



The Implementation of Virtual Labs in Aerospace Structures Education

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Abstract

Virtual laboratories are valuable resources to support students' learning in engineering and science. They allow students to perform experiments with minimum resources, be prepared for other hands-on activities or lectures, and better understand the conceptual knowledge of the discipline. Due to those benefits, the School of Aeronautics and Astronautics at Purdue University has been implementing virtual labs in the lab course of AAE 20401 Aeromechanics II. AAE 20401 is an aerospace structural mechanics lab course for second-year students where they had the opportunity to use the Virtual Lab software. When implementing the Virtual Labs, we characterized the content, assessment, and pedagogy of the course under the Backward Course Design Model to identify how the Virtual Lab software could be integrated into the coursework. After a year of getting feedback on the software from the students and investigating the pedagogical approaches on how to use it, we introduced a new format on the use of the virtual lab in Fall 2019. This paper describes the latest version of the lab course with the integration of the Virtual Lab software. The curriculum design, presented in this paper, is a useful reference for educators who seek to integrate virtual technologies into their new or existing laboratories.

1. Introduction

The School of Aeronautics and Astronautics (AAE) at Purdue University recently experienced a dramatic surge in new undergraduate student enrollment. One of the difficult tasks is to accommodate the increased number of students with physical facilities that were built for fewer students. To this end, we proposed a countermeasure to cope with the situation without increasing the physical lab space by creating a virtual lab (VL) space. We had several thoughts on the possible positive outcomes as a result of the VL implementation. First, VLs could improve the educational efficiency during the hands-on lab if students complete VLs as a part of pre-lab assignments. This means that physical lab may take less time; therefore, we can accommodate larger number of students. Second, any enrolled students can use VLs anytime, which means that the restrictions to gain hands-on experience on the physical lab apparatus can be compensated by the use of VLs. Third, VLs can address problems for those experiments that cannot be reasonably performed during hands-on labs due to space limitations (e.g., experiments with very large or very small specimens), due to time limitations (e.g., fatigue experiments that takes several days to complete), and due to safety limitations (e.g., experiments with dangerous chemicals). These are positive consequences of VLs that we foresaw.

In Fall 2018, we implemented VLs for AAE 20401, Aeromechanics II Laboratory, a one-credit lab course for the aerospace engineering students. However, we were unable to confirm the educational effectiveness of VLs since we implemented VLs without the Scholarship of Teaching Learning (SoTL) research activities. Therefore, in Fall 2019, we initiated the SoTL research project on the implementation of the AAE 20401 VLs. Since we wanted to pursue the excellence in VLs by creating the innovative virtualized lab of the existing hands-on labs, we used the Backward Course Design Model to analyze and characterize the course context, content,

assessment, and pedagogy of the course so that we can integrate VLS into the existing lab coursework smoothly. However, no matter what aspect of VLS we choose to implement or what specific approach we choose to pursue for the VLS implementation, the objective of creating the VLS space remains the same: VLS must improve the quality of education for students, which is the thesis of the virtual lab project. In order to achieve this thesis, we want to answer the following research questions.

- a) How did students perceive VLS?
- b) What connections did students make between VLS and Physical Labs?

2. Literature Review

One of the earliest use of VLS in higher education was Project Athena at Massachusetts Institute of Technology (MIT) [1]. Project Athena began in 1983 to improve the educational quality for students at MIT. In Project Athena, MIT researchers used the philosophy of “gedankenexperiment” (German for “thought experiment”) [2], a term coined by German-born physicist Albert Einstein to create the theory of relativity conceptionally, rather than physical experiments [3]. Project Athena at MIT was an educational experiment to use advanced computers throughout MIT’s academic departments [2]. Interestingly, Project Athena was meant to be for nonprogramming courses since the programming courses at MIT were already utilizing, and had a great access to, computers [4].

Another earlier use of VLS was introduced by William Wulf in 1989 [5] as “Collaboratory,” which was a combined word of collaboration and laboratory, where scientists to “perform their research without regard to geographical location” [6], [7]. Wulf intended VLS to be a collaboration tool that allows “interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries” [8].

Since the initial introductions of the VLS concepts, research on the effectiveness of VLS confirmed that properly designed virtual simulation tools can enhance students’ learning processes [9], [10]. As a result, VLS have been implemented and/or studied across the wide variety of disciplines, such as life science (e.g., biology) [11], [12], [13], [14], [15], physical sciences (e.g., physics and chemistry) [16], [17], [18], [19], [20], mathematics/computer sciences [21], [22], [23], [24], [25], and engineering [26], [27], [28], [29], [30]. However, we will need to be careful when using the term “virtual lab” since there is no set definition for “virtual lab.” For instance, in some papers, the term “virtual labs” refers to the remote operation of physical labs [31], [32].

Furthermore, we identified that in certain cases, the term “virtual lab” is used in place of “simulation” especially for those fields that are numerical in nature [33], [34]. One of such fields is the mechanics education in aerospace, mechanical, and civil engineering [35], [36]. We found this observation to be interesting because the use of finite element method to solve problems is essentially an elaborate (i.e., more rigorous) approach to solving mechanics problems. In other words, if students understand how to setup a computer model in a finite element (FE) software, apply a load and boundary conditions, and complete the FE analysis, the use of VLS becomes unnecessary. Thus, at this point, we realized one of the potential target audience for the VLS use:

VLs are effective in educating undergraduate aerospace/mechanical/civil engineering students who are trying to learn the basis of mechanics of materials. That is, the use of VLs is a great bridge between the first-year engineering students who have not had any exposure to structural mechanics and fourth-year engineering students who have experienced both hands-on experimentation and some simulation.

The process of the Backward Course Design Model, according to Wiggins and McTighe [37], is i) to identify the desired outcome at the beginning of designing a course, ii) to assess evidences, and iii) to design the learning experience and instructions. This process stems from the fundamental philosophy of the Backward Course Design: Focus on the outputs of the instruction, rather than the instruction itself, when designing a course [37]. That is, the primary attention in education must be paid on student learning and understanding, not instructor teaching. Thus, the Backward Course Design Model provides a framework for an effective curricular designing and redesigning [37], [38], [39]. Based on the literature review presented above, we used the Backward Course Design Model to analyze and characterize the course context, content, assessment, and pedagogy of the course so that we can design and implement the VL software as a part of effective learning tool for the Purdue AAE students.

3. Methods

In order to incorporate the use of VLs as a part of curriculum, we analyzed the course context of AAE 20401, Aeromechanics II Laboratory. Furthermore, we characterized the course content, assessed student learning, and developed the pedagogy of the course using the Backward Course Design Model [37] so that we were able to identify how VLs could (and should) be integrated into the curriculum. Using the knowledge we gained from these analyses, we integrated VLs as a part of AAE 20401 curriculum during the Fall 2018 semester as a preliminary implementation followed by a full-on implementation with the SoTL activities during the Fall 2019 semester. For SoTL results and discussion on the research questions, please see the subsequent section.

Course Context

AAE 20401, Aeromechanics II Laboratory, is a one-credit laboratory (lab) course in aerospace structural mechanics at Purdue University. The lab course offers six lab preparatory lectures and six physical (hands-on) labs. The durations of the lectures and labs are 50 minutes and 110 minutes, respectively. During the lab preparatory lecture session, a faculty member delivers a lecture. Then, at the beginning of the physical lab sessions, graduate teaching assistants (TAs) leads the guided physical lab sessions. All individuals in the teaching team are Purdue AAE members. Table 1 shows the summary of AAE 20401 using abstract terms in Structural Mechanics. The course provides the students with the opportunities to conduct guided hands-on experiments on the mechanics of materials. Through conducting experiments and understanding the fundamental behavior of materials, the enrolled students will be in a better position to understand the fundamentals of structures and materials as well as the basic engineering requirements used in the aerospace vehicle design.

Table 1: Summary of Aeromechanics II (AAE 20401) Labs

Lab #	Lab Title	Abstract Terms in Structural Mechanics
1	Strain Gages and the Wheatstone Bridge	Instrumentation
2	Material Characterization	Uniaxial Members
3	Truss Structures	Truss Members
4	Beam Bending	Beam Members
5	Torsion and Shear	Shaft Members
6	Biaxial Stress and Strain	Biaxial Members

In the current academic year (i.e., Fall 2019–Spring 2020), 297 Aerospace students are taking AAE 20401 at Purdue University. We worked with these students to conduct the SoTL activities. As far as the historical enrollment for AAE 20401 is concerned, Figure 1 shows the course enrollment for the past 12 academic years (i.e., Fall 2008–Spring 2009 to Fall 2019–Spring 2020). As Figure 1 depicts that the increase in the student enrollment in AAE 20401 was a recent phenomenon, especially for the last three academic years. To this end, if we calculate the average enrollment per year for each of the four 3-year intervals starting Fall 2008 and ending Spring 2020, the numbers are 190, 183, 193, and 275 students/year for Fall 2008–Spring 2011, Fall 2011–Spring 2014, Fall 2014–Spring 2017, and Fall 2017–Spring 2020, respectively. These numbers demonstrate the dramatic surge in new undergraduate student enrollment in the last three academic years.

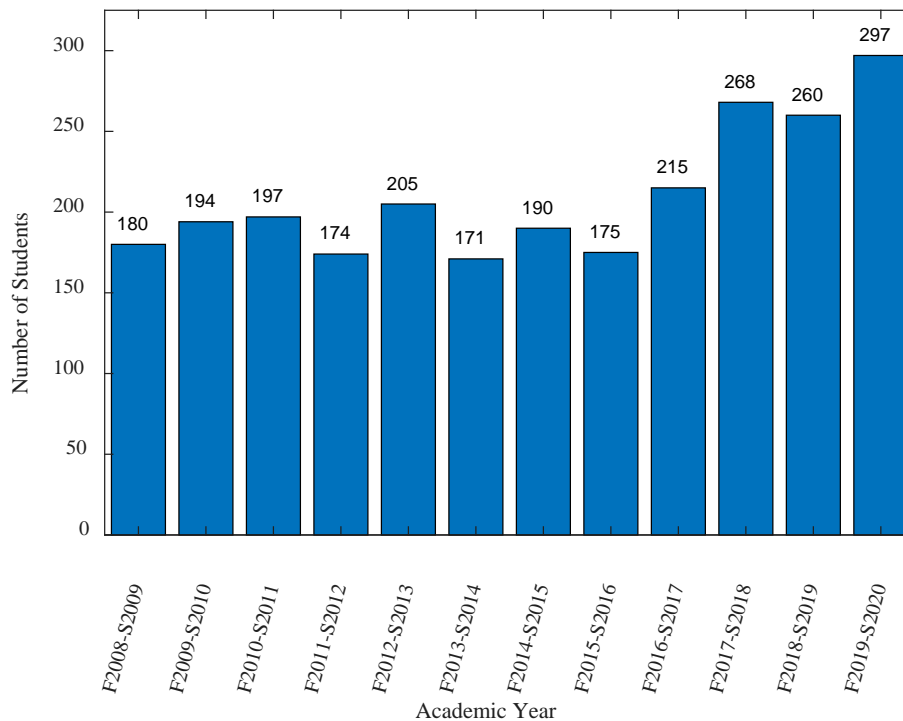


Figure 1: Historical Student Enrollment in AAE 20401 [40]

The implementation of VLs coincided with the increase in the number of the student enrollments. In fact, the VL conceptualization and development started in the Academic Year Fall 2017–Spring 2018, followed by the implementation of VLs without the SoTL activities in Fall 2018–Spring 2019, and the implementation of VLs with the SoTL activities in Fall 2019–Spring 2020. This was the direct result of our hope to help and improve students’ learning environment without increasing the physical space. We will discuss the specifics of VLs under the “Implementation of VL” section.

Course Content

Each lab has “big ideas,” enduring outcomes in which students must learn upon the conclusion of each lab activity. Determining the enduring outcome for the course is the key to the course design; in other words, we must have a clear idea of what we want student to know at the end of the coursework and many years after they completed the study [41]. The “big ideas” remains the same whether the experiments were conducted virtually or physically. Table 2 shows the big ideas (i.e., enduring outcomes) for the lab; since this is a practical, skill-based course, our big ideas are around the procedural knowledge that we expect students keep for the rest of their careers.

Table 2: Big Ideas – Enduring Outcomes

Lab #	Items
1	Conduct basic measurements using strain gages and the Wheatstone bridge circuit.
2	Characterize the behavior of materials based on how they respond under mechanical loadings.
3	Calculate the internal loads of truss members based on applied external loads.
4	Predict and analyze the behavior of beam structures using the Euler-Bernoulli beam theory.
5	Predict and analyze the behavior of shaft subject to torsion and plates under pure shear.
6	Calculate the principal stresses and strains for a pressure vessel by applying the thin-walled structure theory.

In addition to enduring outcomes (Table 2), the labs will educate students on the “important to know” topics (Table 3). These are specific (i.e., more detailed) topics that students learn when they participate in the lab and write a lab reports afterwards.

In addition, students confirm lab results with the theoretical results as a part of lab report write up so that students will be able to understand the theories behind the lab activities and also to understand potential errors associated to each activity during the lab.

In addition to the contents of Table 3 for specific topics, students must become proficient with the equipment usage to conduct hands-on experiments all labs. Also, they must be able to analyze the raw data, confirm lab results with the theoretical results, and predict the potential outcome through modeling as a part of lab report write up so that students will be able to understand the theories behind the lab activities and also to understand potential errors associated with lab activities.

Table 3: Important-to-Know Topics

Lab #	Items
1	Students learn the following topics related to the experimental instrumentation: Electrical resistance strain gages, Wheatstone bridge circuit which is used inside commercial strain indicators, circuit tester, and power supply.
2	Students learn the following topics related to the material characterization: Behavior of solids under the uniaxial mechanical loading, modulus of elasticity, yield strength, ultimate tensile strength, toughness, Poisson's ratio, and analysis and comparison of measurements with the literature data.
3	Students learn the following topics related to truss structures: Measurement of axial strain in a truss structure, conversion of axial strain into stress (based on material behavior learned in Lab #2), determination of internal forces of each member, and analysis and comparison of measurements with the truss theory.
4	Students learn the following topics related to beam bending: The Euler-Bernoulli beam theory, loads, reactions, beam deflections, stresses, strains, neutral axis, the use of a mechanical press and sensors for measuring strain, and analysis and comparison of measurements with the theoretical data.
5	Students learn the following topics related to torsion and shear: Torsion of shafts, shear modulus of elasticity, torque, angle of twist, angle of twist per unit length, and analysis and comparison of measurements with the theoretical data.
6	Students learn the following topics related to the biaxial stress and strain: 3D Hooke's Law, thin-walled theory, principal stresses and directions, stresses and strains in a cylindrical pressure vessel, and analysis and comparison of measurements with the theoretical data.

In addition to enduring outcomes (Table 2) and the important-to-know topics (Table 3), the lab activities also promote “good-to-be-familiar with” topics as follows: Students are expected to learn and demonstrate the following topics throughout all six labs: Teamwork, report writing, and communication. If we, for instance, take modeling as an example, being able to model constitutes an important and direct predictor of conceptual understanding of often-complicated engineering topics, such as heat transfer [42]. To sum up on these “good-to-be-familiar with” topics, they are covered in all labs (Labs #1–#6) and will become a part of necessary skills as a practicing engineer in the future no matter what field of engineering s/he choose to practice.

Assessment of Students Learning

Once we identified the course content, we aligned the learning goals of the six labs with the content. Later, we verified that we had the evidence to assess that students reach each of the goals. We will only enlist the learning goals and expected evidence related to Lab #6 since we conducted our SoTL activities (e.g., video recording, interview, revision of pre-lab assignment, and revision of report rubric to include VL experiments) during this lab (Table 4).

The assessment part of the course was the first place where we observed that VLs could be integrated. Since some of the learning goals of this lab focused on the application of different models of mechanics to analyze experimental data, we could include VLs as a source of virtual data. This virtual data is different from the experimental data as it is generated by using a

specific mathematical model with a predefined percentage of uncertainty. Thus, with this new data, students will be able to not only apply the mechanical models to analyze data but also compare the results from two different sources of data (i.e., the experimental and the virtual data).

Table 4: Assessment of Students Learning for Lab #6

Learning Goal	Expected Evidence
Students will be able to calculate principal stresses and principal directions.	In the pre-lab assignment, students are expected to confirm the overall purpose of this lab. By knowing that the stress element is experiencing only normal stresses when the element is oriented at 0 degree with respect to the axis of loading, students are expected to comment on the significance of pure normal conditions (i.e., no shear stress), which is essentially the principal stresses and directions.
Students will be able to calculate hoop, longitudinal stresses and associated strains by applying the theory of thin-walled pressure vessels.	In the pre-lab assignment, students must derive the expressions for axial and hoop strains in terms of internal pressure, Young's modulus, Poisson's ratio, and specimen thickness. Furthermore, in the lab reports, students are expected to calculate the hoop and longitudinal stresses.
Student will be able to conduct the transformation of stress and strain components from one coordinate system to another.	In the pre-lab assignment, students must derive a relationship between a strain in generic direction (with respect to theta) as a function of the measured axial strain and angle with respect to the loading direction. Also, in the lab report, students are expected to discuss the transformation of strain by comparing the theoretically calculated transformed results to the experimental results which was measured using the strain gages oriented at the specific angles with respect to the axis of loading.
Students will compare among theoretical results, experimental results, and virtual results.	In the lab reports, students must compare the theoretical results, experimental results, and virtual results so that any deviation of the data from the hands-on lab will be identified.
Students will identify different sources of error.	In the lab reports, students must identify sources of errors associated to the experimental data based on the data comparison explained above.
Students will enhance their teamwork skills by performing the experiment and elaborating the inform in groups.	During the hands-on lab, students conduct experiments as a group. After the lab activities, students will prepare lab reports as a group. Students will evaluate each other's work using a peer review sheet individually and submit with the group report.
Students will exercise professional behaviors by sending a clear written report on time.	Students are expected to prepare a clear and concise pre-labs and lab reports. Students are also expected to submit both pre-lab and lab reports on time at the beginning of lab period and one week from the day of lab, respectively.)

Pedagogy

The current course provides students with virtual and hands-on experiences in order to apply and enhance their understanding of the following fundamental concepts in aerospace structural mechanics: Strain gages and Wheatstone bridges, mechanical characterization, truss structures, beam bending, torsion and shear, and biaxial stress and strain. In addition, the course promotes the learning of data analysis, modeling, equipment usage, error analysis, teamwork, and communication by engaging the students in six lab modules. In each lab module, we implemented the following sequence of learning activities.

1. A professor introduces the concepts of the lab module and provides general guidelines for data analysis and modeling (Before the physical lab).
2. Students complete the pre-lab assignment individually to refresh their theoretical background and technical details of the upcoming hands-on experience (Before the physical lab).
3. Students conduct VL experiments to familiarize themselves with the equipment and collect virtual experimental data as a part of the pre-lab assignment (Before the physical lab).
4. Lab instructors deliver a brief lecture on the equipment usage, modeling considerations, and error analysis of the lab module (During the physical labs).
5. Students perform the hands-on experiment in teams to learn the correct operation of the equipment and collect data for subsequent data analysis (During the physical labs).
6. Students apply the module concepts, make comparisons among the results from the theory, virtual, and hands-on labs, discuss their discrepancies and analyze the potential error sources to complete their final lab report as a group (After the physical labs).
7. Lab instructors provide feedback on the lab reports to the students (After the physical labs)

Implementation of Virtual Labs

In the development and integration of VLs as a part of the Purdue AAE undergraduate education, our target is to recreate the current-state of the AAE 20401 hands-on lab activities in a computer-generated virtual environment. Table 5 shows lab titles, physical lab activities in each lab, and corresponding VLs. Each lab has two lab activities, except for the Lab #3. Out of 11 potential lab activities, we selected 9 activities for VLs based on the order of importance. We completed the initial development of the VL software together with Algetec Corporation at the end of Spring 2018 [43], [44]. After we completed logistical requirements (e.g., creating the VL user manual for students, installing software on the computers at Purdue AAE, and proof-testing VLs in the computer-lab environment) in Summer 2018, we started using VLs for AAE 20401 in Fall 2018.

Table 5: Physical Lab Activities and Corresponding VLs

Lab #	Lab Title	Physical Lab Activity	VL
1	Strain Gages and the Wheatstone Bridge	Strain Gage and Wheatstone Bridge Experiments	Figure 2
		Strain Gage and Multimeter Experiments	n/a
2	Material Characterization	Tensile and Rupture Experiments	Figure 3
		Linear Properties Experiments	n/a
3	Truss Structures	Truss Experiments	Figure 4
4	Beam Bending	I-Beam Experiments	Figure 5
		Rectangular Beam Experiments	n/a
5	Torsion and Shear	Shaft Experiments	Figure 6
		Shear Plate Experiments	Figure 7
6	Biaxial Stress and Strain	Uniaxial Specimen Experiments	Figure 8
		Pressure Vessel Experiments	Figure 9

In Fall 2018, we started using VLs as a part of pre-lab and post-lab activities although the activities at that time were limited to simply follow the VL manual to a) familiarize the users (students) for the upcoming physical lab activities and b) repeat the experiments virtually after the completion of hands-on lab sessions to confirm experiments and to understand the subjects better. Furthermore, the activities at that time did not include a systematic SoTL approach although the instructor was able to observe students' comments as a part of the continuous improvement process. Using the students' comments, VLs made a steady and gradual improvements during the Fall 2018–Spring 2019 academic year.

In Fall 2019, we had students start conducting VL experiments at various experimental parameters, which stimulated the pre-lab assignment activities in preparation for hands-on labs. We revised the contents of both pre-lab assignments and final lab report rubrics in such that students must include the VL experimental results as a part of pre-labs and final lab reports. In addition, we asked students to compare physical lab results, VL results, and theoretical calculation results in the final lab reports.

Figure 2 shows the screenshot of VL #1, Strain Gages and the Wheatstone Bridge. In this VL exercise, the users (i.e., students) start the VL experiment by turning the resistor knobs to balance the Wheatstone bridge circuit (Figure 2, left). Then, the user places a virtual beam with a strain gage onto a fixture/jig with a known radius of curvature (Figure 2, right) to obtain the voltage output from the Wheatstone bridge circuit. Students will convert the voltage values into strains (using the theory of the Wheatstone bridge circuit and gage factor), which will be compared against the physical lab results as well as the theoretical calculation based on the beam theory.

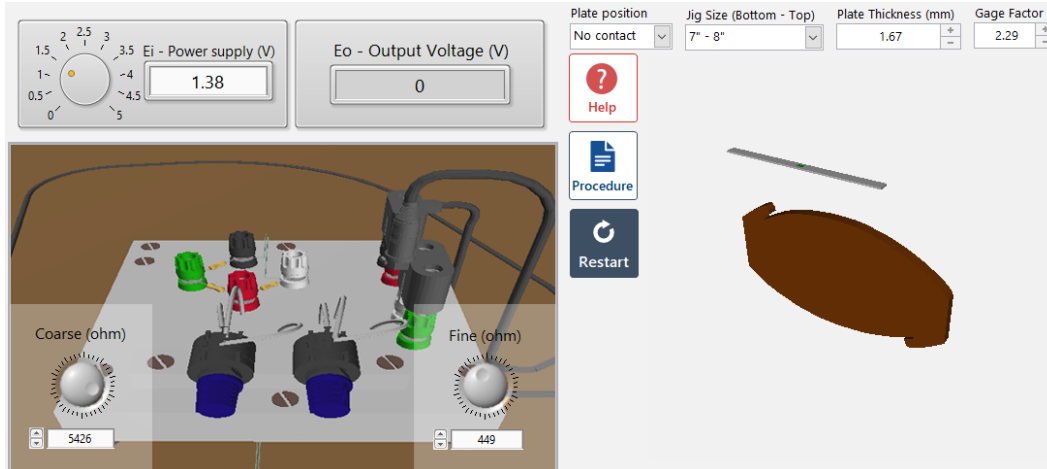


Figure 2: Screenshot of VL #1: Strain Gages and the Wheatstone Bridge

Figure 3 shows the screenshot of VL #2, Material Characterization. In this VL exercise, the users start the VL experiment by loading the specimen into the fixture, followed by the closing of the upper and lower jaws to mount the specimen onto the fixture. After that, students hit “Go” button to start experiments. As the specimen is being elongated, students can see the specimen’s deformed shape and stress distribution to have a better understanding of what is happening with the specimen as the force increases. Finally, the specimen fractures which concludes the experiments. By using the results of the virtual experiments, students can plot a stress-strain curve and calculate Young’s modulus of the material. Students can also see the yield stress from the stress-strain plot.

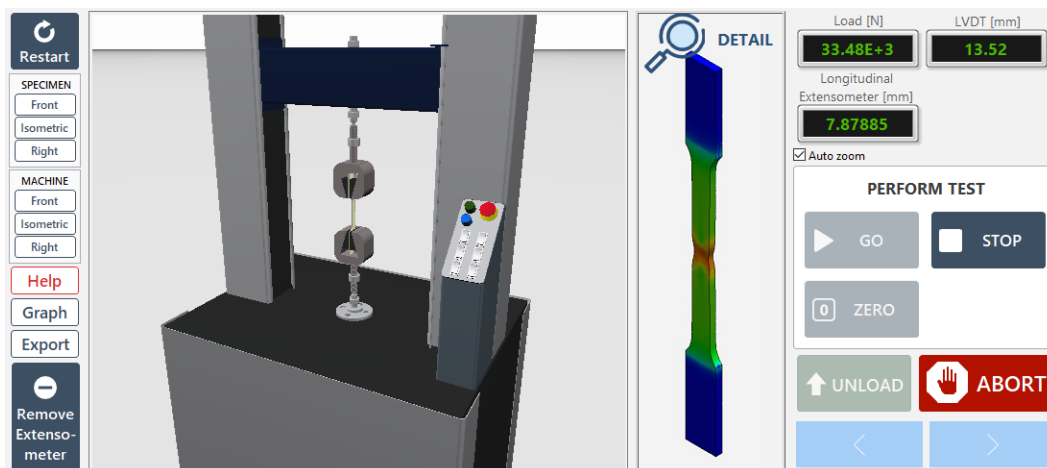


Figure 3: Screenshot of VL #2: Material Characterization

Figure 4 shows the screenshot of VL #3, Truss Structures. In this VL exercise, the users start the VL experiments by applying the downward force at the middle of the truss structure. As the force increases, the virtual strain gages at various locations in the truss structure measures the strains. As the force increases, the users can see the increase in the strain magnitude. Based on the experiments, students can calculate the stresses and internal forces of the structure. Students

can also calculate the theoretical internal force by using either the method of joints or method of sections.

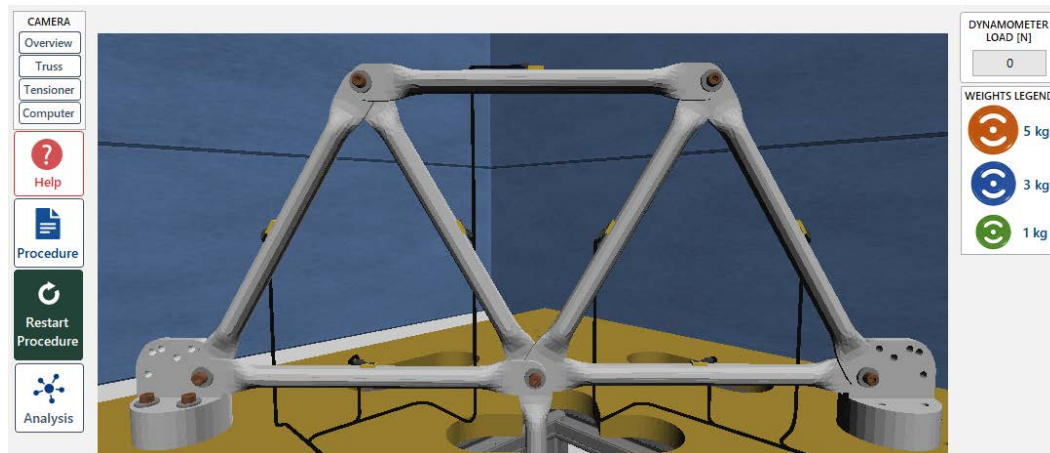


Figure 4: Screenshot of VL #3: Truss Structures

Figure 5 shows the screenshot of VL #4, Beam Bending. In this VL exercise, the users start the VL experiment by applying the downward force at the middle of the upper fixture that is attached to the I-beam specimen. This is a four-point bending (flexural) experiment, so the applied force from the top is separated into two forces while the I-beam specimen is supported by two supports on the bottom. As the force increases the virtual strain gages at various locations of the I-beam structure measure the strains. After the conclusion of the experiments, the users can plot the experimental data against the theoretical data that is based on the beam theory. Students can also draw a shear force and bending moment diagrams in order to further understand the theoretical background of the beam problem.



Figure 5: Screenshot of VL #4: Beam Bending

Figure 6 shows the screenshot of VL #5, Torsion and Shear (Shaft). In this VL exercise, the users start the VL experiment by applying the torsional loading onto the specimen, which is a

hollow tube, through the turning wheel. The VL apparatus measures not only the strains from the virtual strain gages but also the linear travel distances from the virtual dial gages at the top of the shaft. Based on the experiments, students can calculate the shear strains as a function of torque. Students can also calculate the shear modulus, which is the slope of the initial linear portion of the in the shear stress–shear strain curve.



Figure 6: Screenshot of VL #5: Torsion and Shear (Shaft)

Figure 7 shows the screenshot of VL #5, Torsion and Shear (Shear Plate). In this VL exercise, the users start the VL experiment by applying the upward force onto the specimen. Due to the specimen's L-shaped holding fixtures, the specimen experiences a shear loading. Based on the results, students can plot the shear stress vs. shear strain. Students also can compute shear modulus, similar the exercise above.

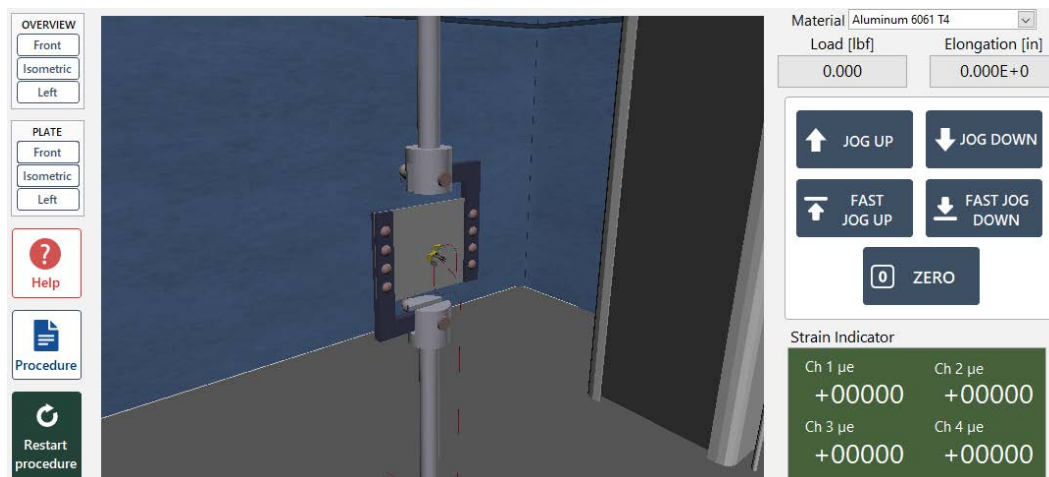


Figure 7: Screenshot of VL #5: Torsion and Shear (Shear Plate)

Figure 8 shows the screenshot of VL #6, Biaxial Stress and Strain (Uniaxial Specimen). In this VL exercise, the users start the VL experiment by applying the upward force onto the specimen. The virtual strain gages are oriented at various angles with respect to the longitudinal axis (i.e.,

axis of loading). Based on the results, students can observe how the strains change based on the angle with respect to the axis and compare them with the theoretical values.

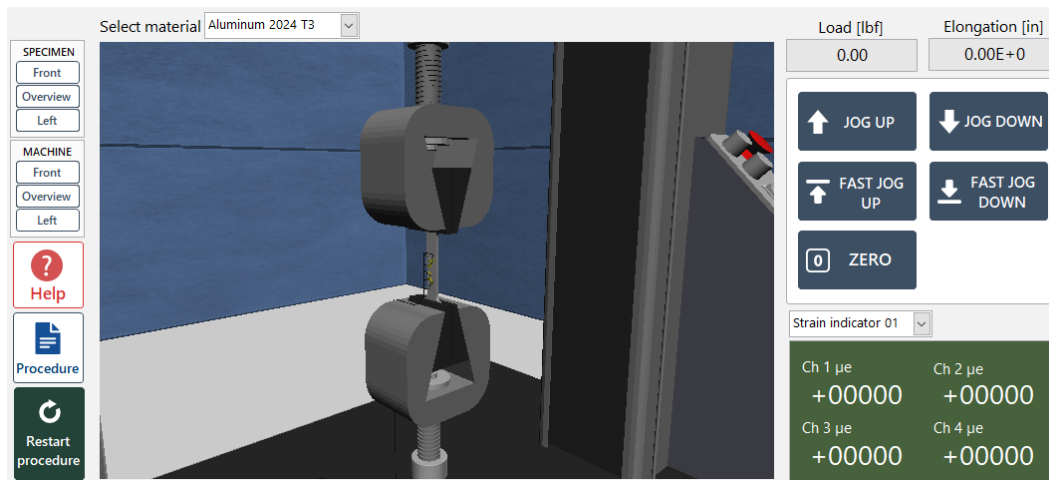


Figure 8: Screenshot of VL #6: Biaxial Stress and Strain (Uniaxial Specimen)

Figure 9 shows the screenshot of VL #6, Biaxial Stress and Strain (Pressure Vessel). In this VL exercise, the users start the VL experiment by pressurizing the virtual pressure vessel with the pump. Students observe the increase in the strain values measured by the strain gages that are mounted on the pressure vessel in the longitudinal (axial) direction as well as in the transverse (hoop) direction. Based on the results, students can observe how the strain values change depending on the angle of the strain gage with respect to the longitudinal direction. Students can also calculate the stress from the hands-on lab experiments and from the pressure vessel theory so that students can compare the VL results to both the experimental and the theoretical results.

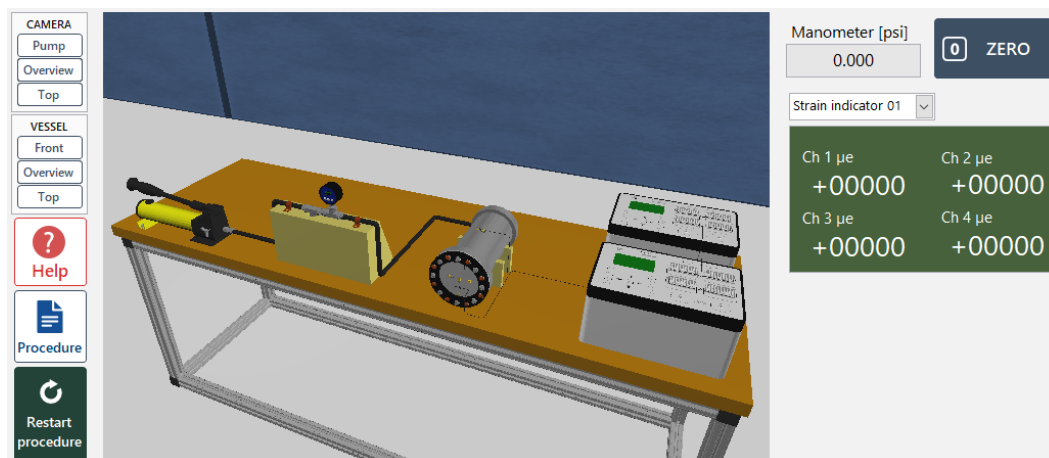


Figure 9: Screenshot of VL #6: Biaxial Stress and Strain (Pressure Vessel)

4. Results and Discussion

During the Fall 2019–Spring 2020 academic year, we worked with the enrolled students while video recording them and asked questions about the use of VLs as a part of AAE 20401 lab activities. More specifically, we conducted the video interviews on nine students while they were performing VL experiments on computers. Then, we transcribed the video interviews so that we can assess the VL implementation qualitatively and answer the following research questions: a) how did students perceived VLs and b) what connections did students make between VLs and Physical Labs?

Research Question #1: How did students perceive VLs?

Overall, the students perceived the VL as a useful part of the AAE 20401 course. They provided mostly positive comments during the interviews such as *“I think, it [the VL] does a really good job”* or *“I think the virtual lab itself is great and it’s been really helpful.”* When we, as researchers, were more into why students like the VL, we found that they help students to be more prepared for the physical lab. For instance, one student said, *“I kind of like it because it can give me an idea of the equipment before I get through the lab.”* We would expect this response from the student as we initially conceived the VL as tools to help students to be more prepared for the hands-on experiments. On the other hand, since the VL helps students to prepare the experiments, we wonder what happened with the rest of the available material that have a similar goal. For example, one student mentioned the VL *“is not as kind of complicated as the lab manual can be.”* In this case, the lab manual seems to present an implicit cognitive challenge for this student that the VL helps to overcome. Further research needs to be conducted about the cognitive load that studying the lab manual generates in the student and how the VL could reduce it.

The students provided suggestions about how to improve technical elements of the VL in addition to their positive comments. They mostly focused on technical aspects of the VL such as the slow speed of the software when it run remotely. This comment was common also in the previous semesters. Consequently, the development team has modified the future VLs, which is beyond the scope of this paper, so that they will work online instead of using remote software. Additionally, other students complained about how the camera worked. For example, one student said:

“The only thing that I can think would be, like a bottom for a camera alignment, because a lot of times it rotates like ... [the student moves the cursor on the screen in a circular motion to show how the camera moves] spherically, this is like when things are hard to look at”

In this example, the student described the problem with the camera and also provided a solution: create a new bottom on the interface. Finally, another student mentioned the software is not totally user friendly. He would prefer the VL gives some additional instructions about how to use all the features. The camera issue and user friendlessness are problems that we were not aware until this research was performed. We will try to fix these issues in the current and future VLs.

One final comment that called our attention was one student who did not perceive any learning from the VLs. Specifically, the student said, “*in terms of like actual learning something, I don't think I get much of it other than just know how do it* [the hands-on experiment].” The student saw the VL as a tool useful only to know what to expect from the experimental lab. However, we believe the VL helps the students to develop cognitive skills such as data analytics and error analysis. To determine how the VL supports the students’ learning, more research needs to be done. We will inform the future findings to the upcoming students; so, they will be more aware of their learning through the VL.

Research Question #2: What connections did students make between VLs and Physical Labs?

Students made a positive connection between VLs and physical labs in general. The following section discusses the answer to Research Questions #2 by using the lab reports, videotaping interviews, and end-of-semester student assessment.

Based on the review of the Lab Report #6, what we found was that all groups have attempted some form of comparison between the VLs and physical labs. This was a predictable result since we explicitly stated in the lab report rubrics to make the comparison between the VL and physical lab results. Therefore, the evidence of students trying to make a connection was very clear. However, what we found interesting was that we observed vastly different approaches that each group chosen to make the comparison. For instance, some groups created separate plots: one for VL and the other for physical lab. Then, they expressed the characteristics of each plot, such as linear fit equations and R^2 values. For these groups, this approach was their version of the “comparison” although no direct comparison was made between VLs and physical labs. On the other hand, some other groups put VL and physical lab data into one plot and made the comparison visually and directly. Based on this experience, what we learned was that if we are looking for something specific from the students (e.g. asking students to compare VL and physical lab results on one plot, not two separate plots), we should say so in order to further clarify the content of the rubrics. By simply stating to compare VLs and physical labs generated different types of answers.

For those groups that plotted the VL, physical lab, and theoretical results in one plot, the VL and theoretical results are on top of each other. One of the groups was wise to identify the error in the VL results as follows: [After talking about the errors in the physical lab results] “*The same errors could apply to the VLs although these errors are programmed into the VL.*” The group’s error analysis was excellent in such that the group identified the inherent (and intentionally added) error in the VLs.

From the videotaping interviews, the feedback was positive in terms of how they connect VLs and physical labs. Since the AAE 20401 VLs gave the students with theoretical data (with some built-in intentional errors), some students used it as a reference to troubleshoot potential issues during their experiments and/or identifying potential errors after the experiments in their own experimental data as a quick data verification tool to check the experimental data without going into the full-blown theoretical calculations. The comments from the video taping interviews

sounded slightly inarticulate since the students were working on the VLs while also giving their opinions on the VLs.

"It [the virtual lab] is useful to do because you have some data to confirm to, and if something is going to go wrong in the lab, then, you know this is the experimental data that you got from the virtual lab, and our experimental data has this error in it because something got wrong"

Another example of students using the VLs as a quick check tool although this student's expression is somewhat inarticulate, and he appears to be just using VLs as a simple tool without being overly enthusiastic. Again, we felt this was the result of student talking to the interviewer while also working on the VL, simultaneously.

"Sometimes I just [inaudible] see writing that numbers, I don't really think about why I am writing that those numbers or why they make sense, because I know they are not going to be like any major data on the virtual lab data, that they gave us, so I don't need to consider anything like that, I know the values theoretically should be correct."

From the end-of-semester student assessment, the feedback was positive in terms of how they connect VLs and physical labs. The VLs appeared to provide students with a physical sense of what they will be doing in the upcoming hands-on lab, which is beneficial for student learning.

"Virtual labs help with the actual labs and give a good visual of what to expect on the actual lab day."

Instructor Reflection about the VL Implementation

The AAE 20401 instructor shared his experience during the VL implementation. The instructor specifically talked about the challenging issues that he faced during the implementation.

"When we first received the Virtual Lab software (Spring 2018), we received the prototype version of the software. Thus, it needed some work before implementing it in the student learning environment. In Spring 2018, we had graduate student lab TAs run the prototype VL program so that we can get a proper feedback. Then, during Summer 2018, I hired one graduate student to go through all the functionality of VLs in the actual computers in the computer lab to give feedback to the software company and create VL user manual for students. Finally, in Fall 2018, we were able to implement VLs although it was without the SoTL activities at that time. From this experience, what we learned was that we should not underestimate the amount of work involved for the VL launch. The most challenging task was to make the user interface as friendly as possible without abbreviating the certain equipment operations that are essential during the physical lab sessions."

The AAE 20401 instructor shared his opinion on what he thought he would have done differently to improve the AAE 20401 based on his experience with the [Course number removed] VL implementation.

“It would have been better if we made AAE 20401 VLs as a web-based program that is hosted on a web server. Currently, the AAE 20401 VLs are installed on physical computers in the computer lab because the AAE 20401 VLs requires software installation on the computer that runs the program. We chose to take this option since we did not want students to install this software on their laptops due to potential licensing issues. Although there are no issues with the user experience and functionality, this option is not very convenient for students since they have to come to the physical computer lab to do VLs.”

“We also had the program installed on the Purdue servers so that we can access it via Purdue Software Remote, which is a Purdue in-house remote app solution. However, the Software Remote has an issue with the user experience because the Software Remote application does not appear to work well for graphics-intensive programs, such as VLs, due to its sluggish response. Thus, the use of the AAE 20401 VLs via Purdue Software Remote became a test of patience for students.”

The AAE 20401 instructor shared his opinion on a byproduct of the VL implementation. He specifically talked about the use of VLs during the lab preparation lectures.

“I use VLs during the lab preparation lecture. How I teach the lab preparation lectures is to go through the theoretical reviews for the upcoming labs in the first part of lectures. Then, in the second half of the lecture, I demonstrate the apparatus in VLs and conduct virtual experiments in front of the class. Students seem to be more confident and have a better idea of the upcoming physical labs after my lab preparation lectures because of the VL demonstration.”

The AAE 20401 instructor shared his experience on the SoTL activities on VLs. The instructor explained how the improvement of the VL software before SoTL activities made sense. Also, the instructor gave his view of the SoTL activities (Note: The AAE 20401 instructor is not the faculty of engineering education).

“The SoTL activities went smoothly, and one of the reasons was that the VL software worked very well by the time we started working with the engineering education researcher in Fall 2019 so that we did not have to worry much about the issues on the VL software itself by then. I felt that the qualitative research with VLs was a significant task simply because it involves time-consuming activities, such as video recording and interviewing students. The key to the SoTL activities on VLs was to get early assistance from engineering education researchers. They have know-how on dealing with qualitative research, which is fundamentally different from the research on the aerospace structures and materials where we drive project with numerical numbers like force, displacement, stress and strain.

5. Conclusions and Future Work

The AAE 20401 VLs are the innovative virtualization approach of the current hands-on labs in order to improve course instruction. The thesis behind the VL implementation at Purdue remains the same as the thesis for MIT Project Athena almost four decades ago: Improvement of the educational quality for the students. However, there were slight differences in the approach, where we used the Backward Course Design Model to analyze and characterize the context, content, assessment, and pedagogy of the course which allowed us to identify how this VL software should be integrated into the existing lab coursework. Based on the pedagogy we developed, VLs help students to familiarize themselves with the equipment before the hands-on experiment and allow them to collect virtual data. The use of VLs after the hands-on lab activities allows students to further reflect during the data analysis process.

As future work, we will conduct qualitative research to further characterize VLs' contribution to the students' learning of data analysis, modeling, and error analysis. Although our VL SoTL activities specifically focused on the second-year aerospace engineering students, VLs are a disruptive technology that can propagate to other age groups (e.g., K-12, upper-class undergraduate/graduate students, and working professionals) as well as other disciplines (e.g., life sciences, physical sciences, mathematics/computer sciences, and continuing education for workforce development). Therefore, SoTL activities on VLs will be beneficial to educational researchers at all levels and will need to be expanded to other disciplines.

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