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Mobile, hands-on experiments for classroom demonstrations and student team-based exercises

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Introduction

Experiential learning can be very effective in getting students to interact with the engineering concepts and see them in action shortly before or after being exposed to the theory. Team based activities that accompany hands-on learning are a further way of enhancing learning as students collaborate with each other to discuss and test their ideas. This project aims to amplify such hands-on experiences by developing new mobile experimental platforms in mechanics, thermal systems, and electrical/electronic systems for use in core and multidisciplinary courses. The project also concerns effective instruction and classroom practices to ensure that diverse student teams function well, with all students feeling comfortable and confident to work together to learn new concepts.

Beam Bending

Mechanics of materials in general and beam bending in particular is a subject that challenges many undergraduate students. An introductory course in mechanics of materials is required of all AE, ME, and CE students in the authors' university, and advanced courses in structural mechanics (required and elective) are taken by many students. Given the wide variation in backgrounds and mathematical competencies of the students, many instructors have noted how difficult it can be to teach new concepts, and at times, to "un-teach" misconceptions that students have already formed on some of the fundamental topics [1]. Examples of mechanics experiments have been reported to help with students understanding, motivation, and concept retention [2], [3], [4], and [5].

An experimental platform to study the bending behavior of beams has been under development for several years by the authors [6], [7], and [8]. Originally, a portable, beam-bending apparatus was designed and fabricated that (a) could fix a variety of metallic and nonmetallic beam specimens in a cantilever fashion, (b) could apply point loading and monitor beam tip displacement and bending strains at one or more points, and (c) could apply specified point displacements and monitor bending strain. One of the objectives of the research was to develop portable hands-on beam bending experiments that would go beyond qualitative behavior and would be able to yield moderately accurate quantitative data from which students could see qualitative and quantitative agreement of the textbook theory with physical experiments. Another goal was for students to be able to accomplish short projects and experiments within the classroom, during regularly-scheduled lecture times. Eventually, the goal is to have highly portable measurement systems (leveraging student-owned smartphones, webcams, and perhaps myDAQ data acquisition devices [9]), to allow students to perform the experiments remotely on beams they have designed and fabricated in student "maker-spaces" from stock material or using 3D printers.

For a number of reasons (including Covid restrictions over the past two years), the hands-on experiments have been conducted in "demo-mode," by the instructor in the front of the class, with minimal student involvement. Past research by the authors has shown that students prefer being able to actually touch and perform the experiments themselves and seem to feel that it helps them to learn the material better [10.] So, an important research goal remains the simplification of the apparatus and measurement equipment so that the projects can truly be done by the students entirely using optical measurements accomplished using smartphone cameras or laptop cameras. More will be said about this below.

Assessment data gathered from pre- and post-demo surveys showed that many student misconceptions on mechanics of materials are firmly established and difficult to dispel. The data was collected from a sophomore/junior level strength of materials class (pre-Covid) taken primarily by AE, CE, and ME majors. For example, our experiments specifically targeted the idea that stresses are dictated primarily by geometry and loading and are not influenced by material. However, even after seeing the experiment and doing a short project write-up, only 64% of the students answered a question on this concept correctly; this is a sharp increase over the 29% correct prior to the experiment, but still far short of our hopes and expectations [6]. Similar results were found for the complementary concept that strains are dominated by displacements rather than material properties [6.]

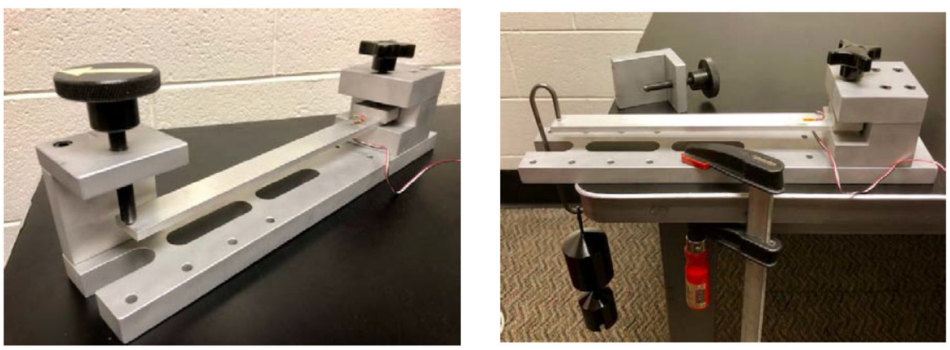

Figure 1. Beam-bending apparatus configured for application of tip displacements (left) and for tip loading (right.)

A third concept targeted in our preliminary experiments is the concept of shear center [11]. This concept is not central to the introductory class in strength of materials, but it is covered more thoroughly in an advanced structures class taught in aerospace engineering. Beams with open, thin-walled cross sections, in particular, behave in very counterintuitive and intriguing ways when bending loads are applied. Figure 2 illustrates (in an exaggerated manner) what can happen if a beam with a thin-wall open cross section is not loaded through its shear center, and the resulting torsion induces significant twisting in addition to bending. This behavior can be so significant that for sections (a) and (b) in the figure, the shear center lies completely outside the horizontal planform of the beam so in order to apply loads at the shear center, a bracket must be affixed at the load point. Consequently, the ability of students to actually *see* the behavior with their own eyes and to touch and feel the way the beams react to tip loads is very instructive.

The theory of shear center is a bit esoteric for many civil and mechanical engineers, but it becomes more germane in the study of thin-walled structures such as beams with open cross sections, for example, folded metal beams and especially composite and built-up beams which

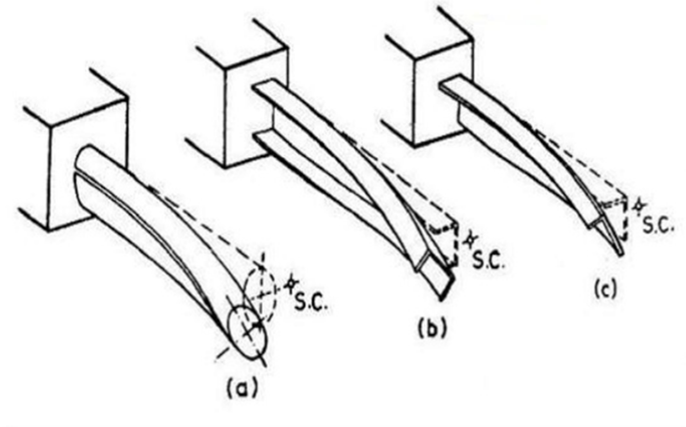

Figure 2. Twisting effect on some cross sections if tip loads are not applied through the shear center (from [12].)

are often assembled from beams and/or plates that are welded, glued, or fastened together. These form critical components in many engineered structures. Of particular importance is whether the joints or fasteners will fail when the beams are loaded in bending. To answer this question, students must first learn about shear stresses and *shear flow* [11] and then learn the modeling and analysis tools to calculate shear stresses induced in particular cross-sections. Shear flow can be used to qualitatively “reason-out” trends and to predict high stress and low stress portions of composite beams. When fully understood, shear flow can also be used to predict the location of shear centers, as well as the occurrence of twisting when transverse loads are applied. Twisting can be seen in all three examples in Figure 2 when loads are not applied at the shear center; this twist does not occur if the load is applied through the shear center, which is one of the important reasons for students to understand the concept.

The existing apparatus developed for beam bending already supported the ability to study the concepts of shear center, torsion, and transverse (lateral) displacement [7]. However, we wanted to test students understanding of the concepts through a series of surveys that were administered pre- and post-demo of the experiments conducted in class. The post survey was also timed to occur after students had completed a short homework where they used the actual data collected in the classroom. The pre and post surveys contained the same questions and were conducted using Qualtrics. There were two different demos conducted:

Project 1 was designed to explore the behavior of beams with thin-walled unsymmetrical sections. Such beams are often fabricated by folding sheet metal to create lightweight, low-cost designs, and they are used for a wide range of structures such as industrial shelving, control panel racks, and temporary structures. Thin-walled open and closed sections also are widely used in aircraft structures. A key characteristic of beams with unsymmetrical sections is the presence of a nonzero cross-bending stiffness which determines the extent to which lateral deflections are coupled to vertical displacements in the presence of vertical loading alone [11]. The primary purpose of this project was to measure vertical and lateral tip deflections (using a webcam) and compare their ratio with that predicted by the Euler-Bernoulli theory developed in class.

Project 2 was designed to further explore the behavior of beams with thin-walled open and closed sections. Beams with open thin-walled sections have very low torsional stiffness, and they will twist appreciably unless the vertical loads are applied at the shear center of the cross section. In the experiments performed in class, the shear center location was measured for three beams fabricated from 3D-printed ABS plastic. As in Project 1, various loads were applied to the beam off axis, and the beam tip displacements and rotations were measured optically.

The projects and surveys were administered in an advanced class in structural mechanics required by aerospace majors. Overall, the pre- vs post-survey performance of the students left a lot to be desired. For Project 1, the overall performance of the students ($N = 24$ students who took both the pre- and post-test survey) went from 55.8% to 62.0% ($p = 0.059$). However, there were some interesting features buried in the data. For example, some questions had over 40% improved response from pre- to post-test. Further thought and discussion is needed to determine what, if anything, in the demonstrations or associated homework assignment was particularly helpful in elucidating these three concepts. The scores on the pre and post tests for the 3 questions depicted in Figures 3, 4, and 5 is shown in Figure 6.

Q7: Question 7 asked for the ratio of bending stiffnesses H_{22} to H_{33}. Roughly speaking, this ratio would relate the resistance to loads applied about the i_2 vs i_3 directions. (see Figure 3.)

Q9: Question 9 asked basically if vertical loads would result in lateral displacements for three different cross-sectional shapes. (see Figure 4)

Q10: Question 10 asked which of three shapes would have the greatest lateral displacement (see Figure 5)

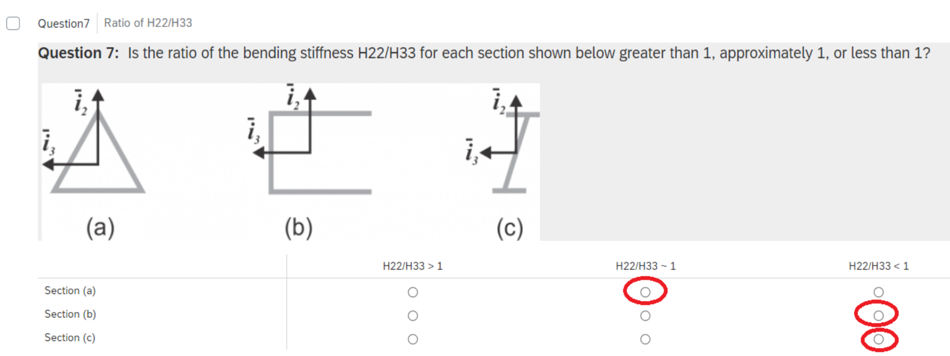

Figure 3. Question 7 from Project 1 survey of understanding. Circles denote the correct answers.

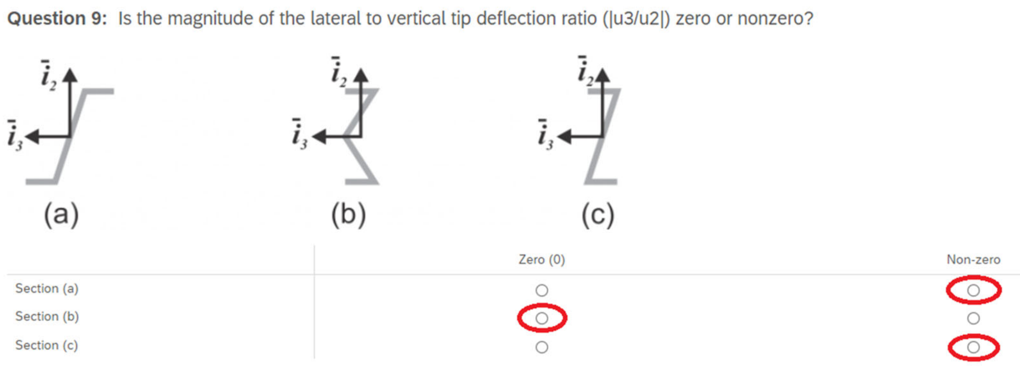

Figure 4. Question 9 from Project 1 survey of understanding. Circles denote the correct answers.

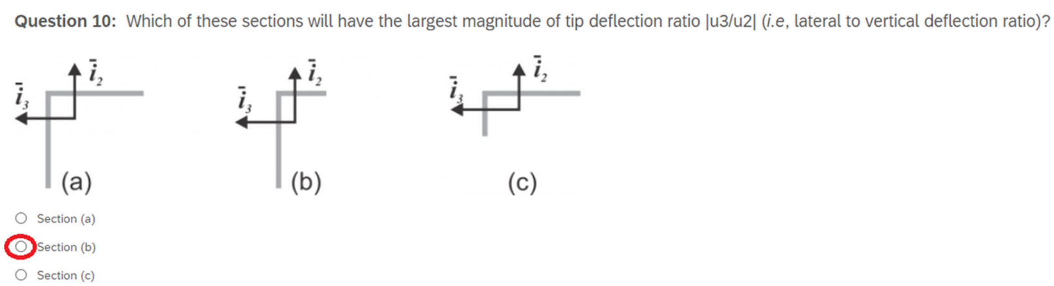

Figure 5. Question 10 from Project 1 survey of understanding. Circle denotes the correct answer.

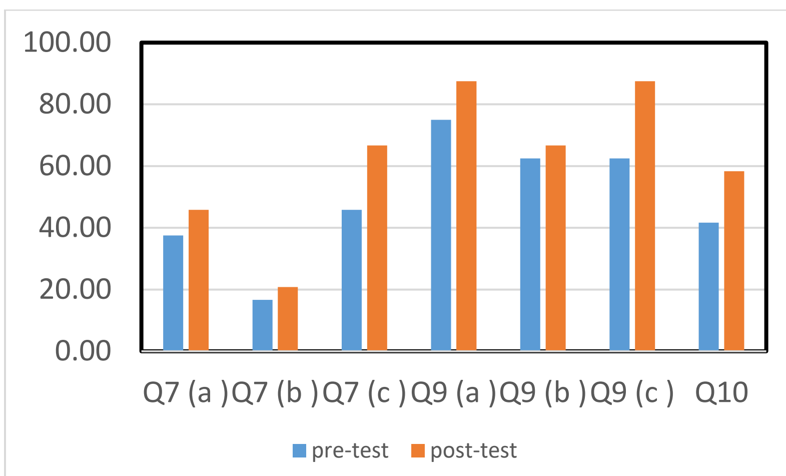

Figure 6. Percent of students having the correct answer on selected questions (N = 24).

Hands-On vs Demo Experiments

In the spring of 2022, the beam-bending apparatus was used in a junior level class in strength of materials. The class size was relatively small (N = 8 including 5 male and 3 female students, and the students came from a variety of majors including AE, CE, ENVE, ME, and MSE). The small class size gave us an opportunity to run two different projects during two different class periods during the semester. One project was conducted as a hands-on experiment in which students actually performed the tests themselves in teams of 4, and the other project was conducted in a demo-mode by the instructor at the front of the lecture room.

The hands-on experiments were conducted during a single 75-minute class period. In the first 30 minutes, a 4-person team conducted a series of loading tests on beams of identical geometry but different materials. The procedure consisted of clamping a beam into the base fixture to create a fixed-free cantilever arrangement. Each beam had a strain gauge affixed near the root a fixed distance from the tip, and a handmade modular Wheatstone bridge, instrument amplifier, and low pass filter were used to convert the gauge resistance change into a voltage signal that was digitized with a National Instruments myDAQ device. Measurements were acquired using a MATLAB program which plotted strain vs load in real time and computed a linear regression of the results. After the first team finished, the beam fixture was switched from prescribed tip load to prescribed tip displacement, and the second team performed experiments for roughly 30 minutes. The same beams tested by the first team were used, but the second team applied increasing amounts of tip displacement using a calibrated thumbscrew. Data from the strain gauge was again captured and plotted in real time by a MATLAB program. Following the two sets of experiments, the data from each group was shared with the other group so that they both would have all of the raw results gathered during that class. Further details of the experimental procedures used by each team can be found in [6]. Post-processing, analysis of the results, comparison with theory, and conclusions were incorporated as one of 4 problems in the weekly homework assignment.

The instructor-conducted demo was carried out in the lecture classroom. The purpose of the second experiment was to investigate the phenomenon of lateral deflection of a cantilever beam with an unsymmetrical cross-section loaded by a vertical tip load. Instead of strain gauges, the main experimental results used a webcam and optical measurement techniques implemented in a MATLAB program using the Image Analysis toolbox to determine the amount of vertical and lateral tip displacement and tip rotation in response to vertical tip loads. A sketch of the setup is shown in Figure 7, and details of this measurement procedure may be found in [8]. Students watched the process in which the data was generated and asked questions but had far less opportunity to participate in the experiment. Data collected from the demo was provided to the students, and the students post-processed the data and compared the tip deflection ratio to theory as one of 4 problems in a weekly homework assignment.

Although the number of students involved in these experiments was relatively small, their reactions to and impressions of the experiments were valuable. The students had a much more positive reaction to the hands-on experiment than to the demonstration. In fact, during the hands-on experiments, the students showed a lot of engagement and were eager to take turns applying loads or displacements, or taking data using the MATLAB program. As mentioned previously, the preference of students to actually do the experiments themselves rather than passively observe a demo has been observed in the past; for example [10].

A second reaction expressed by multiple students was that they enjoyed both experiments because it broke up the usual delivery of content via lectures. For the hands-on experiment, some students commented that it was one of the few times over the semester that they got to interact with their classmates in a meaningful way.

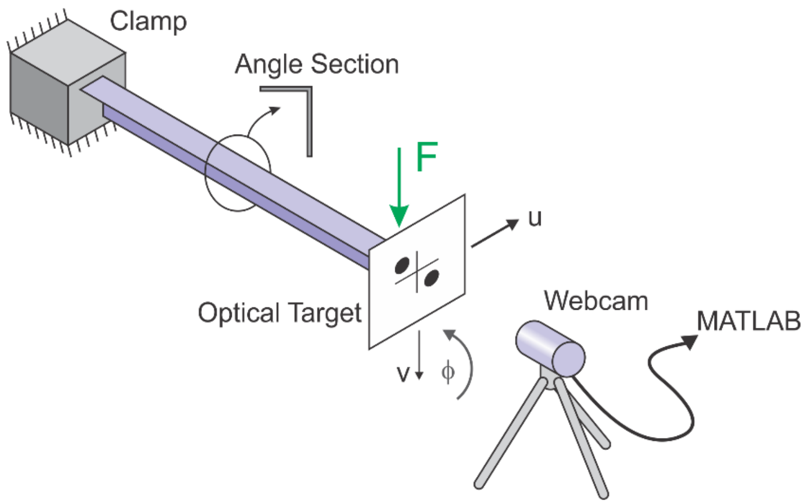

Figure 7. Optical measurement of beam 2D tip deflection and rotation using a webcam.

A third reaction was more unexpected. The students were given an overview of how the strain gauges worked, and how a resistive bride was used to determine changes in resistivity and, ultimately, to determine quantitative measures of strain. The general operation of the MATLAB code was also described at the start of the experiment. They were provided much more detail through the documentation of the experimental procedure (including all MATLAB code listings) that was posted as background material at the class Canvas course site. We were concerned that the diversion of discussion from what was observed to how it was observed may detract from their feeling of confidence in the experience. However, none of the students said that it caused confusion, and those students who had already taken the circuits and electronics class (required for non EE-majors) mentioned that it helped to tie together material from the two classes. They saw it as a welcome application of electrical circuits to a different domain.

Concluding Remarks

The beam bending apparatus developed by the authors was purposely designed to facilitate a range of test specimens as well as to use a range of measurement techniques to produce quantitative data of reasonable accuracy. Assessment data gathered through pre- and post-test surveys conducted in a junior-level aerospace engineering structures class showed modest gains in understanding.

Although social distancing protocols have made it difficult to study hands-on learning these past two years, we hope to conduct further observational studies now that instruction modes are returning to normal. A particular consideration is the ability of students to work in impromptu groups, or in teams that are formed for a one-day exercise, where there isn't time for familiarization with their teammates or to develop effective patterns of interaction. As part of a multi-school grant from the Kern Family Foundation, AE is investigating experiential and community learning and is considering using some of the hands-on experiments we have developed.

Observations of team dynamics in a junior-level circuits class are continuing. Observational protocols developed for problem-based learning will be adapted to study these teams as they construct and test electrical and electronic circuits in a classroom setting.

Acknowledgement

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