

Pedagogy Improvement in Aerospace Structures Education Using Virtual Labs: Before, During, and After the COVID-19 School Closures and Remote Learning

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Abstract

We implemented Virtual Labs as a tool to assist students in familiarizing themselves with the hands-on lab in aerospace structural mechanics. Subsequently, we learned that Virtual Labs also allowed students to collect virtual data that prompted students to further reflect during the data analysis process in addition to the data obtained during the hands-on labs. Thus, the course provided students with both virtual and hands-on experiences to enhance their understanding of the subject matter. At the same time, the course promoted the learning of data analysis, modeling, equipment usage, error analysis, teamwork, and communication by engaging the students in both the virtual and hands-on labs. In Spring 2020, we experienced an extraordinary event: the school closures and remote learning caused by the COVID-19 pandemic. During this period, Virtual Labs became the only available means to provide instructional labs to the enrolled students since all students were sent home. That is, the school closures made us change the way that we used Virtual Labs and necessitated us to modify the course delivery method so that the lab courses could be performed fully online. Therefore, in this paper, we explained how the transition took place in the aerospace structures lab for the use of Virtual Labs before, during, and after the COVID-19 school closures. Then, we discussed lessons learned during this period. This paper will be a useful reference for engineering educators who seek to implement or integrate virtual technology into their pedagogy.

1. Introduction

In our previous study [1], we implemented Virtual Labs (VLs) for AAE 20401, Aeromechanics II, a one-credit lab course for second-year aerospace engineering students, in Fall 2018–Spring 2019. Following the AAE 20401 VLs, we also implanted VLs for AAE 35201, Structural Analysis I, a one-credit lab course for third-year aerospace engineering students, in Spring 2019–Spring 2020. The implementation of the VLs coincided with a particular period of time: the COVID-19 school closure and remote learning in March 2020–August 2020. Thus, this paper talks about the following two main topics: 1) the implementation of AAE 35201 VLs and 2) pedagogy change before, during, and after the COVID-19 school closure and learning. Then, as a part of the discussion, we will talk about how the COVID-19 school closure and remote learning affected the use of VLs in terms of educational pedagogy.

2. Background

We experienced extraordinary events during the COVID-19 pandemic. Many educational institutions in the U.S. closed their in-person courses and transferred to remote online learning. Research has shown that if an asynchronous online teaching/learning tool is implemented with appropriate pedagogy, the asynchronous online learning can be as effective as (or more effective than) a conventional classroom course [2]. To this end, a recent improvement of computer technology allows us to use virtual technologies in job training and education [3], [4]. For instance, virtual technologies can be used to train teachers [5], [6], train medical practitioners [7],

[8], [9], and train engineers [10], [11], [12]. Since virtual technologies enable us to see a subject matter with our own eyes, it is a much more intuitive approach than imagining the subject matter in our minds. Therefore, the virtual technologies are useful visualization tool in learning the complex and conceptual problem that requires spatial understanding [13]. Due to the overwhelming advantages of virtual technologies, the use of such technologies during the COVID-19 pandemic and beyond is a must. However, how we can incorporate virtual technology into our teaching depends on how and what each instructor wants to capitalize on the potential of virtual technologies [14]. Therefore, the research question to which we would like to contribute is as follows: How can we incorporate virtual technologies as a part of effective pedagogy?

3. Course Context

At Purdue University School of Aeronautics and Astronautics, we have two aerospace structures courses that use VLs: AAE 20401 Aeromechanics II and AAE 35201 Structural Analysis I. For AAE 20401, please review our previous publication [1] on how we implemented the VLs. In the section below, we will talk about AAE 35201 VL implementation that occurred during the Spring 2020 semester (January 2020–May 2020). The lecture for the AAE 35201 lab course is called AAE 35200, which is described in the separate publications [15], [16].

Description of the Course

AAE 35201, Structural Analysis I, is a one-credit laboratory (lab) course in aerospace structural mechanics at Purdue University. AAE 35201 offers six lab preparatory lectures and six physical labs. Table 1 shows the summary of AAE 35201 labs and abstract terms in structural mechanics.

Table 1: Summary of Structural Analysis I (AAE 35201) Labs

Lab #	Lab Title	Abstract Terms in Structural Mechanics
1	Stress Analysis of I-Beams	I-Beam Bending Member
2	Bending of Aircraft Wings	Thin-Walled Symmetrical Bending Member
3	Torsion of Airfoils	Thin-Walled Torsion Member
4	Thin-Walled Shear Beams	Thin-Walled Nonsymmetrical Bending Member
5	Stability of Structures	Column Buckling Member
6	Fatigue	Rotating-Bending Fatigue Member

From the viewpoint of pedagogy, each lab module consisted of five learning activities throughout two weeks as follows. 1) A lecture instructor introduces the concepts of the lab module and provides the theoretical background that is necessary for data analysis and modeling. The lab preparation lecture lasts for 50 minutes. 2) The enrolled students complete the pre-lab assignment individually to refresh their theoretical background and technical details of the upcoming hands-on experience. Additionally, students conduct VL experiments to familiarize themselves with the equipment and collect virtual data. 3) The lab instructor delivers a brief lecture to review the equipment usage and modeling considerations of the lab module. 4) The students perform the hands-on experiment in teams to learn the correct manipulation of the equipment and collect data for subsequent analysis. Each lab lasts for 110 minutes. 5) The 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 in teams their final lab report.

Course Enrollment

Figure 1 shows the historical student enrollment in AAE 35201 based on the information from the Purdue University Office of the Registrar [17]. The figure reveals two things: 1) the course enrollments have ups and downs and 2) the course enrollments have not largely changed since the Fall 2008–Spring 2009 academic year. If we compare the average enrollment between AAE 20401 and AAE 35201, AAE 20401 had an average course enrollment of 210.5 students [1] between Fall 2008 to Spring 2020. On the other hand, AAE 35201 had an average course enrollment of 52.0 students between Fall 2008 and Spring 2021. Thus, the enrollment numbers for AAE 20401 were about four times larger than those of AAE 35201.

There is a reason for the difference in the course enrollment between these two lab courses. Unlike previously reported AAE 20401 [1], AAE 35201 is not a mandatory course. At the Purdue University School of Aeronautics and Astronautics, the third-year undergraduate students have a choice between AAE 35201 Structural Analysis I Lab and AAE 33401 Aerodynamics Lab as a part of “Junior Lab Requirement.” At this point, a more significant percentage of students choose to take the aerodynamics lab (AAE 33401). This is why the enrollment numbers for AAE 35201 are much smaller than those of AAE 20401, which is a required course.

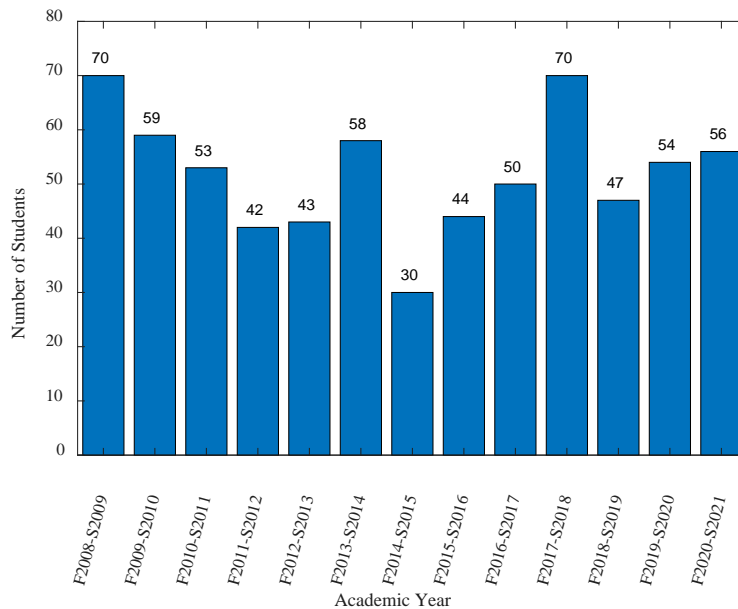


Figure 1: Historical Student Enrollment in AAE 35201

Figure 2 Left and Right show the historical enrollment for AAE 35201 in the fall and spring semesters, respectively. The average course enrollment for the fall semesters (Figure 2, left) was 22.8 students, whereas the average course enrollment for the spring semester (Figure 2, right) was 29.2 students. Thus, on average, the course enrollment for the spring semester was 28%

larger than that of spring semesters if we normalized the fall number with respect to the spring number.

If we closely take a look at how the fall (Figure 2, left) and spring (Figure 2, right) enrollments change within the past years, we observe that the fall enrollment is relatively more stable than the spring enrollment. If we convert this qualitative observation into the quantitative observation, the fall enrollment data has a standard deviation of 7.1 students, whereas the spring enrollment data has a standard deviation of 9.1 students. In other words, if we assume the standard distribution, we can state that about 68% of the time, the enrollment was expected to fall within 22.8 ± 7.1 students (i.e., 15.7–29.9 students) and within 29.2 ± 9.1 students (i.e., 20.1–38.3 students) for fall and spring semesters, respectively.

We provided the course enrollment numbers since implementing a new educational method or practice could depend on the size of the student body. For instance, if we were to conduct statistical analysis (e.g., regression analysis) with a course with a larger enrollment, such as AAE 20401 (i.e., average enrollment of 210.5 students per academic year), statistics can reveal trustworthy results. On the other hand, the course with smaller numbers, such as AAE 35201 with 22.8 or 29.2 average enrollment per semester, the analysis per semester is somewhat borderline. According to Jenkins [18], research activities based on regressions should have a sample size of 25 or more. Thus, for smaller courses, such as AAE 35201, we will need data from multiple semesters in order to conduct quantitative research.

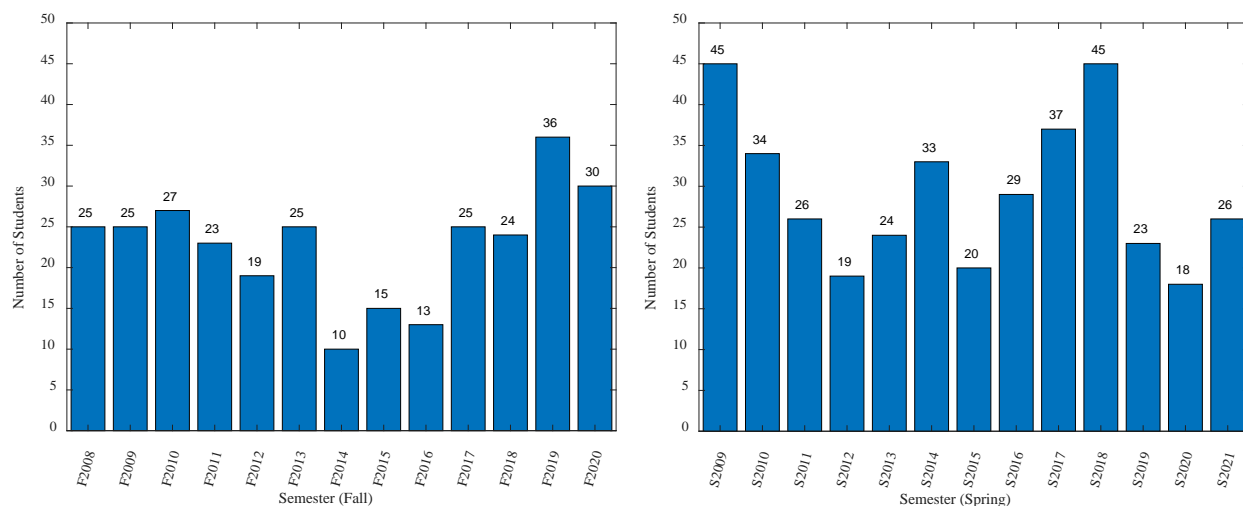


Figure 2: Fall (left) and Spring (right) Course Enrollment in AAE 35201

In addition, from a practical standpoint, courses with larger enrollment, which is generally toward the 1st and 2nd-year undergraduate study, are different from courses with smaller course enrollment, which is generally toward 3rd and 4th year undergraduate study in their context and form. Apart from the level of sophistication, the audience in the large introductory (i.e., 1st and 2nd year) college courses is different from the audience in smaller advanced (3rd and 4th year) college courses, which means that the instructor’s underlying assumptions about course planning are different. Therefore, the instructor’s execution of teaching activities will change as well.

4. Methods

Virtual Lab Implementation

In addition to the previously-reported VLS for AAE 20401 [1], we developed VLS for AAE 35201 in collaboration with the Purdue University Envision Center. We first conducted the brainstorming and conceptualization of the VLS in Spring 2019. Then, in Summer 2019, we started working on the computer modeling of the VLS. The Purdue Envision Center used Unity, a virtual reality software, to create the computer models. Then, the Purdue University School of Aeronautics and Astronautics provided the engineering data. Toward the end of Fall 2019, basic models were ready; thus, we conducted the trial use of the virtual lab with the students (i.e., a trial implementation) for the last lab (Lab 6) of the semester. Then, from the beginning of Spring 2020, we implemented the VLS from Labs 1–6. Table 2 shows lab titles, physical lab activities, and corresponding VL. The corresponding VL column of Table 2 contains the figure numbers, Figure 3–Figure 8 in the subsequent sections for Labs 1–6, respectively.

Table 2: Physical Lab Activities and Corresponding VLS for AAE 35201

Lab	Lab Title	Physical Lab Activity	VL
1	Stress Analysis of I-Beams	Analysis of principal strain and direction using an I-Beam	Figure 3
2	Bending of Aircraft Wings	Analysis of a symmetric, light-weight aircraft wing	Figure 4
3	Torsion of Airfoils	Analysis of thin-walled multi-celled airfoil subjected to torsion	Figure 5
4	Thin-Walled Shear Beams	Analysis of shear flow and shear center in three-stringer thin-walled beams	Figure 6
5	Stability of Structures	Analysis of structural stability using column buckling	Figure 7
6	Fatigue	Analysis of fatigue failure using rotating-bending specimens and exploration of safe-life design using S-N curve.	Figure 8

Virtual Lab Description

Figure 3 depicts the screenshot of VL 1, Stress Analysis of I-Beams. The I-beam structure is a four-point bending virtual specimen. In this VL exercise, the users start the VL experiment by moving the head of the press downward using either the Jog Slow or Jog Fast button to the left of the screen. The users can choose the speed of the head movement by using the speed adjustment knob just above the aforementioned buttons. When the tip of the downward moving head touches the top of the specimen, the users must slow the speed (i.e., turn the knob counter-clockwise). Then, the users can slowly load the I-beam specimen to a certain force value (e.g., 0 to 8,000 lb with 2,000 lb increment). At each force value, the users record the strains from the virtual strain gages at various locations of the I-beam structure.

After the completion of the virtual lab experiments, as depicted in Figure 3 and explained above, users can plot the virtual experimental values against the theoretical values based on the Euler-

Bernoulli beam theory. Then, the users can also plot the experimental values from the hands-on experiments. Since we measure the strains at three separate locations, with each location having three rosettes, the students were able to calculate further information, such as principal strains and their directions at each of the three locations.

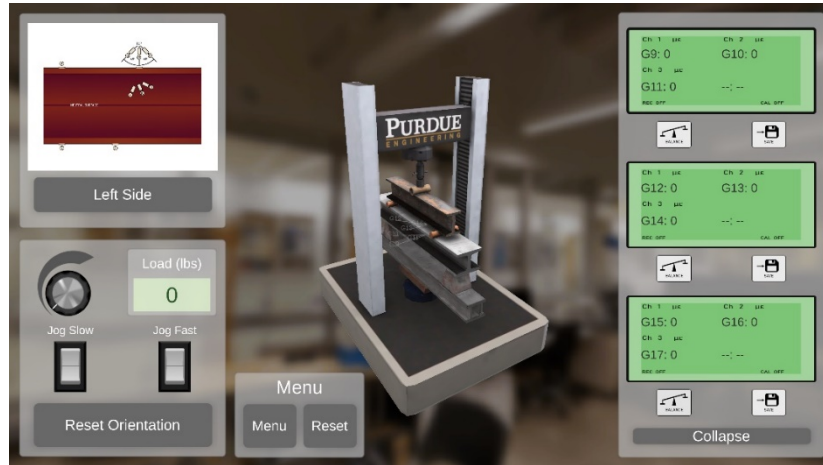


Figure 3: Stress Analysis of I-Beams (Lab 1)

Figure 4 depicts Lab 2, Bending of Aircraft Wings. The wing has a thin-walled cross section, and it is symmetric with respect to the horizontal axis. In the experiments, the users change the horizontal location of the shear force, V_z by using the “Force Location” button. When the users select the location, they apply a force using the “Force Amount” button. If the shear force is applied through the shear center, the dial gauges to the left and right of the cross section show the same amount of deflection. At this point, the users click the “Confirm Shear Center” button. If the shear center that the user selected is located at the shear center, further experiments can be conducted. If not, the VL gives an error message so that the users need to keep going until the users find the shear center location by trial and error.

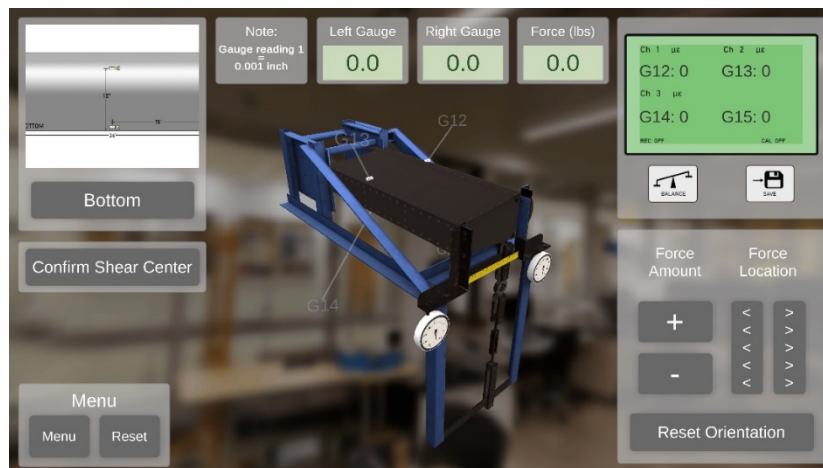


Figure 4: Bending of Aircraft Wings (Lab 2)

Since the cross-section is symmetrical (i.e., with respect to the horizontal axis) for Lab 2 (Figure 4), students can calculate the deflection by solving the governing differential equation [19] to obtain the general solution of deflection in the vertical direction. Students can also calculate the bending stress using the reference material [19] as well. Since the cross section is symmetrical, the product of inertia of the cross section I_{yz} is zero, which makes the calculation for the symmetric cross section easier than those of the nonsymmetrical cross sections. The students can obtain the strain values and deflections from the VL. The virtual results are plotted against the experimental and theoretical results. Then, students draw conclusions based on the analysis from these three sets (i.e., VL, hands-on experiments, and theory) of data.

Figure 5 depicts Lab 3, Torsion of Airfoils. In the virtual lab experiments, the students apply virtual torque to the airfoil. The airfoil has strain gauges, where strains were measured at three locations, with each location having three rosettes. The airfoil also has two dial gauges on the top that measures the linear displacement based on the angle of twist. Thus, using the dial gauge readings, students can calculate the angle of twist for the airfoil at two locations. Since the distance between these two points is a known value, students can calculate the twist angle per unit length. The results from the experiments are compared against the hands-on experimental results and theoretical calculation based on the multi-cell thin-wall theory.

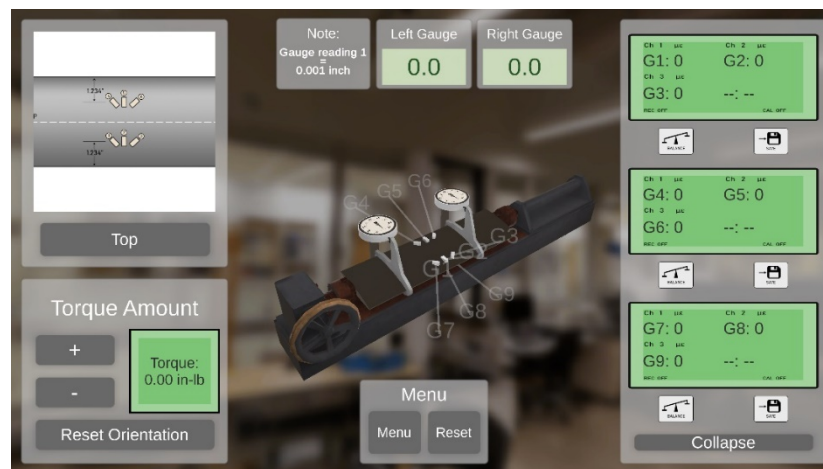


Figure 5: Torsion of Airfoils (Lab 3)

Figure 6 depicts Lab 4, Thin-Walled Shear Beams. The cross-section of the thin-walled beam is a right triangle; thus, the cross section is an unsymmetrical cross section. Procedures for the virtual lab experiment follow those of VL 2 (Figure 4). However, the difference is that the cross-section being unsymmetrical in VL 4, whereas VL 2 cross section was symmetrical. Furthermore, in Lab 4, the students are required to calculate the shear center location. This means that the students must calculate shear flow in each domain of cross section so that the students can set the moment based on the shear flow equals the moment based on the shear force in order to calculate the shear center location. Finally, the students compare the VL, experiments, and theory to draw a conclusion on the comparison.

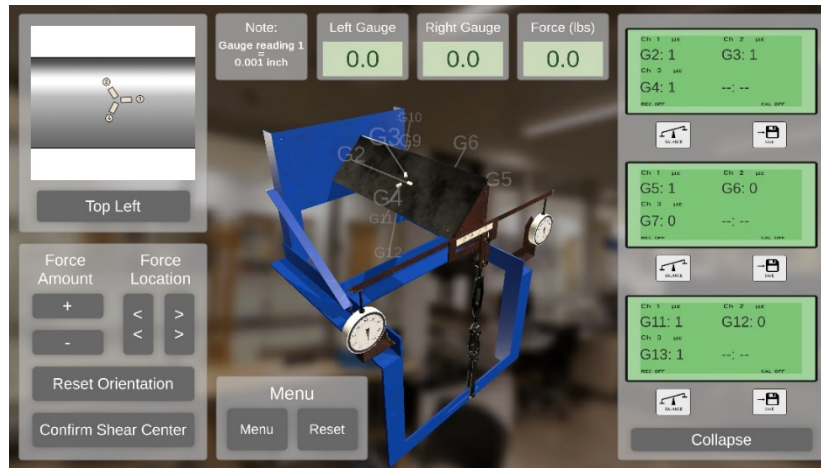


Figure 6: Thin-Walled Shear Beams (Lab 4)

Figure 7 depicts Lab 5, Stability of Structures. In this lab, we study the Euler column buckling. The procedures for the VL experiments are straightforward. The students start adding weight to the tray that applied downward force to the columns until the columns start buckling. One of the columns has strain gauges on both sides so that the students can measure the strain values while keeping adding the dead weights. The use of strains to monitor the buckling is better than a simple visual observation since the column's stability/instability can be monitored effectively using quantitative measurement rather than qualitative visual observation. Based on the VL experiments, the students can find a critical load. Students can also do the same using hands-on experiments. Then, the students can calculate the theoretical critical load using the Euler buckling theory. Students can compare the values from VL, experimental, and theory in order to draw conclusions.

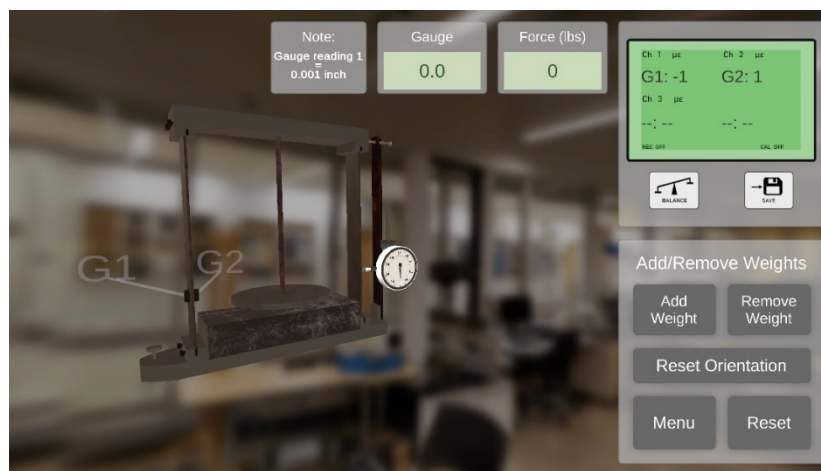


Figure 7: Stability of Structures (Lab 5)

Figure 8 depicts Lab 6, Fatigue. In the experiments, we use a rotating bending beam, originally developed by Wöhler [20] according to Zahavi [21]. We use this virtual rotating-bending machine to apply stress onto a rotating specimen until the specimen fails. Based on the applied

stress value and the number of reversals at which the specimen failed, we plot the S-N curve originally developed by Kloth [22] according to Schütz [23]. In the VL experiments, we start the experiments by choosing a specimen, rotational speed (i.e., revolution per minute), and load (N). Then, we start rotating the beam virtually. However, since we have to deal with a very wide range of reversals (e.g., 10^6 , 10^7 , etc.), we implemented the “fast-forwarding” button. As a result, students can hit the “fast-forwarding” button to complete each experiment in a matter of seconds, instead of a matter of hours or days, so that students can obtain the data, immediately.

Based on the S-N data in the log-log plot, students can find Basquin’s law [23] (i.e., the power-law relation) fitting parameters for the data from the VL experiments. By using the S-N data, students will be able to predict the number of reversals to failure based on the applied stress (or vice versa), which is essential when following the safe-life design of engineering structures such as aircraft. The safe-life design of structures is one of the two fundamental philosophies in engineering design. The other design philosophy is the damage tolerant design, which is a concept that is generally taught in graduate-level fatigue courses through fracture mechanics.

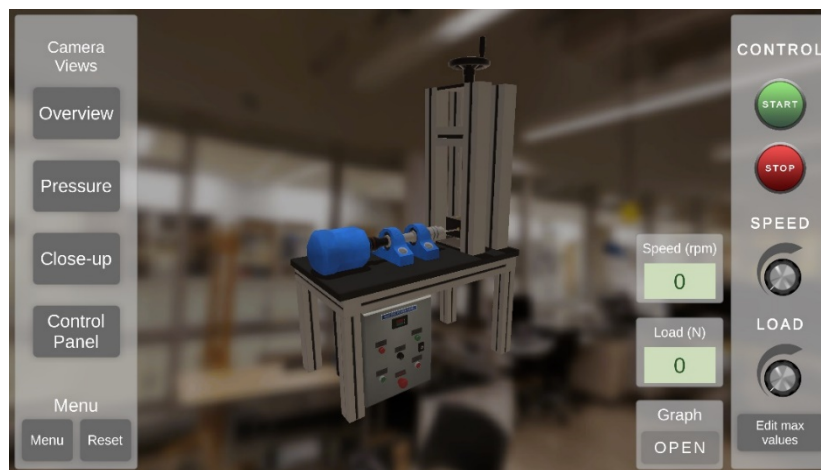


Figure 8: Fatigue (Lab 6)

5. Results and Discussion

Pedagogy Change Before, During, and After the COVID-19 School Closures and Remote Learning

In the following sections, we will discuss how the pedagogy changed before, during, and after the COVID-19 pandemic school closure/remote learning. During the COVID-19 pandemic, Purdue University shifted from the in-person courses (before the pandemic started) to school closure/fully-online remote learning (during the pandemic) to hybrid in-person/online courses (during/after the pandemic). Please note that at the time of preparing this manuscript, the COVID-19 pandemic is still taking place.

Before (January 2019–March 2020)

As described in the previous section, our AAE 35201 VL effort started with brainstorm and conceptualization (Spring 2019), computer modeling and trial implementation (Summer 2019–Fall 2019), and full implementation (Spring 2020). At the same time, we were continuously using AAE 20401 VLs, which was reported in our previous publication [1]. As we were implementing the AAE 35201 VL, we had modified the pre-lab assignments to make sure that we are using VLs to the best of their capacity for student learning. We added specific VL experiments to be conducted as a part of the pre-lab assignments, which are later used as a part of lab reports.

Furthermore, we added some further details on the lab report requirements so that the students can correlate the lab activities (i.e., both virtual and physical) to the practice of engineering. For instance, in addition to the previous lab report requirement, where the lab activities are only derived from engineering and science, we start asking students a big-picture question, such as “What is one application that an engineer in practice might use with the skills you learned in this lab?” A question of this kind makes students think hard about what they are doing so that they can correlate their lab activities to the application of engineering. Thus, to conclude the section of “before” COVID-19, we were using the hybrid of virtual activities and hands-on activities in order to maximize the learning opportunity for the students.

During (March 2020–August 2020)

In the middle of March 2020, the Purdue University campus in West Lafayette, IN, experienced school closure due to the COVID-19 pandemic. At that time, the learning environment shifted from in-person learning to online/remote learning. As a result, the hybrid virtual and physical learning activities shifted to the fully-online learning activities. Since we had already completed Labs 1-4 in the hybrid virtual and physical labs by then, the activities for the last two labs (i.e., Labs 5-6) became fully-online virtual activities.

During this time, we created new lab assignments that are solely based on virtual lab and theoretical analysis. Since the campus was closed and students were sent home, the assignment we created for Labs 5 and 6 were individual assignments rather than group assignments. Since we had no physical lab assignments, there was no need for us to separate the prelab and lab reports. Thus, we combined these two lab assignments to create one assignment per lab. The newly created assignments, which we called “Individual Assignment,” consists of the following two parts: 1) Technical Review and 2) Lab Report. The first section, 1) Technical Review, consists of questions that were based on the prelab assignments and ask questions about theoretical backgrounds on the subject matter. The first section was 20% of the total score. The second section, 2) Lab Report, was based on the content of the group lab report that we previously used. However, we asked students to conduct in-depth experiments using VL. Then, we asked students to analyze the VL results and compared the results against the theory. Since we included some intentional errors while designing VLs, the VL results had some scatter, which worked great.

As with the rest of the university, we provided pre-recorded lab preparation video for the students to watch. In addition, since we were unable to submit lab assignments in-person, we started using the online tool to collect lab assignments. During this period, we used Blackboard Learn, a learning management system (LMS) used at Purdue University at that time, to collect assignments. Also, we needed to find a way to interact with students, and the e-mail communication alone was not suitable for the discussion of subject matter; thus, we started using Piazza, another type of LMS. Piazza made it possible for us to have a discussion asynchronously. The fully-online course at Purdue University lasted until the end of Summer 2020, although there were no AAE 20401 and AAE 35201 courses that took place during Summer 2020.

After (August 2020 – May 2021)

We used the experience that we obtained before and during the COVID-19 school closure and remote learning in order to improve the hybrid virtual and physical learning activities for the Fall 2020 and Spring 2021 semesters. The following are the summary of lessons learned and how we implemented (or in the process of implementing) the countermeasures.

The first lesson we learned was that the ease of connecting to the VL software was important. There are two types of software: a desktop application and a web application. The desktop application is a traditional software, wherein a user must use the computer that the software is installed. In other words, if the users want to use the software on their computers, they have to download the software installation file from either the internet or a physical form (a USB drive, CD, etc.). On the other hand, the web application is a newer approach to the software, where the user does not need to install software because the software is delivered “on-demand” via the internet. In other words, the web application is delivered whenever and wherever the users require as long as the users have an internet connection.

The previously-reported AAE 20401 VL [1] was a desktop application, and the currently-reporting AAE 35201 VL is a web application. In order for the students to use the AAE 20401 VLs, a desktop application, we asked the Information Technology (IT) department of the university to allow us to use its in-house application, “Software Remote.” In the “Software Remote” application, the software is installed locally to the server that the IT department maintains. Then, students access the server using the in-house “Software Remote” program. However, the use of the “Software Remote” application for the VLs was not optimal since it had a significant delay (i.e., input lag) in the user response. After the completion of the Spring 2020 semester, we heard from the students based on the end-of-semester evaluation that the remote aspect of the VL should be updated, whereas we never had the same issue when the students use the VL software at the on-campus computer lab in-person prior to the COVID-19 pandemic.

Based on this experience, we learned that 1) the desktop virtual lab software worked totally fine and 2) the in-house “Software Remote” solution caused the input lag which is undesirable. To this end, the university allowed students to use the “Remote Desktop Protocol” (RDP), a commercial application developed by Microsoft, as a countermeasure for the COVID-19 remote learning. When using RDP, the students connect to the computers at the on-campus computer lab from their homes. Therefore, we did not have to rely on the in-house “Software Remote”

application. From the start of the Fall 2020 semester, we mandated the use of the RDP for VLs, and we never had any issue afterward. Furthermore, we are currently developing the web application for the AAE 20401 VLs with the original manufacturer of the AAE 20401 VLs so that we will forgo the use of the desktop application. Finally, the AAE 35201 VLs did not have any issues with the connectivity since it was designed as a web application from the start of the development.

The second lesson was that how we present the VL to students makes a huge difference in the student perspective of using VLs. Before the COVID-19 pandemic, the instructor was able to introduce the VL module during the lab preparation lecture. For Labs 5 and 6 during the COVID-19 school closure, we replaced this procedure with the written instruction on how to use VL during the COVID-19 pandemic. This was not optimal since this method of instruction appeared to confuse some students. Thus, what we started doing was to create a short 10-minute video on the introduction of each VL module so that students can use the VL without any difficulties. After we started using the short introductory video, students understand the procedures and use the VL without any difficulties. From this experience, what we know is that given the same VLs, how we introduce VLs is a very important aspect of using VLs.

The third lesson was that the VLs are not replacements for the physical labs. However, if you use VLs wisely, VLs can provide better learning opportunities than the physical labs alone. During the COVID-19 school closure/remote learning, our only option was to use the VLs. Thus, in an extreme case like this, where the physical labs are not accessible, VLs are the effective approach to education. Does it mean that the physical labs are always better? More specifically, do the VLs need to be always the supplement for the in-person physical labs? Not necessarily. In a fatigue lab (Lab 6), for example, being able to conduct the rotating-bending experiments to plot the S-N curve is costly since the fatigue experiments are destructive since we need to apply cyclic loading until the failure of the structure. Also, fatigue experiments may take a long time since, in some cases, we need to apply a very large number of cycles in order to cause a fracture in the specimen. Both of these issues (i.e., cost and time) are not an issue in VLs since a) it is free for students to run as many experiments as they desire and b) the aforementioned “fast-forwarding” button allows students to conduct all experiments within a matter of seconds. Thus, in the case of the fatigue lab, we can easily plot the S-N curve based on the VL results, whereas doing so based on the hands-on experiments alone is difficult.

6. Conclusions and Future Work

In this project, we implemented the six VLs for AAE 35201 Structural Analysis I Lab at Purdue University. We implemented AAE 35201 VLs 1-4 and VLs 5-6 before and during the COVID-19 school closure, respectively. Through the implementation of the AAE 35201 VLs, as well as the continuous use of the AAE 20401 VLs, during the COVID-19 closure and remote learning, we learned the following three lessons as the keys to the successful implementation of VLs: 1) ease of connectivity, where the students must be able to access and operate VLs without any connectivity/technical issues, 2) a proper VL introduction to students, where an instructor must pay attention to how VL modules are presented to the students, and 3) an instructor can use VLs as an effective tool to improve the teaching and learning in the aerospace structures education.

As a future work and continuous improvement, we will 1) implement animation that connects the ideas of VLS to the engineering applications and 2) add an additional VL module. For 1), when students open the virtual labs on their computers, the animation will be automatically played on the computer screen. In the animation, students will be able to see the engineering application for the virtual lab module. For instance, the wing bending of an aircraft is visualized in the animation for Lab 2. Then, a cross-sectional view of the wing is visualized, followed by the application of bending moment (M), torque (T), and transverse shear force (V). By doing so, the students can see the stringer-web cross section of an aircraft and how the cross section deforms based on the application of M, T, and V. For 2), we will add an additional VL module, namely, the stress concentration VL. In this new VL module, we will create a visualization tool on how the hole size affects the stress profile around a hole in a finite 2D plane stress panel subjected to uniaxial tension. Then, we will be able to observe how the von Mises stresses ($\sigma_{von\ Mises}$), principal stresses (σ_1 and σ_2), and cartesian normal and shear stresses (σ_{xx} , σ_{yy} , and τ_{xy}) change based on the hole size. In addition, we will add the functionality to change the mesh size so that the students can instantaneously observe how the mesh size affects the stress ($\sigma_{von\ Mises}$, σ_1 , σ_2 , σ_{xx} , σ_{yy} , and τ_{xy}) profiles around the hole without the use of finite element software. The stress concentration VL will be beneficial to undergraduate students who study mechanics of materials and machine design in aerospace and mechanical engineering.

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