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JUNE 22 - 26, 2020 #ASEEVC
Paper ID #30319

Scaffolded Laboratory Sequence: Mechanics Lab

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Abstract

Laboratory courses are a platform for students to practice skills essential to the engineering profession. They also foster lower-level learning (e.g. understanding of fundamental concepts) and higher-level synthesis and creativity. The undergraduate programs for Mechanical and Aerospace (MAE) Engineering at the University of Virginia have been enriched with an updated experimental laboratory sequence, which include three 2-hour courses: 1) Mechanics Laboratory, 2) Thermal Fluids Laboratory, and 3) Aerospace or Mechanical Laboratory. The first two courses were designed to supplement lecture-based theory courses during the same semester students are taking them. The third course challenges students to design and execute their own experiments, building upon skills they learn in the earlier labs. Thus, the new sequence includes horizontal integration with discipline courses across the curriculum, and vertical scaffolding of skills related to experiment design and analysis.

The Mechanics Laboratory course was offered to the first cohort in Spring 2019. It was designed to give hands-on experiential learning to complement foundational courses such as Statics, Dynamics, and Strengths of Materials. Students used research grade equipment in the new Undergraduate Materials Testing (UTM) lab including a 250 kN universal test machine, a 2000 in-lb torsion tester, new hardness testing machines, and heat treatment ovens. In addition to supporting content from core courses, the lab introduced students to principles of experimentation including data acquisition, data analysis, and presentation of results. Several experiments were conducted using PASCO Capstone or National Instruments LabView software to collect data from a variety of sensors including load cells, accelerometers, and motion sensors.

This paper describes the integration of the new sequence into the curriculum and includes details on the development and implementation of the first course, Mechanics Laboratory. It describes the motivation behind the redesign, discusses logistical challenges and solutions, and outlines specific modules within the Mechanics lab. Finally, the paper includes student feedback, an assessment of student learning, and recommendations for improvement.

Motivation for Reinventing the Experimental Lab Curriculum

Lab experiences are an essential part of any engineering curriculum. Expected outcomes for these experiences are explicitly communicated through ABET Crtierion 3, Outcome 6, which states that program graduates should have "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions."[1] To meet this outcome students must develop cognition on multiple levels from comprehension and analysis to synthesis and evaluation.[2]. This is an ambitious goal for which engineering programs have varied ways of achieving. Feisel and Rosa present an interesting history of the role of labs in engineering education that chronicles the tension between practical skill and theoretical knowledge. They also discuss societal changes that effect how these are balanced, and suggest thirteen objectives for lab courses. These include several objectives that address ABET Outcome 6 (e.g. instrumentation, model, experiment, and data analysis), teamwork and communication objectives, and few others. [3] In terms of incorporating courses into the curricula to achieve these objectives, two approaches are often seen. First, the lab course may be 'attached' or integrated into a course that otherwise has a focus on engineering concepts and content presented in lectures. For example, Le et. al. outline a Mechanics of Materials course offered in a 3-2-4 format (3 hours lecture, 2 hours lab, 4 credit hours) which includes material testing and simulation labs. [4] Miller discusses an alternative format that completely blurs the lines between lecture and lab, with three 110 minute sessions a week.[5] This coupling of theory and practice has advantages in helping students gain insight into foundational principles. However, accomplishing course objectives relating to experimentation in in addition to those related to engineering problem solving can be daunting. For this reason, many schools have installed courses dedicated to laboratory skills. For example, Schertzer et. al discusses the structure and content for an 'Engineering Measurement Lab' at the University of Rochester.[6] A dedicated course has the advantage of a singular focus on developing and assessing laboratory related objectives. A potential drawback, however, is that students could miss connections between lab activities and concepts from other courses.

In the distant past, the Mechanical and Aerospace Engineering program at the University of Virginia included several labs which focused on 'hands-on' experience with engineering concepts. These labs developed some aspects of experimental design and thinking, but there wasn't a strong focus on technical writing or more modern data acquisition methods. Then, as standards for laboratory related skills received more attention, a shift was made to lab courses centered on experimental methods. In addition, as this shift occurred, increasing enrollment and new demands on the curriculum led to an overall reduction in student laboratory experiences. However, in 2018 the department faculty decided to revisit this balance between experimentation skills and hands-on experience with engineering concepts, which has led to an overhaul of the experimental lab sequence. The reinvented experimental lab curriculum replaces two 3-hour lab courses (Experimental Methods Laboratory and Mechanical Engineering Laboratory) focused on experimental skills with three 2-hour lab courses (Mechanics Laboratory, Thermal-Fluids Laboratory, and an updated Mechanical Engineering Laboratory). The first motivation for this change was to horizontally align lab experiences with required courses in mechanics and thermal sciences so that students' experiential learning serves not only to build their experimentation skills but also to help them understand foundational principles. The need for better connection originated from the faculty teaching the required courses. They felt students needed more tangible experience with the concepts they were learning. In some cases, experiences directly related to these principles were included in the previous lab courses, but it was coming 1-2 semesters after the relevant course. With the redesigned curriculum, the Mechanics Lab is aligned in the same semester students are taking Strengths of Materials and Dynamics, and one semester after they have had Statics. The Thermal Fluids Lab is aligned in the same semester students take Fluid Mechanics, a semester after they have had Thermodynamics, and a term before they take Heat and Mass Transfer.

The second motivation was to increase the overall quantity of lab experiences the students get. The original labs were each 3 credits, with two hours of lecture, and a two hour lab each week. Though some lectures focused on experimentation principles (e.g. data acquisition, uncertainty analysis), additional lecture time was needed to refresh concepts from other required classes. With the new sequence, each lab course is two credits, with a single lecture hour and a two-hour lab each week. The rationale in removing one of the lecture hours was that the alignment of the lab with co-requisite theory courses could shorten the amount of time needed to re-introduce those concepts. The net effect is an increase in lab time by 50% while reducing the lecture time by 25% without a net effect on the total number of credits.

A final objective for the new sequence was to create an experiential learning sequence with vertical scaffolding. In other words, the lab sequence should build student skills from lower level learning of fundamental principles to higher level skills of synthesis and creativity. For example, writing a full detailed lab report requires a synthesis of knowledge about the principles involved in an experiment, mastery of experimental design and analysis techniques, and effective writing skill. This is a tall task for students working with new principles and concepts for the first time. By adding another semester to the experimental lab sequence, there is time to build upon student experimental skills incrementally. In the Mechanics Lab, students focus on concepts and how to use tools and sensors for mechanical measurement; there is minimal writing, but students regularly present and interpret graphical results. The Thermal Fluids Lab expands upon experimentation skills such as data acquisition and uncertainty analysis. In this class, students also write a single detailed lab report on an experiment that undergoes an two-stage peer review process.. Both of the first two labs include a small group project that challenges students teams creativity to design, execute, and communicate their own experiments. For the final course, Mechanical Engineering Lab, students work in teams throughout the semester to design, execute, and write a full report on more complex experiments.

The new experiential lab sequence began in Spring 2019 with the first offering of the Mechanics Lab. The succeeding sections of the paper specifically discuss the design of this course, highlighting a few specific modules and how they align horizontally with required foundational courses as well as their place in the vertical scaffold of experimentation skills. This is followed by an assessment of the first offering of the course and a discussion of plans for future improvement.

Mechanics Lab Outcomes, & Activities

The Mechanics Lab course is the first course of an enhanced experimental methods sequence for the Mechanical and Aerospace Engineering undergraduate curricula, designed to give students hands-on experiential learning to complement theoretical courses such as Statics, Dynamics, and Strengths of Materials. It is the intent that students gain experience in teamwork, experiment design, and technical communication during this course in addition to seeing practical applications for fundamental concepts in Mechanics. The course is required for all Mechanical and Aerospace Engineering majors and is typically taken in the second semester of their sophomore year. At this point, students have finished three semesters of Calculus and Ordinary Differential Equations. In addition, they have had one semester of Chemistry and two semester of Physics, each with lab components. Finally, they have take an introductory mechanical or aerospace engineering course where they practiced computer aided drawing. In the same semester, students take Strengths of

Materials and Dynamics courses, which are delivered in a lecture style to 100-150 students. For Spring 2019, there were 108 students in six lab sections of no more than 24 students each. Students worked in 3-4 person teams within their section. There was a single lecture each week (on Monday) and the two-hour lab sections met Monday or Wednesday afternoons.

Course assessment fell into five categories. Short prelab assignments, worth 15%, help students prepare for the coming laboratory activities. They are based on information obtained from the laboratory handouts and supplemental background documents. Post-lab assignments (40%) require lab teams to synthesize, document, and analyze results from tests and experiments. Two quizzes (30%) were given to assess retention of concepts from the various lab activities. A material test project gave teams freedom to develop and execute a unique mechanical test or experiment, which they presented orally at the end of the semester. Finally, five percent of the course grade was based on teamwork and professionalism including participation in required activities, and instructor and peer evaluations of individual student contributions.

Course learning objectives covered three ABET outcomes:[1] experimentation outcome (#6), teamwork (#5), and an ability to communicate (#3). Activities were planned for students to put into practice theoretical concepts, progressing from knowledge-based learning to application. In addition, the experimentation skills developed include an ability to use common measurement tools such as load cells, accelerometers, and strain gauges; and an ability to conduct and interpret standard material tests like the tensile and hardness tests. Furthermore, for each experiment students evaluated experimental results against predictive models. A frequent mantra of the course is a quote attributed to statistician George Box, “All models are wrong, but some are useful.” Students were asked to think critically about the differences between their predictions and experimental results (i.e. error) by examining the assumptions in their ‘wrong’ models as well as the precision of their experimental procedure.

Teamwork is an integral part of the lab structure. Groups are assigned for the duration of the semester using the CATME (Comprehensive Assessment of Team Member Effectiveness) team builder survey.[7] A group forming exercise is incorporated into the second lab meeting based on the team policies and student expectations assignment presented by Oakley et. al.[8]. At the end of this meeting, groups submit a team expectation agreement which they each sign. A team peer assessment survey is administered via CATME at mid-semester and at the end of the term.

Technical communication is an element of all three lab courses. However, written communication is a more substantial part of the second two courses. Within the Mechanics Lab, post-lab assignments emphasize certain elements of a lab report, such as effectively presenting results in well-formatted graphs and tables and discussing errors between theoretical predictions and experimental results. Full reports are not yet required. Instead, students are introduced to other elements of a report as they write an executive summary for one experiment, and create a academic style poster for another. Finally, teams orally present results from their group project.

In the following section, the individual lab experiments are outlined, and select activities are highlighted to illustrate how they serve the learning outcomes for the course. A few details on equipment are also provided.

Experiments

A list of the lab activities are shown in Table 1. These activities took place in two separate spaces. First, a dedicated laboratory room includes seven work stations with a National Instruments chassis containing data acquisition modules for analog input and output, accelerometers, half and full bridge strain gauges, and temperature measurement. In addition to LabView, the workstations are loaded with PASCO Capstone software.[9] Equipment for specific lab experiments are brought out as needed. This included commercial grade sensors (e.g. accelerometer and eddy current proximity sensor), instrumented torsion and bending apparatuses that were built in-house, and a suite of PASCO sensors (e.g. load cells, 3-axis accelerometers, motion sensors, etc.) Second, the Undergraduate Materials Testing (UTM) lab is an interdisciplinary space with a 250 kN universal tester, a 22.5 N-m torsion testers, heat treatment ovens, and a Rockwell Hardness tester, among other equipment. In general, activities in the UTM lab worked best when scheduled so that no more than one or two teams were there at a time.

Table 1: Mechanics Lab Experiment Modules

Lab Activity	**Aligned Course**
Truss lab. Verify member force calculations with load cell measurements.	Statics
Team Forming Exercise. Teams develop policies and expectations for their group.	–
Connections testing. Destructive testing on bolted joints using Universal test machine.	Strengths of Materials
Tensile Testing. Conduct tensile test for steel or aluminum specimen. Students will manually convert force vs. elongation data to a stress-strain curve and calculate elastic modulus, yield strength, tensile strength, percent elongation, and static toughness (requires numerical integration).	Strengths of Materials
Torsion Lab. Plot shear stress vs. strain and find shear properties based on torsion test.	Strengths of Materials
Sensor & Data Acquisition. Build virtual instrument to read eddy current proximity sensor.	Strengths of Materials
Heat Treatment. Determine the effect of 3 different treatments on the hardness of 4340 steel.	Materials Science
Beam Bending. Test the effects of area moment of inertia, span, and material on beam stiffness. Validate predictions for beam deflection.	Strengths of Materials
Rotational Inertia Lab. Test the relationships between mass moment of inertia, torque, and angular acceleration.	Dynamics
Kicking Lab. Build a leg model and test conservation of momentum during kicking.	Dynamics
Group Project. Teams design and execute a unique experiment or material test of their choosing.	Various

The first experiment was chosen as a conceptual transition from Statics to Strengths of Materials. One paradigm that can be difficult for Statics students to understand is that of an internal force. This is a serious liability when they transition to Strengths since identifying the internal force (or moment) is a first step to determining stresses within the material. Truss analysis is typically the first introduction to internal forces, so this seems a logical place to start the Mechanics lab. The implementation of PASCO bridge kits is well documented [10, 11]. In the PASCO bridge system, in order to measure member forces, one must replace a member with two half-sized beams joined by a load cell. The simple act of making this swap shows that the internal force is inside the member. The truss lab also provides an first case study on why theoretical predictions might not match experimental results, as students must consider the assumptions needed for truss analysis and whether those apply or not to the physical system.

The Connection Lab builds upon the idea of internal forces and presents physical examples of the various stresses in a joint, namely pin shear stress, plate tension, and pin-to-plate bearing stress. Homework problems involving these calculations are common in the early weeks of Strengths of Materials. An example from Beer et. al. is shown in Fig. 1. To determine each type of stress, a free-body diagram (FBD) with the member cut at the relevant stress location is constructed. For example, Fig. 2 contrasts the bearing and shear forces in a pin from a double shear joint vs. a single shear joint. However, students may not immediately appreciate why the FBDs would be drawn this way, or how the internal forces develop. The lab activity aims to remedy this by providing examples of each type of stress leading to failure. This lab involved four types of connected specimens: a lap joint with 1/4 inch bolts, a lap joint with 3/8 inch bolts, a butt joint with 1/4 inch bolts, and a butt joint with 3/8 inch bolts. The plates used in each joint are 1/8x2.5 inch steel. Each group tests one lap joint and one butt joint, using the universal tester in the UTM lab to pull it apart until failure. The peak load and the broken specimens are shared with the entire section. Students are required to calculate all stresses (e.g. pin shear stress, plate tensile stress, and bearing stresses) at the peak load and identify which stress led to failure. Fig. 3 shows samples of the connected specimens after they have been broken. The lab exercise provides practice in calculating each type of stress. More importantly, in the broken specimens, students have a tangible representation of the free-body diagram for the stress that caused failure. For example, students can count the circular cross-sections to determine the bolt shear stress; the single shear specimen has one fractured surface for each bolt while the double shear specimen has two fractured surfaces for each bolt. The specimens that failed in plate tension have a fracture surface created by the reduced cross section at the hole. Finally, as seen in Fig. 4, bearing stress between the bolt and the back of the plate lead to yielding around the hole, i.e. the hole is elongated and slightly swollen.

Several of the lab experiments, like the Connection lab, are strongly aligned with material in Strengths of Materials. These include the tensile test, torsion test, and beam bending labs. However, these also provide the first layers of scaffold for student's skills in experimentation by introducing them to mechanical tests and measurements. For example, the torsion module has two different tasks. In the first, students conduct a destructive test using the Instron MT-1 torsion tester in the UTM lab. They create shear stress vs. shear strain graphs and find material properties. As this follows the tensile test, they are asked to compare the fracture planes from the torsion test and the tensile test. Students observe that in both cases the material fails on a plane where shear stress is largest, i.e. the plane oriented at 45 degrees from the specimen in the tensile test and the one at 90 degrees in the torsion test. (Both specimens are aluminum and were fabricated by student work-

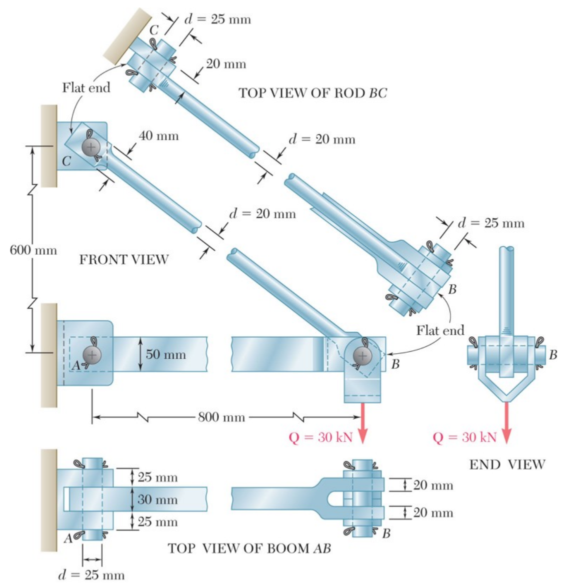

Figure 1: Example problem for Mechanics of Materials[12].

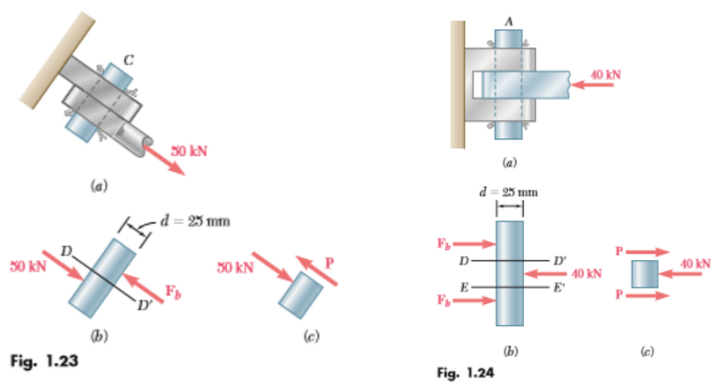

Figure 2: FBDs for single (left) and double shear (right) pins. Image from Mechanics of Materials[12].

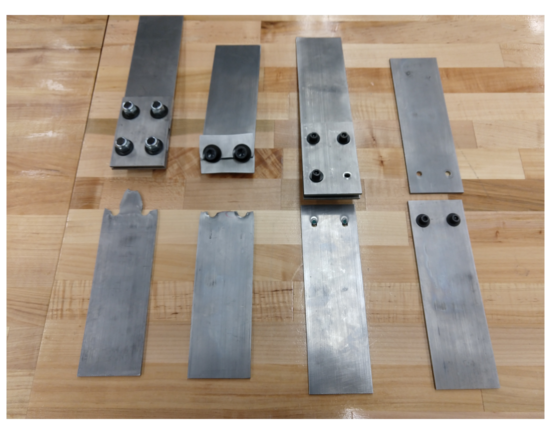

Figure 3: Broken lap and butt joint specimens from the Connection Lab.

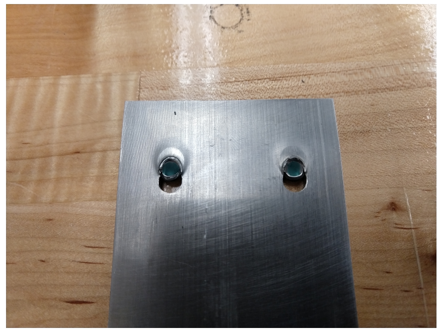

Figure 4: Broken member showing yield at bolt-plate interface due to bearing.

ers.) For the second task, students conduct a non-destructive test on a torsion bar instrumented with strain gauges. This requires they connect the gauge leads into a full Wheatstone bridge, write a LabView Virtual Instrument (VI) code to read the voltage signal from the bridge, and calibrate the bar by applying known masses at a given distance. Fig. 5 shows a picture of the instrumented bar. Thus the torsion lab provides an introduction to several important concepts in data acquisition. For example, electronic sensors have a particular design so that an electronic signal is produced that is proportional to a physical response. Data acquisition involves both capturing this signal and converting it to the response of interest. Calibration is the process of comparing the sensor response to a known standard. Students will continue to use these skills in the Thermal-Fluids Laboratory as they build VIs and calibrate sensors for temperature and pressure measurements.

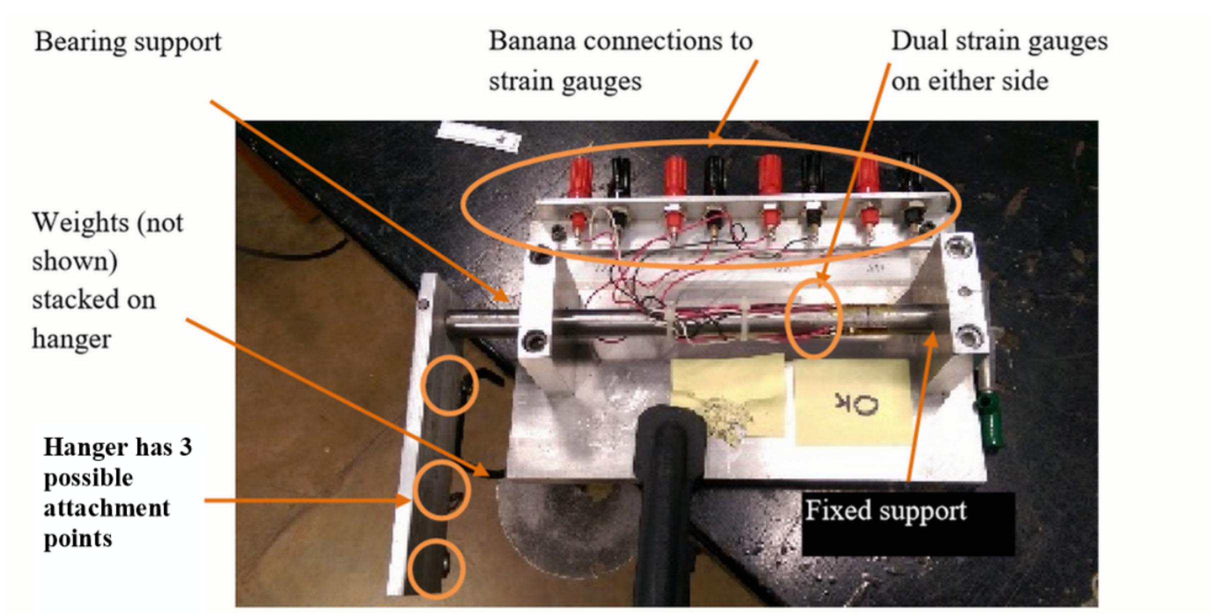

Figure 5: Instrumented torsion bar.

The heat treatment lab was the one experiment not directly tied to Statics, Dynamics, or Strengths of Materials. However, it serves to introduce hardness testing as well as demonstrate the effect of thermal processing on steel. The post-lab assignment for this activity included a one page executive summary. This succinct writing effort lays the foundation for developing a full lab report format in the second lab course. This lab experiment also introduced concepts in experiment design (e.g. how to develop a concise experiment objective with clear control vs. response variables) which students were asked to model later in their group project.

Two experiments during the semester build upon concepts from Dynamics. In the Rotational Inertia lab, students measured the effects of changing moment of inertia on rotational acceleration. For the second dynamics experiment, teams designed an experiment to test principles of impulse-momentum. They built a mechanical 'leg' using the PASCO bridge pieces, instrumented the 'foot' with load cells, and measured acceleration of various types of objects as they were kicked. A picture of the experimental equipment is provided in Fig. 6.

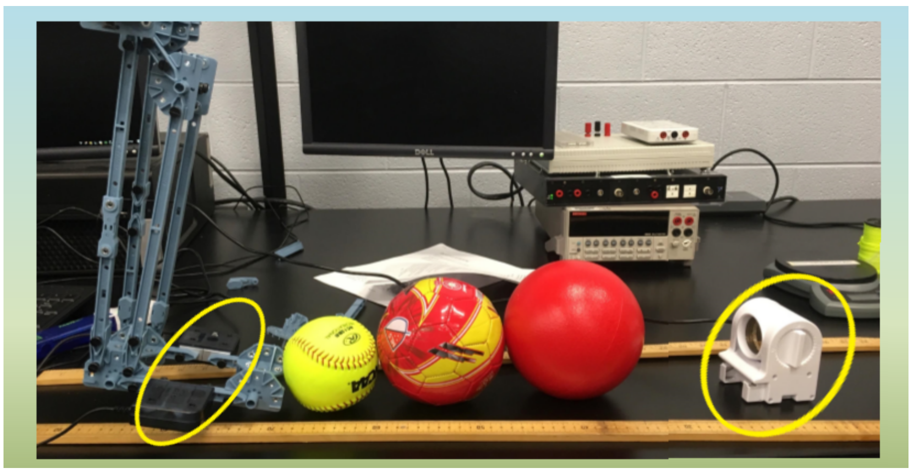

Figure 6: Kicking Lab Equipment. PASCO 'Leg' has load cells, circled on the left. A ultrasonic sensor, circled right, was used to measure exit velocity of the three different types of balls.

The final activity for the semester was a group designed experiment and oral presentation. This project served to encourage student creativity as they used skills developed throughout the semester to acquire new knowledge. Some examples include destructive tests (tension, torsion, bending, or compression) of 3D printed specimens with varying infill properties; strength of adhesives such as glues, JB Weld, and tape; flexural stiffness of fencing blades; the effect of anodizing on micro-hardness; and puncture testing of wood flooring. Photos from a few of the projects can be seen in Fig. 7. Students presented their work orally to the section during the last lab period of the semester.

Assessment

Assessment metrics for the Mechanics lab were taken from a student exit survey, tensile test post-lab grades, performance on the Heat Treatment executive summary and group project, and CATME final peer survey. Seventy-one students completed a post-course survey which included 3 Likert scale questions, one selection, and two free response questions. The Likert questions addresses their agreement that the course would prepare them for the engineering profession, that prelab activities were useful in preparing for labs, and post lab activities were appropriate in scope and level.

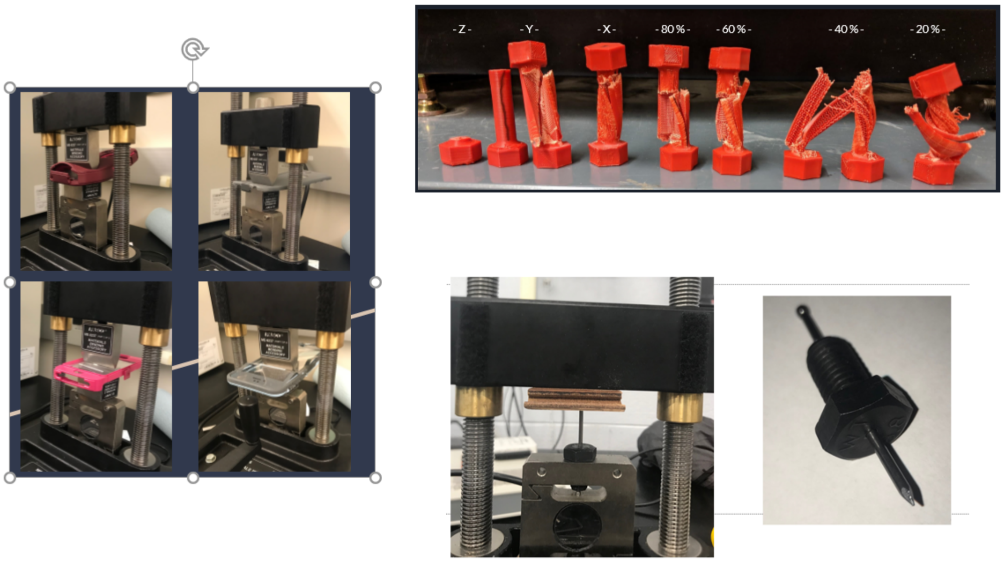

Figure 7: Images from three group projects. Left: Bending test of phone cases. Top right: Torsional test of 3D printed specimens with varying infill density. Bottom right: Puncture test on various brands of wood flooring.

Students were also asks to select which activity was the most helpful in understanding concepts from the pre- or co-requisite courses. Finally, the survey asked for free responses for students to identify how a lab activity helped them better understand a concept from one of their Mechanics courses, and to suggest improvements. Eighty-nine percent of respondents agreed or strongly agreed that the laboratory course will improve their preparation for the engineering profession. In addition, 68 of the 71 respondents provided a clear example of how a lab activity improved their understanding of an engineering concept, with the bolted connection lab and tensile lab being the most commonly cited. A common suggestion for improvement was to better sync lecture material with prelab assignments. In general the placement of the lecture on Monday was not ideal as labs took place on Mondays and Wednesdays. In fact the first lab started ten minutes after the lecture finished. Thus, prelab material would need to be given right before lab or an entire week in advance. For the Spring 2020 semester, the lecture was moved to Friday which worked out much better. Another common student recommendation was to reduce the weighting for quizzes. However, the quizzes provide individual accountability for a course that has a lot of group work.

Student performance of the tensile test post-lab was excellent, with an average score 98%. However, they did not do as well on related questions from the first quiz, earning an average of 87%. The averages for the Heat Treatment executive summary and group project were in the mid to high B range. Though these are reasonable marks, a higher standard could have been set for student written and oral communications. This is one area in which students may have benefited from additional lecture time. One option is to providing more lab time for instruction and student preparation. Another possibility is to provide asynchronous mini video lectures to help during post-lab work.

The CATME peer survey revealed ’conflicts’ in 2 of the 28 teams, but most team members were very positive about the team experience. In future labs, it would be useful to have groups follow-up on their team expectations mid-semester, in addition to completing the CATME survey.

Another area of needed improvement was the dynamics experiments. Dynamics proved to be a very difficult course this term, and the two experiments conducted in lab did not go far enough to help. The rotational inertia lab was most likely too basic, and the kicking lab suffered from significant measurement uncertainties. A Dynamics instructor has helped develop better labs for the 2020 lab course.

Finally, to more accurately assess whether the lab is fostering mastery of foundational principles and concepts, a future study could look at student performance in co-requisite and/or follow-on courses.

Conclusions

Experimental lab courses are often expected to meet a diverse set of outcomes, from teaching experimentation principles to developing soft skills in teamwork and communication, to providing tactile examples of concepts in a wide-variety of other courses. At the same time, one hopes the experience is enjoyable for students and that their learning persists well beyond the end of the course. The University of Virginia has adopted a new experimental lab sequence that accomplishes several goals. First, it aligns content to enhance student understanding of concepts in foundational courses, striking a better balance between content devoted to engineering concepts and those that build experimentation skills. Second, it provides more lab experiences for students with the belief that experiential learning fosters deep and lasting knowledge. Finally, it creates a scaffolded structure for experimental skills. As students progress through the lab sequence, they build skill in measurement techniques, experiment design principles, analysis methods, technical communication, and teamwork. This paper discussed the first course, a Mechanics Laboratory, which is aligned with Statics, Strengths of Materials, and Dynamics. In addition to providing physical examples from principles students learn in these courses, the lab activities provide the first layer in experimentation skill development. Students learn how to conduct standard mechanical tests, how to use strain gauges and other measurement tools, and how to present experimental results and compare them with theoretical predictions. They are also introduced to technical communications, and have the opportunity to design and execute their own mechanical test. Preliminary feedback from the first course indicates that the change has been positive, but improvements are forthcoming in several areas, most notably in the dynamics experiments.

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