3	54	7

Table 3. Breakdown of participants in groups by grade on Exam 1.

Group	A	B	C	D	F
A	22	21	6	8	3
B	20	17	14	5	8

The two problems given to students were based on material that they were tested on earlier in the week during their midterm exam. The questions also focused on different topics to ensure having the 3D model for one question would not affect their performance on the other question. Both questions will be briefly reviewed to put the results in context.

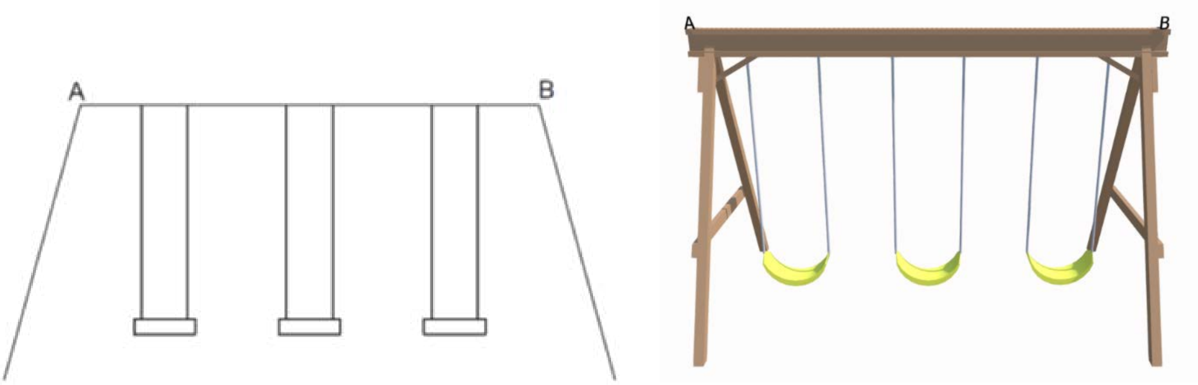
Problem 1 focused on eccentric loading. The problem description was “The crane shown in the model is lifting an 8-kN object. It is installed on a concrete foundation with length of 4 m, width of 3 m, and depth of 2.4 m. The total weight of crane itself is 18 kN and it is being applied at the center of crane’s tower”. Views of the visualizations provided to Group A and B are shown in Figure 4a and b, respectively. The specific question studied was, “If this crane lifts a load larger than its capacity, list the possible modes of failure that may occur (list what comes to your mind).” Problem one was scored based on the number of correct failure modes identified by students, i.e. the number of points awarded was the same as the number of correct failure modes listed.

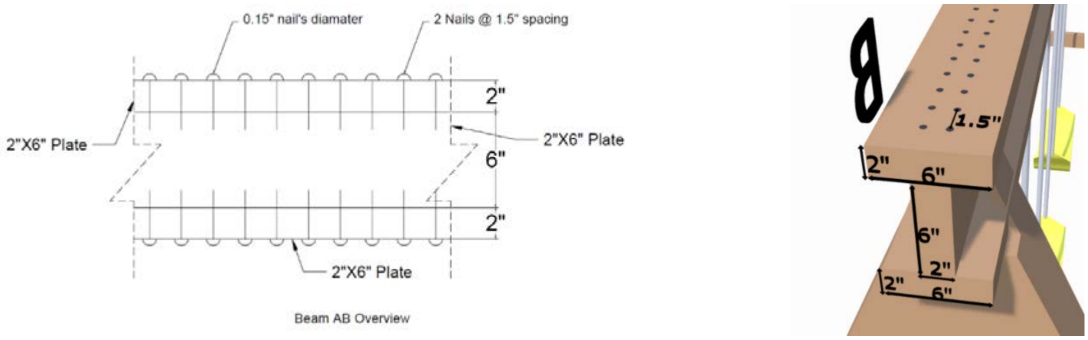


(a) (b)

Figure 4. View of visualizations provided for problem 1 including a) screen shot of 3D model given to Group A and b) 2D schematic given to Group B.

Problem 2 focused on shear flow. The problem description was “The horizontal beam AB support three swings. The beam is made of three pieces of wooden planks. All the planks are 2” × 6“. Two nails are used to connect each flange to the web. Nailing is repeated with spacing of 1.5” along the length of beam.” Views of the visualizations provided to Group A and B are shown in Figure 3a and b, respectively. The specific question studied was, “Draw the cross section of the beam and show the nailing details on that.” Problem two was scored by assigning either 0, 0.5, or 1 based on if the students got the wrong, partially correct, or correct, respectively. Partial credit was given if students drew the cross section correctly but did not correct identify the nailing detail.





(a) (b)

Figure 5. View of visualizations provided for problem 2 including a) 2D schematic given to Group A and b) screen shot of 3D model given to Group B.

Results

The results for Problem 1 are shown in Table 4. The number of students from each group that listed different numbers of failure modes (1 through 6 modes) were reported. An equal variance T-Test was used to compare the responses of the two groups based on the result of Levene's test for Equal Variances. The null hypothesis for the T-Test was that there is no difference in the performance of the two groups at a 5% significance level (95% confidence level). The results of the T-Test are shown in Table 5.

Table 4. Breakdown of Scores on Problem 1 by Group.

	Number of Correct Failure Modes						
	0	1	2	3	4	5	6
Group A	3	12	8	16	16	4	1
Group B	9	16	11	18	6	3	1

Table 5. T-Test Results for Problem 1.

	Group A (3D)	Group B (2D)
Mean	2.767	2.141
Variance	2.046	2.155
Observations	60	64
Hypothesized Mean Difference	0	
df	122	
t Stat	2.403	
P(T<=t) two-tail	**0.018***	
t Critical two-tail	1.980	
*5% significance level, ** 1% significance level		

As the p value is less than 0.05, we can reject the null hypothesis that there is no difference between the performance of the groups. This suggests that the 3D model was beneficial in the students reporting a higher number of correct potential failure modes. However, Group A had a slightly higher average score on exam one compared to Group B (2.85 vs 2.56, on 4.0 GPA scale). To ensure the higher score did not impact the results, an ANOVA analysis was conducted to compare the effect of both score on Exam 1 and group (i.e. 2D vs. 3D model). The scores on Exam 1 were separated into three approximately equal groups: students who received A's, students who received B's, and students who received C's or lower. The ANOVA analysis was originally run assuming interaction between the groups and grade on Exam 1, but this termed was removed once it was deemed insignificant in the first analysis. Tables 6 and 7 show the model summary and results of the ANOVA analysis, respectively. It was found that there is a statistically significant effect from the Group (2D vs. 3D) on the number of failure modes, but the effect of grade on Exam 1 is not significant. This suggests that the visualization tool provided will affect students' performance, but their grade on Exam 1 is not necessarily a predictor of how they will perform on this question. Figure 6a and b show the effect of group and the interaction plot for grade on Exam 1 and group on the results.

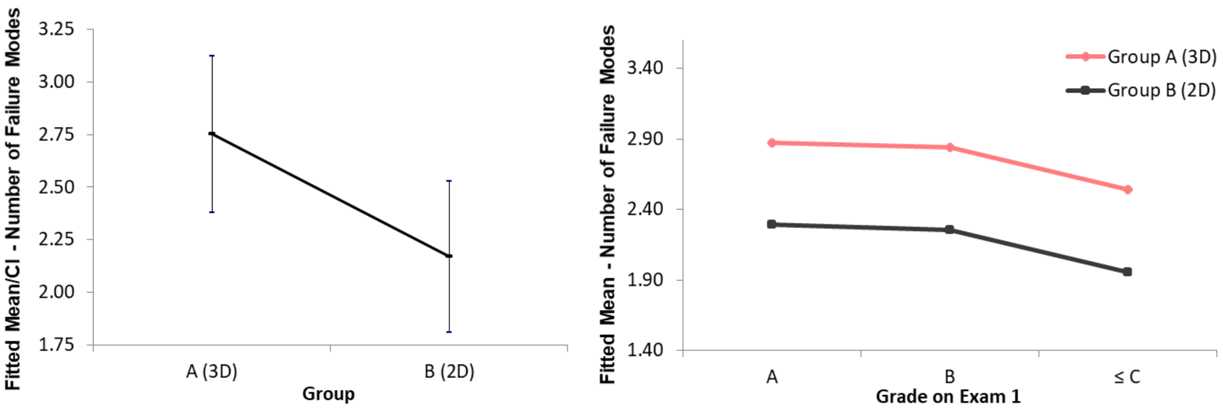
Table 6. Factor and Model Summary for Two-Way ANOVA for Problem 1

Number of Levels - Groups	2
Number of Levels - Grade on Exam 1	3
Number of Replicates	N/A
Design Type	Unbalanced
Confidence Level	95
R-Square	5.57%
R-Square Adjusted	3.21%
S (Pooled Standard Deviation)	1.454

Table 7. Analysis of Variance Results for Problem 1 ANOVA

Source	df	SS	MS	F	**P**
Group	1	10.287	10.287	4.867	**0.029***
Grade on Exam 1	2	2.827	1.414	0.669	0.514
Error	120	253.64	2.114		
Total	123	268.60	2.184		

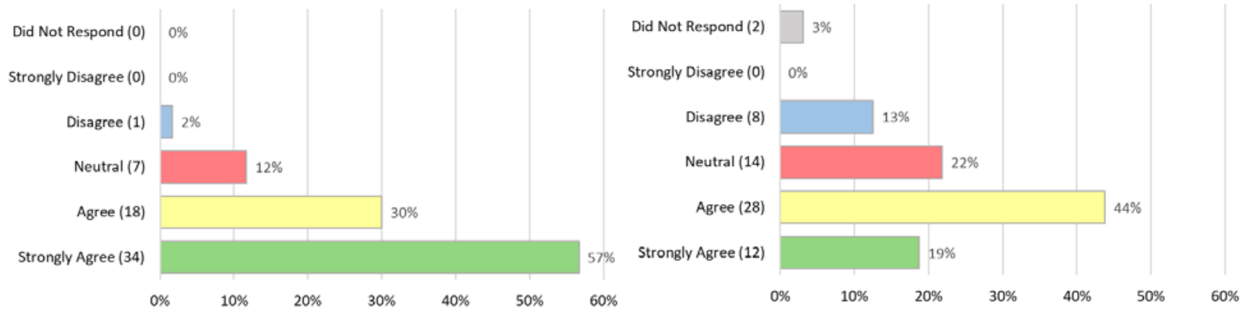
*5% significance level, ** 1% significance level



(a) (b)

Figure 6. ANOVA results for Problem 2 showing a) the effect of group on number of failure modes and b) interaction plot for number of failure modes, Group, and score on Exam 1.

In addition to answering the question, students were asked to rank their level of comfort in understanding the project geometry. The survey responses to the question for Group A and B are shown in Figure 7a and b, respectively. In general, total of 87% of students in Group A noted they either agreed or strongly agreed that it was easy for them to understand the geometric parameters. Only total of 63% of students from Group B found it easy (agreed or strongly agreed) to comprehend the problem by having access to 2D model.



(a) (b)

Figure 7. Survey responses from Problem 1 noting the ease of understanding the project geometry for a) Group A with the 3D model and b) Group B with the 2D model.

Problem 2 required students to visualize and correctly identify the correct cross section based on the visualization and problem statement provided. The results for Problem 2 are shown below in Table 8. It is immediately clear that students in Group A struggled with the problem, with over 56% of the students getting zero credit. As the scores for Group A were not normally distributed, a Mann-Whitney test was used to interpret the results. The null hypothesis is that there is no difference between the medians. The results of the Mann-Whitney Test are shown in Table 9. Given the P-value of 2.27E-06, we can conclude the difference in median score is statistically significant between the two groups.

Table 8. Breakdown of scores on problem 2 by group.

Group	0 (Incorrect)	0.5 (Partially Correct)	1 (Correct)
A	34	16	10
B	7	36	21

Table 9. Mann-Whitney Results for Problem 2.

	Group A (2D)	Group B (3D)
Count	60	64
Median	0	0.500
Mann-Whitney Statistic	2884.00	
Exact P-Value (2-sided)	**2.27E-06****	
*5% significance level, ** 1% significance level		

As group A had the higher average score on Exam 1, it is more telling that Group B (3D model) substantially outperformed Group A on this question. This may also suggest 3D models are most beneficial on problems with more complex geometries. It should also be noted that the students' performance on Exam 1 was correlated to their performance on Question 2, with the average score on Problem 2 improving with the Exam 1 score. While an ANOVA analysis could not be used, the Mann-Whitney test was repeated for students who received the same score on Exam 1 (A's, B's, C's or lower) (Table 10). The results show that the 3D model consistently resulted in significant differences between Group A and B for each set of Exam 1 scores.

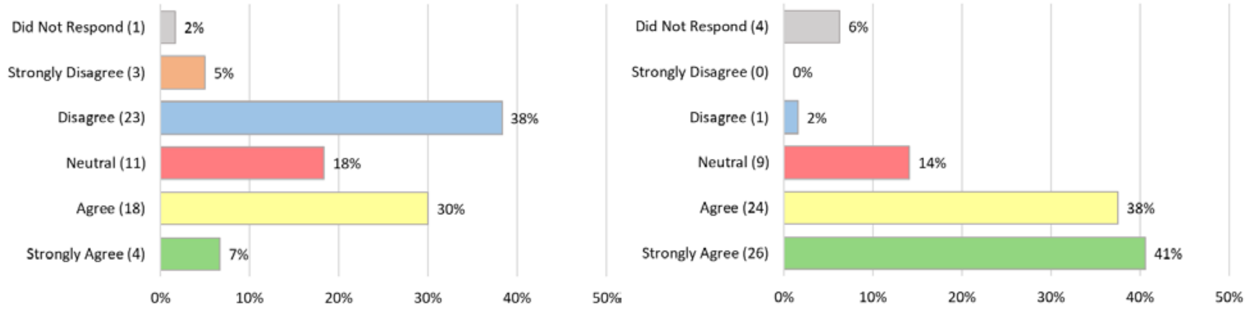
Table 10. Average Score separated by Grades on Exam 1 for Problem 2.

	A on Exam 1		B on Exam 1		C or Below on Exam 1	
	Group A (2D)	Group B (3D)	Group A (2D)	Group B (3D)	Group A (2D)	Group B (3D)
Count	22	20	21	17	17	27
Median	0.500	1	0	0.500	0	0.500
Mann-Whitney Statistic	387.00		296.00		278.50	
Exact P-Value (2-sided)	**0.0208***		**1E-04****		**0.0078****	

*5% significance level, ** 1% significance level

Another interesting finding from this study is how the partially correct answers differed between groups. In Group A with the 2D drawing, 100% of students who received partial credit only showed one nail in the top and bottom flanges. For Group B, students received partial credit for a variety of cases including only showing the nails on the top flange (67%), showing an incorrect spacing of the nails (17%). showing one nail on the top and bottom flanges (11%), or not showing any nails (6%). The most common mistake for Group B was not including the nails connecting the bottom flange to the web even though the problem statement that noted, “Two nails are used to connect each flange to the web”. This may suggest that having the 3D model could make students feel overly confident in the answer and pay less attention to the problem statement or think less critically. This also suggests that the students did not fully examine the model, which included nails along the bottom flange.

In addition to answering the question, students were asked to rank their level of comfort in understanding the project geometry. The survey responses for Group A and B are shown in Figure 8a and b, respectively. Students in Group B were substantially more confident in understanding the project geometry compared to Group A, which was reflected in their respective scores on the problems. A total of 79% of students in Group B noted they either agreed or strongly agreed that it was easy for them to understand the geometric parameters. Only 37% of students from Group A found it easy (agreed or strongly agreed) to comprehend the problem by having access to 2D model. The survey also showed that Group B participants were quite confident in their understanding, despite many of the students making minor errors in understanding the nailing details in the problem.



(a) (b)

Figure 8. Survey responses from Problem 2 noting the easy of understanding the project geometry for a) Group A with the 2D model and b) Group B with the 3D model.

Conclusion

The following findings were concluded from this study:

- Demonstrating 3D models in AR can be accomplished by building models in a 3D modeling software such as SOLIDWORKS or SketchUp and launching them in the Sketchfab application. More than 70% of students found that AR 3D models are beneficial to their learning, but they expressed that it is preferred to see 3D models on the projector rather navigating on their cellphone. They suggested that integrating the discussion of the 3D models with the lecture helps their learning.
- Only 31% of students participated in generating 3D models on their own time. Low reception of this activity can be attributed to the optional nature of this activity and the fact that students were responsible to learn 3D drafting on their own from instructional videos (available on the course website). Future studies should consider if increasing the participation in this activity, either by increasing the extra-credit incentive or making it a required part of the course, may increase students’ geometric comprehension.
- The study on the impact of AR on students’ performance revealed that students with access to 3D models performed better in identifying failure modes and project geometry compared to the students with access to 2D models. The improvement in performance was evident for students of all performance levels on Exam 1. This finding could be further examined by having additional information on the students’ performance in the course such as their final grade or score on Exam 2.
- For Problem 1 in the study, a total of 87% of students with access to the 3D model either agreed or strongly agreed that it was easy for them to understand the geometric parameters of the problem. Only 63% of students with access to 2D models found it easy to comprehend the problem. For Problem 2, 79% of students with the 3D model reported they were comfortable with the problem geometry compared to 37% of those with the 2D model. For both problems, students felt more confident in understanding the project geometry when they were provided the 3D model. However, the extreme difference in responses for Problem 2 compared to Problem 1 may suggest that 3D models are most beneficial for problems with greater complexities.
- While the study provided preliminary data showing incorporating AR improved student performance in identifying failure modes and understanding project geometry, additional

research is required to show the results are repeatable. As such, the test will be repeated in future course offerings to evaluate and validate the testing instrument.

- To respond to students' interest in interacting with handheld models, the creating aspect of 3D modeling will be expanded in future course offerings to allow students to print the models, interact with them, and share them with the class. In addition, future studies may compare the performance of students who create and view AR/VR models to those who build and interact with physical models. This would allow for a comparison of 3D physical and 3D virtual tools to inform future course development.

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