# Development of a Portable Experimental Platform to Demonstrate the Role of Material and Cross-section in Beam Bending

**Dr. Aldo A. Ferri, Georgia Institute of Technology**

Al Ferri received his BS degree in Mechanical Engineering from Lehigh University in 1981 and his PhD degree in Mechanical and Aerospace Engineering from Princeton University in 1985. Since 1985, he has been a faculty member in the School of Mechanical Engineering at Georgia Tech, where he now serves as Professor and Associate Chair for Undergraduate Studies. His research areas are in the fields of dynamics, controls, vibrations, and acoustics. He is also active in course and curriculum development. He is a Fellow of the ASME.

**Dr. James I. Craig, Georgia Institute of Technology**

Prof. Craig has been on the faculty at Georgia Tech for more than fifty years and continues to teach as an emeritus professor and to develop classroom engagement methods and tools. His past research is in the general area of experimental structural mechanics, dynamics and structural control with applications to aerospace and earthquake engineering. He is coauthor of a textbook on structural analysis with application to aerospace structures.

**Dr. Bonnie H. Ferri, Georgia Institute of Technology**

Dr. Bonnie Ferri is a Professor in the School of Electrical and Computer Engineering as well as a Vice Provost at Georgia Tech. She performs research in the areas of active learning, embedded controls and computing, and hands-on education. She received the IEEE Undergraduate Education Award and the Regents Award for the Scholarship of Teaching and Learning. She received her BS in EE from Notre Dame, her MS in ME/AE from Princeton, and her PhD in EE from Georgia Tech.

**Dr. Meltem Alemdar, Georgia Institute of Technology**

Dr. Meltem Alemdar is Assistant Director and Research Scientist II at Georgia Tech's Center for Education Integrating Science, Mathematics, and Computing (CEISMC). Dr. Alemdar has experience evaluating programs that fall under the umbrella of educational evaluation, including K-12 educational curricula, K-12 STEM programs after-school programs, and comprehensive school reform initiatives. Across these evaluations, she has used a variety of evaluation methods, ranging from a multi-level evaluation plan designed to assess program impact to methods such as program monitoring designed to facilitate program improvement. She received her Ph.D. in Research, Measurement and Statistics from the Department of Education Policy at Georgia State University (GSU).

# Development of a Portable, Experimental Platform to Demonstrate the Role of Material and Cross-Section in Beam Bending


## Abstract

Many engineering courses have lecture components but no laboratory component. Although lecture courses of this sort can be strengthened through the incorporation of active or problem-based learning, the addition of short, focused experiments can have a profound effect on student learning, motivation, and retention of knowledge. This paper describes the development of a small, portable beam bending apparatus to highlight concepts of stress and strain in an undergraduate strength of materials course. The experiments are designed to target particular concepts about which students typically have misconceptions. The apparatus was fabricated and implemented in a single section of strength of materials, and preliminary data was gathered on student understanding through use of a concept-inventory test administered before and after the experiment. The paper describes the experimental platform and gives preliminary results from the concept-inventory assessments. It was seen that the experiment helped to dispel some of the students' misconceptions, but that further refinement of the experimental procedure may be needed to address other conceptual errors about stress, strain, and the role of material properties, loading conditions, and beam geometry.


## 1. Introduction

Beam bending is one of the foundational concepts that is critical in several fields including mechanical engineering, aerospace engineering, and civil engineering. At the authors' institution, the topic is treated thoroughly in a lecture-based, sophomore-to-junior level class in mechanics of materials (strength of materials). Many students come to the topics in mechanics of materials courses with significant pre-conceptions and misunderstandings that are difficult to overcome through lecture material alone [1]. Indeed, this presents an important challenge because when students are shown that their preconceptions are faulty, it enhances their retention of the correct material and has the ancillary benefit of developing their critical thinking skills in other engineering topics.

There are many laboratory experiments that focus on beam bending, but they fall into two main categories. The first are experiments that take place in dedicated instructional labs and which make use of sensors to obtain detailed, quantitative data on beam bending. Such labs can study beams under different types of loading, and they are helpful in allowing students to compare laboratory-quality measurements to theoretical predictions. The other category of experiments uses hand-held demonstrations or teaching aids to show qualitative behavior. The main advantage of these types of teaching aids is that they are inexpensive, portable, and can be used within classroom lectures as a means of just-in-time reinforcement of concepts. Several authors [2]-[4] have discussed experiments relevant to the present work.

The goal of this research project is to create an experimental platform that is a compromise between the two extremes. A student team was charged with designing and building a prototype, which was tested in a mechanics of materials course at the authors' institution. The platform is portable, and graduated weights or thumbscrew-type displacement actuators are employed to load the test beams which are instrumented with strain gauges and tilt sensors. Signal conditioning is handled using small (2x3 inches), modular, custom-fabricated two-sided printed circuit boards. Data acquisition is accomplished using a National Instruments myDAQ and a laptop computer running Matlab with its Data Acquisition toolbox. The platform is designed to accept beams of different materials and cross-sections, and it can apply loading in different ways to different points along the beam.

The initial evaluation of the platform reported in this paper is designed to target students' misconceptions about the relationship between the type of loading and the resulting stress and strain in the beam. In particular, experimental exercises are used to show how choice of materials can influence strain, but not stress under identical force loading situations. Conversely, displacement loading of beams having different materials produces the same strain but different stresses. In another experiment, the effect of the beam cross-sectional symmetry in thin-walled sections is investigated to yield quantitative and qualitative data about beam twist resulting from point loading not on the elastic axis. The platform plus all the instrumentation is purposely designed to be very portable and yet be robust and simple to understand by students in ME, AE, and CE courses. Similar to [5], student engagement is reinforced through use of post-demo analysis of the quantitative data.

Ultimately, the goal of this research project is to create many experimental platforms that can be deployed by students, individually or in small groups, in a lecture class several different times over the course of the semester. In this way, a lecture class that has no associated laboratory can still provide students with hands-on experience. This is the model that has been used successfully in circuits and electronics courses at the authors' university [6-10]. In this preliminary study, however, only one platform was fabricated and used by the instructor as a demonstration tool in two "projects" consisting of three separate experiments. The demonstrations focused on just a few critical concepts:

C1: The bending stress in a homogeneous beam depends directly on the applied bending moment and thus on the applied loads. For a given bending moment, the bending stress at a point will be the same for beams of different materials, but the corresponding bending strains will all be different.

C2: Bending strain in a homogeneous beam is due solely to the deformation of the beam and does not depend on material properties. To show this, prescribed tip deformations are applied to beams that differ only in their material composition.

C3: Thin-walled beams with C-cross-sections behave very differently than beams with rectangular cross sections. In particular, the shear center (defined as the axis through which a vertical load can be applied without twisting the beam) actually lies outside the confines of the C-section. Hence, a load applied directly on the section will cause the beam to both bend and twist.

Section 2 of this paper describes the experimental platform and discusses the design features that allow it to be used for several different loading situations. Section 3 describes our initial testing and evaluation in the classroom. Section 4 presents the concept inventory test that was developed for the purpose of gauging students' understanding of the relevant theoretical concepts. Section 5 gives preliminary results from the test which was administered before the experiment was introduced in the class and afterwards. Finally, some concluding remarks are made in Section 6.

## 2. Platform Development and Description

There were several requirements for the beam bending experiment that the student design team needed to incorporate in their design. The apparatus needs to be modular so that it can be reconfigured for a range of different testing configurations. The base and clamping mechanism must be sufficiently sturdy so that they can supply a cantilever boundary condition; i.e., zero deflection and rotation at the clamp. The base also has to be big enough that students can work in a team of two or three and actually see the beam loading and deformation. The target overall length for the apparatus was set to 20 inches. At the same time, since students and instructors must transport the device across campus, it needs to be as light in weight as possible. Another requirement is that the clamp needs to accommodate beams of different cross-sectional dimensions and hold them securely, but it also needs to unclamp and reclamp easily to swap out different beams. Finally, the platform needs a way to impose either prescribed loads or prescribed deformations at the unclamped end or at points along the beam.

As mentioned in the introduction, the platforms developed in this research study are designed to supplement or to replace traditional, instructional labs. Although we wish for students to get a feel for the physical phenomena and to observe qualitative behavior, we also intend for them to take measurements and process the measurements using data-acquisition equipment. As successfully shown in the circuits and electronics courses at the authors' institute, this can be facilitated with student-owned data-acquisition devices such as the National Instruments myDAQ and myRIO devices, plus the students' laptop computers. Two types of sensors are integrated into the experiments- electrical resistance strain gauges and tilt sensors. Strain gauges are bonded to the upper and lower surfaces of the solid beams of different materials while a tilt sensor is mounted at the tip of the thin-walled C-section beam. Bridge circuitry for the strain gauges, signal amplification and filtering units, and power regulation units were also designed for the experiments and fabricated on small, modular, two-sided printed circuit boards with open layout and labeling used to outline and clarify the circuitry.

The beam bending apparatus is shown in Fig. 1. The base is fabricated from an aluminum plate to present a very rigid but lightweight platform. The fixed-end clamp is supplied in the Root Fixture by a screw clamp system (at the right end in the figure below) to support a beam in a cantilever configuration. The platform allows either forces or displacements to be applied to the beam at different points along its length. Vertical forces (loads) are applied to the beam using kilogram weights hooked over the beam and suspended below the fixture (using the clearance slots machined in the base). The Tip Fixture shown mounted on the left end of the apparatus allows prescribed vertical displacements to be applied using a thumbscrew (and can be used to measure tip vertical deflection). The Tip Fixture can be modified, mounted at points along the beam, or even removed as needed for testing purposes. The apparatus can accommodate beams with widths and thicknesses of up to 1 inch and with lengths from 8 to 14 inches.

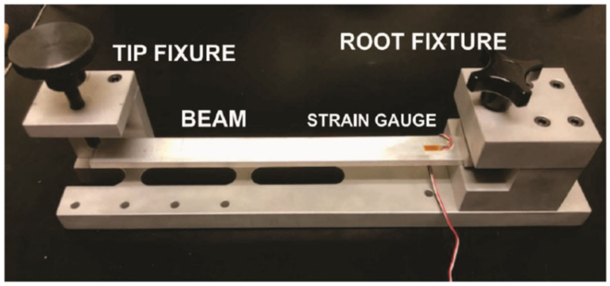



**Figure 1.** Beam Bending Apparatus

Root fixture. The root fixture (on the right end in Fig. 1 above) consists of a stepped base block that is bolted to the base plate from below using four 1/4-20 socket-head cap screws. Two different longitudinal mounting positions are available. A top plate is attached to the base block with four 1/4 -20 socket-head cap screws and is fitted with a knobbed thumbscrew clamp and foot assembly that is used to firmly clamp the beam in a horizontal configuration. Spacer plates are available to allow clamping of beams of different thicknesses.

Tip fixture. The tip fixture (on the left end in Fig. 1) is much simpler and consists of a riser that can be bolted to the base plate from below using two 1/4-20 socket-head cap screws (three different longitudinal mounting locations on either side of the base plate are available). A top plate is attached to the riser with two ¼ -20 socket-head cap screws, and spacers may be included to raise the height of the top plate if needed for a particular test. The top plate is fitted with a 3/8-24 threaded rod with a hemispherical lower tip and a round knurled knob at the top. Turning the knob advances or retracts the rod vertically. This can be used to apply specific vertical deflections at the beam tip (each turn is 1/24 inch = 0.0417 inches). Conversely, this can also be used to measure the tip deflection, for example, when loads are applied with the kilogram weights. It is relatively easy to resolve as small as 1/6 of a turn of the knob and this corresponds to 0.007 inches of vertical displacement. Contact between the rod and beam is easy to determine using a thin paper strip as a "feeler gauge."

Setup. The beam apparatus is designed to be used on a desktop or sturdy tabletop in a clear corner area that is at least 12 inches by 24 inches. The desk or tabletop should extend at least 1 inch from the apron so that the apparatus can be clamped securely to the desk or tabletop using a C-clamp as shown in Fig. 2. Using a corner area allows the apparatus to be cantilevered over an edge so that the kilogram weights can be suspended directly below the beam (as shown in Fig. 4). Measurement equipment including the signal conditioner, power supply, myDAQ data acquisition module, and laptop computer can be placed nearby the apparatus on the same tabletop.

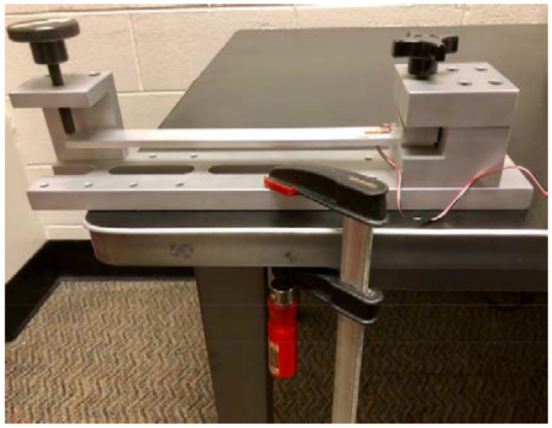


**Figure 2:** Apparatus clamped to desktop

Applying tip displacements. This is the simplest kind of test to perform and can be carried out with the apparatus placed anywhere on the table or desktop (without needing the C-clamp). Tip displacements are applied by first advancing the tip screw until it just touches the upper surface of the beam (see Fig. 3). To apply a prescribed tip displacement, the knurled knob is turned the requisite number of turns or fraction of a turn. As mentioned above, one turn creates a deflection of 1/24 = 0.0417 inches and 1/6 turn creates a deflection 6 times smaller or 0.007 inches.

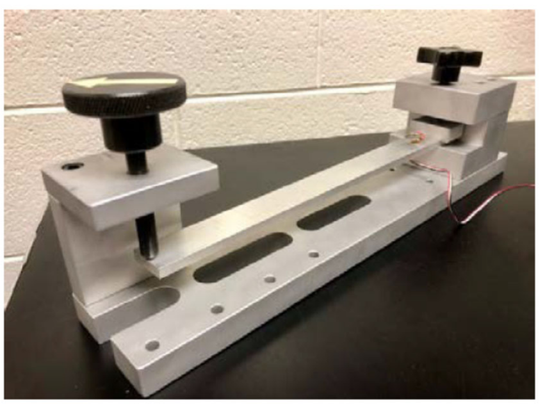


**Figure 3:** Applying tip displacement

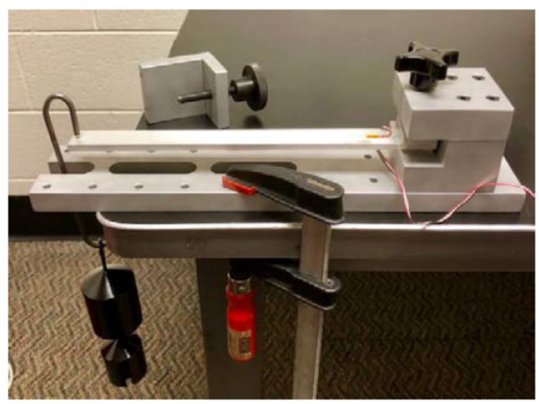
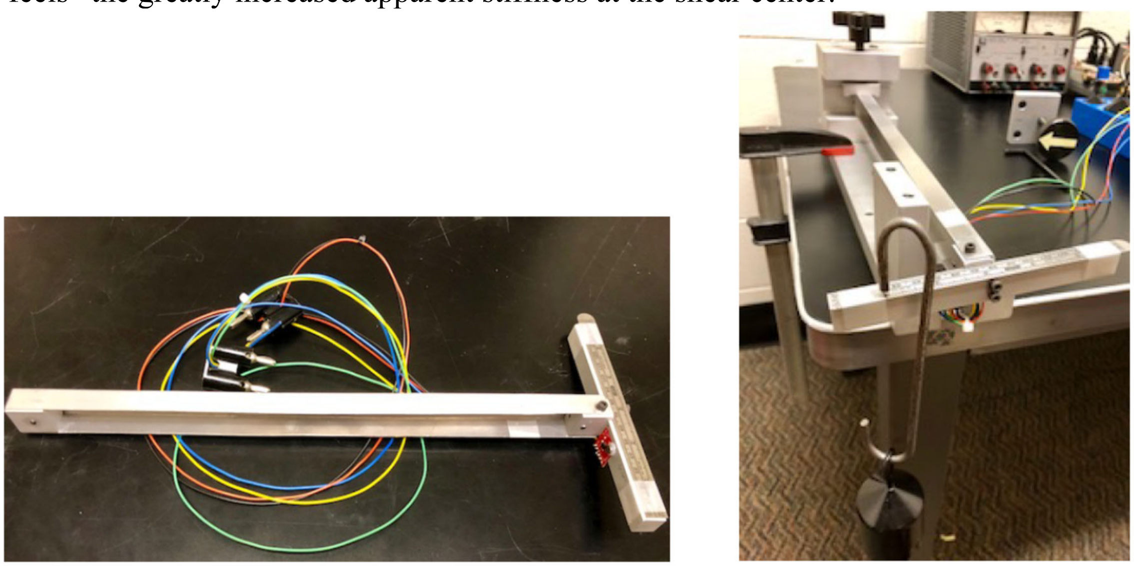


**Figure 4:** Applying tip loading using kilogram weights

Applying tip loads. Tip loads or concentrated forces at a point along the beam are applied using the kilogram weights. The apparatus must be securely clamped to the edge of the table or desktop so that the point on the beam where the load will be applied is over the edge of the table or desktop to allow the weight to hang freely below (see Fig. 4). The weights are attached to the beam using a simple metal "S" hook whose pointed end rests on the top of the beam at the load point while the kilogram weight is attached to the lower part of the hook hanging below the apparatus.

Other configurations. The beam bending apparatus can be used in other testing situations. For example, beams with thin-walled C-shaped cross sections will develop large twist angles if the loads are not applied precisely at the shear center. Figure 5a shows such a beam (CNC machined from an aluminum plate) with a crossbar attached at its tip (right end) and with a small tilt sensor (an Analog Devices ADXL337 three-axis accelerometer) mounted to it. With the standard tip fixture removed, the C-section beam with tip-mounted crossbar can be clamped into the apparatus as shown in Fig. 5b (note the addition of a spacer plate in the root fixture to accommodate the thicker beam). Figure 5b shows how a 100g weight can be placed at specific locations along the crossbar to apply varying degrees of twisting moment along with the downward tip loading. The crossbar tilt is detected by the accelerometer and for small angles is proportional to the axial twist. Thus the point on the crossbar where the load can be applied without producing twisting is easily revealed from a plot of measured twist angle versus load position. This is the horizontal location of the shear center. Because the torsional stiffness of an open section is very small, the apparent vertical stiffness for loads applied at points along the crossbar is quite low unless the load is applied through the shear center. This is dramatically evident if a student lightly presses down on the crossbar at different positions along the bar and "feels" the greatly increased apparent stiffness at the shear center.



(a) Thin-walled C-section beam with tip crossbar and tilt sensor.

(b) Test with 0.5 kg weight applied to tip crossbar.

**Figure 5:** Test of bending and twisting of thin-walled C-section beam

Other boundary conditions. At present, the apparatus can only create a cantilever beam support condition. However, intermediate pinned supports could be placed at one or more points along the beam (these have not been developed yet) to create hyperstatic configurations. There also are some tests that do not need the tip fixture which can be removed, if necessary, simply by unbolting it from the base plate.

Packaging. The complete apparatus configured for a simple bending test is shown in Fig. 6. For portability outside the classroom, the entire apparatus (fixture, beams, instrumentation) is housed in a single rolling toolbox that is slightly larger than a typical piece of carry-on luggage. This is acceptable for transport to/from a classroom, but it is not practical for students to check out for use in their rooms or common areas. For this kind of portability, a typical student backpack is perhaps a more realistic packaging goal.

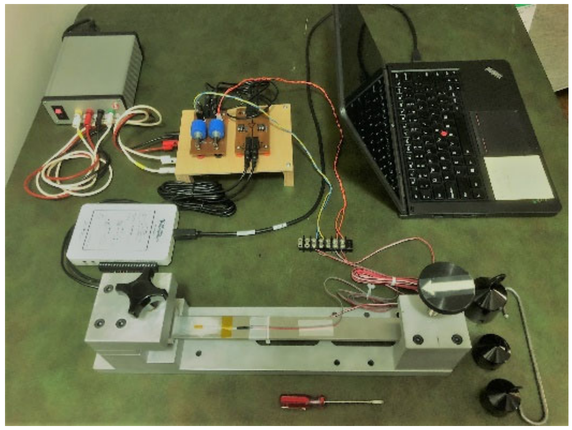


**Figure 6:** Complete apparatus (clockwise from upper left: power supply, modular signal conditioning, laptop, apparatus, myDAQ USB data acquisition device).

**3. Initial Evaluation in the Classroom**

The classroom evaluation of the beam bending platform was carried out in a small section of 36 students in the mechanics of materials course taught by one of the authors (Craig) in the fall 2018 semester. The section was smaller than the usual 60 enrollment for this course because of classroom limitations, but no prior advertisement of the evaluation or enrollment pre-selection process was used. The well-known textbook by Goodno and Gere [11] was used, and parts or all of each chapter were covered. The Canvas [12] learning management system was used along with Piazza [13] (a social question and answer system).

Two demonstration "projects" were scheduled during the 8$^{th}$ and 10$^{th}$ weeks, respectively, of the 15-week semester, and both were carried out within a week or two following the primary theoretical developments in the classroom. Project 1 involved two experiments to explore concepts C1 and C2 described previously in section 1 while Project 2 addressed concept C3. In preparation for these demonstrations, the students were given detailed written descriptions of:

- the test platform to be used for each project,
- the strain gauge bridge, amplifier/filter and transducer power supply circuit boards,
- the Matlab programs used to operate the myDAQ along with full listings,
- the design, installation and operation of electrical resistance strain gauges, and
- the two demonstration projects and their individual experiments, including guidelines for the data reduction and comparison with theory, and
- the format of a short technical report to be completed for each demonstration project (the two reports accounting for 5% of the course grade).

Each project was carried out in a single one-hour class period. The experiments were assembled by the instructor on a table at the front of the class, and students were encouraged to come up and watch and/or watch close-up video of the setup projected on the classroom screen. With student assistance, the instructor then carried out each of the tests with the laptop screen being displayed along with the close-up video of the test on the classroom screens. At the completion of the demonstration, the data files that were acquired were uploaded to the class Canvas web page.

The concept inventory pre-survey described in Section 4 was administered during the 7th week just before the first demonstration. It was followed by the concept inventory post-survey administered at the end of week 12 just after the due date for the second project report.

3.1 Project1 description

Three geometrically identical beams (0.25 x 1.0 x 12.5 inches) made from brass, aluminum and stainless steel are each instrumented with a 0.5 inch strain gauge bonded 9.875 inches from the tip load point (marked on each beam). In the first experiment, each of these beams is mounted in the fixture so that the length from the root clamp to the tip load point is 10.675 inches. The measurement instrumentation consists of a strain gauge board connected to an amplifier/filter board whose output is routed to an analog input channel of the myDAQ unit as shown in Fig. 7. The strain gauge board can be configured for 120 or 350 Ohm gauges in quarter-, half- or full-bridge use with either single-arm or differential manual balancing. The active filter has a 1 kHz bandwidth. Figure 8 shows both boards plugged into a power chassis.

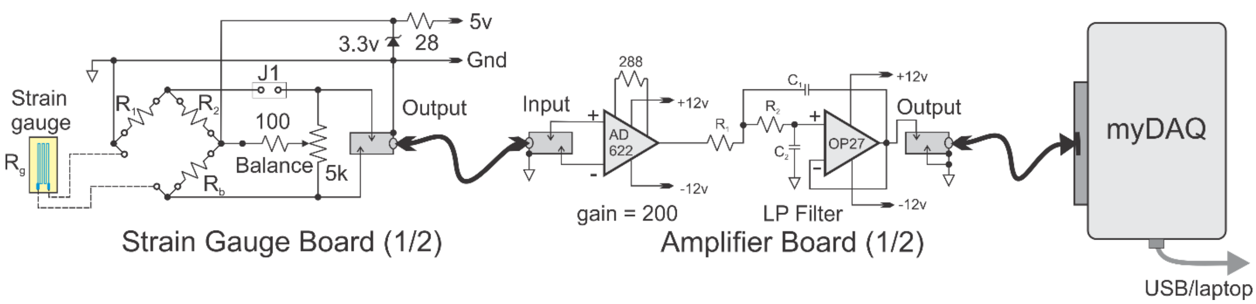



**Figure 7:** Dual-channel modular instrumentation system designed and built for the hands-on learning projects. Interconnections are via stereo mini-audio cables.

The myDAQ device is connected to a laptop computer and can be operated using either Matlab [14] or LabVIEW [15]. For this project, several Matlab programs using the Data Acquisition toolbox were developed. The primary program, under keyboard control, allows the user to take an initial zero reading followed by successive readings at each loading increment (triggered by typing in the tip load followed by a return). When terminated by entering a negative load value, the program creates a plot of the acquired readings versus the loads entered, calculates and plots a linear regression (including parameter values), and finally, asks if the measurements should be saved as a .CSV file for later post-processing. Figure 9 shows a typical screen display. Since initial manual balancing of the strain gauge bridge is needed to insure the output is within the input range of the myDAQ, a simple GUI-based program was developed to emulate the function of a typical digital voltmeter, thus allowing the operator to adjust the bridge balancing potentiometer until the display is zeroed. For diagnostic purposes like checking noise levels, a set of LabVIEW virtual instruments called ELVIS can be used; these include a multichannel oscilloscope, a signal generator, a DVM and several other useful instruments, all implemented in the myDAQ hardware.

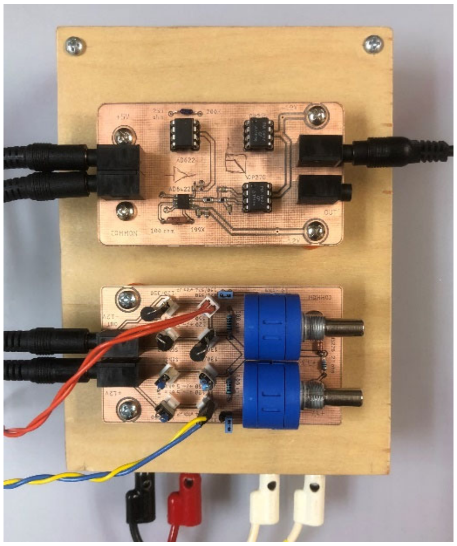


Figure 8. Dual-channel strain gauge (bottom) and amplifier/ filter (top) boards plugged in to power chassis.

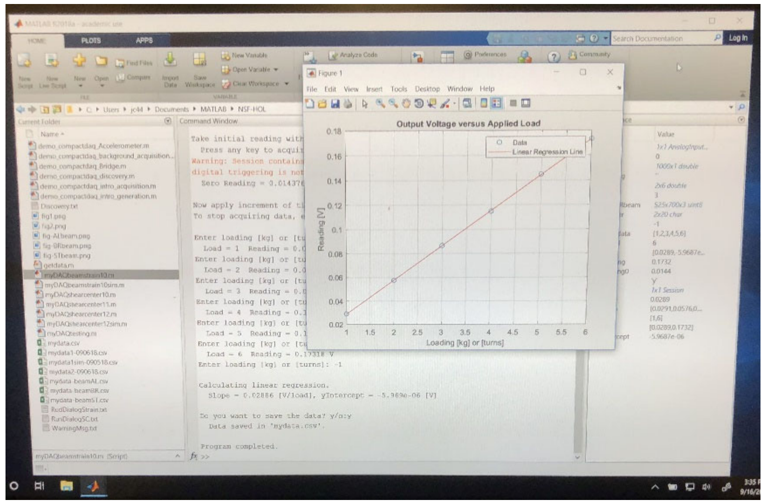
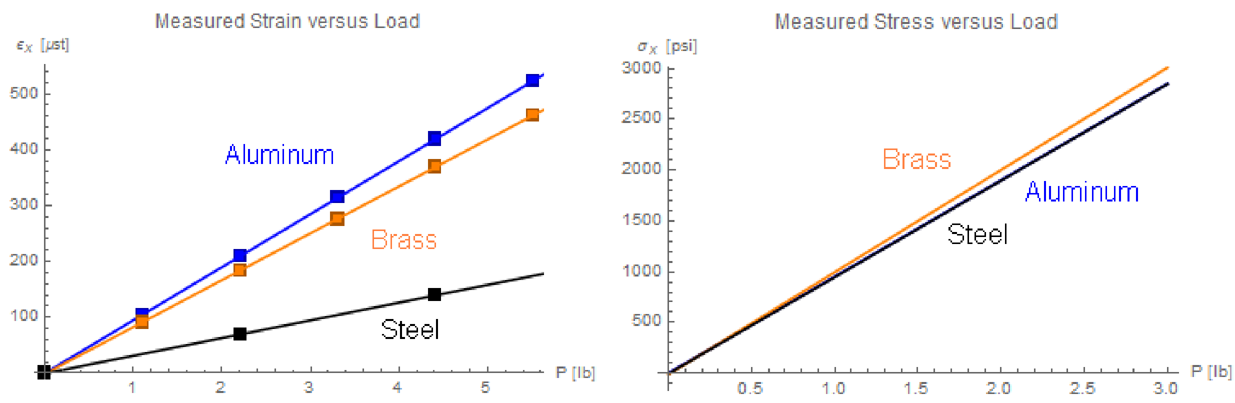



**Figure 9**. Matlab data acquisition program screen display showing plot of acquired data with linear regression.

Experiment 1. In order to test concept C1 that the bending stress is independent of material for a given beam geometry and applied bending moment, the test platform is configured so that tip loads can be applied to each beam using kilogram weights suspended from a load hook (see Fig. 4). The amplified strain gauge bridge output voltage due to the bending strain sensed by the strain gauge are recorded along with the manually entered tip load for six increasing loads for each beam. The raw data plot of bridge voltage versus load similar to that shown in Fig. 9 is used to verify that the expected linear behavior occurred in each test, and the linear regression parameters are recorded along with the raw data.

Experiment 2. Next, in order to test concept C2 that the bending strain is independent of material for a given deformation, the test platform is configured so that a prescribed tip displacement can be applied to each beam using the knurled knob and threaded rod in the tip fixture (see Fig. 3). The same instrumentation and test procedures employed in Experiment 1 are used, but in this case the recorded tip displacement ("load") is the number of turns of the threaded rod displacing the beam tip downwards.

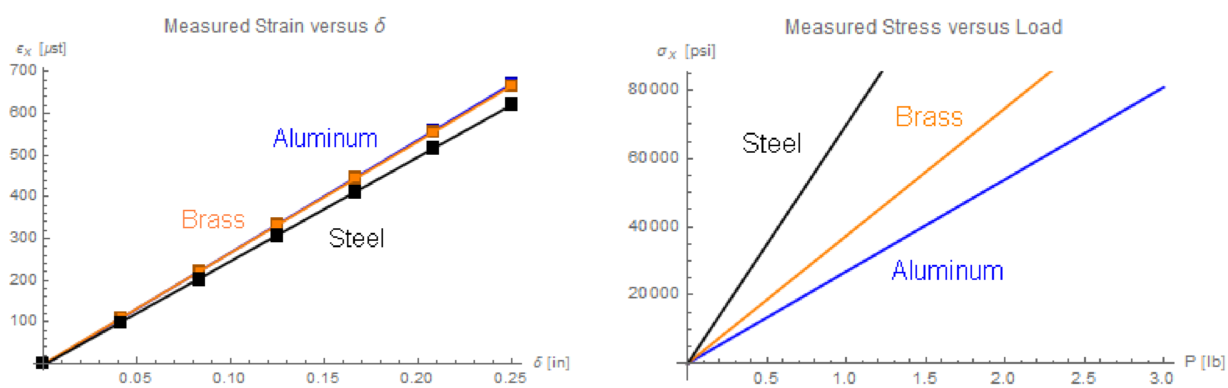
Data reduction and analysis. The data reduction for each of the experiments consists of two steps. The first is to verify that the raw data is, indeed, representative of linear elastic behavior. This is accomplished during testing by verifying that the plot of measured amplified bridge voltage versus the applied tip load or tip displacement created by the data acquisition program appears linear (and that the reported linear regression parameters confirm this). The second step is to convert the bridge voltage readings to measured strain units and either the kilogram tip loads into force units or the turns of tip thumbscrew into displacement units. Finally, the strains are plotted versus the tip loading for Experiment 1 and versus applied tip deflection for Experiment 2. Figure 10 displays the results obtained from the Experiment 1 tests. The directly measured strains show clearly different proportionality with applied tip load (i.e., bending moment) while the stresses computed from these strains using the tabulated elastic moduli for each material lie nearly on top of each other, confirming that the stresses due to an applied bending moment are independent of beam material.




(a) Measured strains and linear regression. (b) Stresses computed from strains.

**Figure 10**. Measured strains and stresses computed from strains for Experiment 1.

The results plotted in Fig. 11 show the same kind of behavior except now the measured strains are almost the same (the aluminum and brass are almost coincident) while the stresses computed from the strains using the tabulated elastic moduli for each material show distinctly different proportionalities. These results confirm that strains due to an applied tip displacement are independent of the beam material.




(a) Measured strains and linear regression. (b) Stresses computed from strains.

**Figure 11**. Measured strains and stresses computed from strains for Experiment 2.

3.2 Project 2 description

Beams with thin-wall cross sections are commonly used in aircraft structures such as wings, and they are also used widely in lightweight metal structures such as industrial racks and shelving systems. In such beams, the shear force on the cross section is distributed as a shear stress acting tangentially along the cross section of the thin walls. This shear stress is distributed uniformly across the wall thickness but varies along the thin wall, and it is simpler to treat it as what is called a "shear flow," $f(s) = \tau(s)\, t(s)$, where $t$ is the wall thickness and $s$ is a perimetric coordinate. The resultant of the shear flow on the cross section must equal the sectional shear force $V$, but because of the complex distribution of shear flow, the point about which the shear flow produces no twisting moment, called the "shear center," is no longer at the centroid of the section. Therefore, any lateral load acting on such beams must be applied such that it acts through the shear center. For thin-wall beams with an open cross section (i.e., no closed off regions), the shear center can be quite far from the centroid. In fact, the shear center for the open C-section shown in Fig. 12 lies entirely outside to the left of the cross section. Therefore, any vertical loads actually applied on the C-section will cause it to twist clockwise as it bends in the vertical direction. Moreover, since the torsional stiffness of an open section is quite small, this twisting moment can create a significant twist rotation of the section. Only when the vertical loading is applied through the shear center (i.e., as $V_y$ in the figure), will the beam bend without any twisting. Clearly, this behavior is not at all intuitive, and the theoretical calculation of the shear center location requires a solid understanding of some of the most confusing concepts in the study of statics.

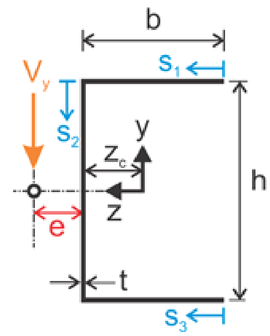



**Figure 12.** Shear center is located distance $e$ to the left of the C-section.

Project 2 employs the CNC machined thin-wall C-section beam and the test setup shown previously in Fig. 5. Since the shear center lies outside the section, a small crossbar must be fitted to the tip of the cantilever so that a vertical tip load can be applied to the left or right of the shear center or at the shear center. Using an engraved metal scale attached to the top of the crossbar, a constant vertical load can be applied at specific positions along the scale using a weight attached to a metal hook (the hook tip is easily indexed to the engraved lines on the scale). By measuring and plotting the resulting twist angle as a function of scale position, it is a simple matter to determine the scale position where the weight must be applied to produce no twist. Finally, the shear center location defined by $e$ in Fig. 12 can be determined using the position of the C-section's vertical wall indicated by the scale.

<u>Experiment 3</u>. The twist angle of the tip crossbar is measured by an inexpensive MEMS inertial accelerometer as described in "Other configurations" in section 2. The accelerometer requires well-regulated 3.3 Vdc power that is supplied by a custom printed circuit board, and the output signal proportional to the horizontal acceleration is then routed to one of the analog input channels of the myDAQ unit. A Matlab program is used to record the initial accelerometer output voltage at zero twist (no tip load applied), followed by measurements of the voltages with the weight applied at successive positions along the scale (along with keyboard entry of the scale position where the weight is applied).

<u>Data reduction and analysis</u>. The horizontal acceleration measured by the MEMS accelerometer is given by $a_h = g \, Sin \, \theta$ where g is the gravitational acceleration and $\theta$ is the twist angle. For

small twist angles, this can be reduced to $\theta = a_h/g$ from which it follows that the twist angle is directly proportional to the measured horizontal acceleration. A plot of the different output voltage from the accelerometer versus weight position along the scale is shown in Fig. 13. A linear regression of this data yields the slope and vertical axis intercept from which the horizontal intercept is easily determined. Finally, the difference between this reading and the scale reading of the left edge of the C-section determines the shear center location $e$ in Fig. 12. Data taken during the demonstration yielded a value for $e = 0.201$ inches, and theoretical calculation is $e = 0.195$ inches, giving a relative error of 3.1%. A more rational measure of error is to compare it to either the sectional width $b$ or height $h$, and using the width yields an error of only 1.2%.

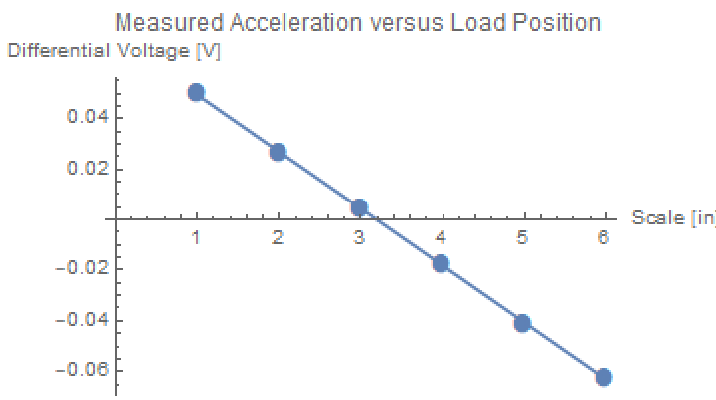



**Figure 13.** Plot of accelerometer output versus load position on the scale.

As a final note, this experiment also can provide a very tactile way to sense the location of the shear center. If a student lightly presses down on the crossbar at different positions across its length, it is quickly apparent that the apparent vertical stiffness is noticeably greater when pressing down at the shear center and much lower when pressing down elsewhere. This is because the low torsional stiffness of an open section allows relative large twist angles which makes the apparent vertical stiffness much smaller as you move farther from the shear center!

3.3 Qualitative assessment

About 25% of the class were very interested in the demonstrations, followed the experiments closely and asked many questions. Another 25% were curious, while the remaining 50% were largely disinterested and seemed to feel the demonstrations and the requirement to submit two short reports for 5% of the course grade to be an imposition on what was normally expected for this course. Not unexpectedly, the quality of the reports varied widely from excellent to poor, but most of the students treated them as they would a weekly homework assignment. Perhaps the most surprising observation is that many students seemed vaguely discouraged that the experimental results didn't agree perfectly with theory. No formal error analysis was included, but this may be warranted in the future.

The platform and the instrumentation all worked very well. Newer versions of the strain gauge and amplifier/filter boards have been created to provide more flexibility. More critically, it appears that the largest errors in the Project 2 experiments occurred with the steel specimen and arose because of deformation of the test fixture caused by the much higher bending stiffness of the steel specimen. When tip deflections were applied, the fixture flexibility reduced the measured strains per unit tip deflection. As a result, the next generation of beam specimens are half as thick (reducing the bending stiffnesses by a factor of 8).

## 4. Development of a Concept Inventory

In order to assess the effect of introducing the experimental platform on student learning in the Strength of Materials class, a short set of 10 questions were developed to be used as a pre and post assessment of the intervention. The questions were carefully written to target students' misconceptions about the role of material properties, loading characteristics, and geometry in beam bending stress and strain. The 10 questions are included as Appendix A of this paper.

Referring to the three conceptual goals stated in the introduction, it is seen that questions 2, 4, and 5 relate strongly to concept C1, while questions 3 and 6 strongly relate to concept C2. Concept C3 is captured by question 10. The remaining questions relate more generally to the three concept goals as well as to other aspects of the course material. Question 9 is the most quantitative of the 10 questions, and requires students to have a command of cross-sectional moments of inertia. This was meant as somewhat of a "challenge question," and it is not surprising that students struggled with this question the most, even after seeing the demonstrations.

**Table 1.** Pre-Test vs Post-Test Performance on Concept Inventory Questions

| Question | % Correct (pre-test) | % Correct (post-test) | Improvement |
|---|---|---|---|
| 1. Loading curve for steel | 85.7 | 86.4 | 0.65 |
| 2. Material with greatest stress at root | 28.6 | 63.6 | 35.1 |
| 3. Material with lowest strain at the root | 54.3 | 50.0 | (4.29) |
| 4. Most likely to yield | 97.1 | 90.9 | (6.23) |
| 5. Highest stress for given displacement | 65.7 | 59.1 | (6.62) |
| 6. Greatest strain for given displacement | 25.7 | 59.1 | 33.4 |
| 7. Greatest deflection for rectangular cross-section | 80.0 | 81.8 | 1.82 |
| 8. Greatest stress at root for rectangular cross-section | 40.0 | 50.0 | 10.0 |
| 9. Ratio of displacements | 17.1 | 27.3 | 10.13 |
| 10. Out-of plane deflection | 57.1 | 72.7 | 15.6 |

## 5. Preliminary Assessment Results

Table 1 shows the pre-test assessment results and post-test assessment results for the class. There were 44 students enrolled in the class; 35 respondents took the pre-test, 22 students took the post-test, with 19 students taking both assessments. The average score on the pre-test assessment was 55.1% and the average score on the post-test assessment was 64.1%, corresponding to a 16% relative improvement and an 8.9% increase in the raw score. Using only the 19 scores from students that took both the pre-test and the post-test, the mean score improved from 5.90 to 6.32. This increase was not quite significant ($p = 0.19$ based on a paired, two sample t-test.) Our notions of theoretical misconceptions for students is confirmed by the very low scores associated with some questions on the pre-test. The greatest improvement in scores occurred for questions 2 and 6, which relate to concepts C1 and C2. Modest gains were found for questions 8, 9, and 10. The remaining questions had either small positive gains or small negative losses. Question 4 had the highest score on the pre-test, so even though there was a slight decline in performance from pre-test to post-test, the performance on this question can be considered to be very good. The other two questions for which there was a decline in performance, questions 3 and 5 are more concerning. Although the decline was not that bad, our expectation was that the demonstrations would have a positive effect on their understanding of these two items.

It is instructive to consider the distribution of answers on some of the test questions in order to discern the possible effect of the classroom demos. For example, question 2 asks which material would have the greatest stress in end-loaded beams. The correct answer is (e), that the stress would be the same for all materials. However, roughly 25% of the students said the steel beam would have the greatest stress, both in the pre-test and the post-test. Question 3 asks which end-loaded beam would have the lowest strain. The correct answer is steel, but 42% of the students chose acrylic in the pre-test. Fortunately, the percent that chose acrylic dropped to 26% in the post-test. Question 5 asks which beam material would have the highest stress in the case of equal prescribed end deflections. The correct answer is steel, which over 50% of the students chose both pre-test and post-test. However, it was interesting to note that about 25% of the students chose acrylic, or chose that the stress would be the same for all materials. These percentages did not change significantly from the pre-test to the post-test. The persistence of some of the students' misconceptions even after the classroom demonstrations attests to how difficult it is to correct their misunderstandings regarding mechanics of materials.

**6. Conclusions**

This paper gives a description of a small, portable, beam bending apparatus that can be used in an undergraduate strength of materials course typically required of AE, CE, and ME students. The apparatus is designed to host a number of different experiments on beams with a variety of cross sections and materials. When combined with the simple modular instrumentation and data acquisition system, it is possible to perform simple experiments in a classroom setting and obtain measurements of near-lab quality.

In this paper we are describing the concept and initial design of the apparatus along with results from three experiments performed in the classroom in a demonstration mode. Several observations can be made as follows:

- The apparatus is designed to be as rigid as possible while still being portable, but care must still be taken when selecting beam materials and cross sections to insure that flexibility in the fixture will not adversely affect measurements. This is particularly important when applying prescribed deflections to beams of relatively high bending stiffness.
- While the modular instrumentation system is designed to be as simple and clear to understand as possible, it is still a challenge for students to grasp. We chose to use Matlab to operate the data acquisition because of student familiarity from a prerequisite

programming class, but the object-oriented layout of the Data Acquisition toolbox is unfamiliar to many.

- Our preliminary assessment results indicate that some student misconceptions were not resolved in spite of evidence in the demonstrations to the contrary. This suggests that better *a priori* in-class explanation of the purpose of each demonstration is needed, followed by in-class discussion of the results after the demonstration, rather than treating each as a special homework assignment.
- We are still seeking inexpensive displacement sensors for measuring beam deflection of up to 0.5 inches. This capability would significantly expand the range of testing that could be performed.

Future plans include the development of additional experiments and enhancements to the signal conditioning system. These include:

- Preliminary tests with acrylic and polycarbonate plastic beams are promising, but the range of moduli available is very limited. In addition, it is necessary to use 350 Ohm or even 1000 Ohm strain gauges which will require redesign of the instrumentation module
- The ability to chemically weld acrylic plastic may allow creation of plastic beams with non-rectangular cross sections. Bending of beams with unsymmetrical cross sections is a challenging topic in the classroom, and availability of demonstration experiments could be very valuable. However, the poor spatial resolution of strain gauges on plastic at this scale and the difficulty of measuring vertical and horizontal beam deflection present challenges. Work is currently underway to develop photographic methods for measuring biaxial beam tip deflection and rotation using a webcam and image analysis implemented with a Matlab toolbox.
- Understanding strain and stress distribution on the cross section of simple bi-material nonhomogeneous beams is a direct way to build on (and reinforce) the similar concepts for homogeneous beams. The initial challenge is to find compatible materials with distinctly different moduli.

**Acknowledgement:**

The authors gratefully acknowledge the support of the National Science Foundation award number 1626362. Dr. Abby Ilumoka is the program manager. We would also like to thank members of the Vertically-Integrated Projects team on Hands-On Learning; in particular, Emily Farmer, Cooper Felkins, and William Thompson.

**References:**


[1] S. Brown, D. Montfort, N. Perova-Mello, B. Lutz, A. Berger, A., and R. Streveler, 2018, "Framework Theory of Conceptual Change to Interpret Undergraduate Engineering Students' Explanations About Mechanics of Materials Concepts," *Journal of Engineering Education*, Vol. 107, No. 1, pp. 113-139, 2018.

[2] B.L. Newberry, "Hands-On Learning in Engineering Mechanics using Layered Beam Design," *ASEE Annual Conference and Exposition*, Nashville, TN, June 22-25, 2003.

[3] R. Sullivan, and M. Rais-Rohani, "Design and Application of a Beam Testing System for Experiential Learning in Mechanics of Materials," *ASEE Annual Conference and Exposition*, Pittsburgh, PA, June 22 – 25, 2008.

[4] K. Lulay, H.E Dillon, K.E. Eifler, T.A. Doughty, D. Anderson, and J.I.B De Jesus, "Increasing Engagement in Materials Laboratory with Backward Design and Quadcopters," *ASEE Conference and Exposition*, Columbus, OH., June 25-28, 2017.

[5] D.J. Pickel, G.W. Broadland, and R. Al-Hammoud, "Hands-On Beam Models and Matching Spreadsheets Enhance Perceptual Learning of Beam Bending," *ASEE Conference and Exposition*, New Orleans, LA, June 26-29, 2016.

[6] Y. Astatke, M.F. Chouikha, K.A. Connor, A.A. Ferri, B.H. Ferri, K. Meehan, D.L. Newman, M.M. Deyoe, and D.J. Walter, " Models of Adoption and Best Practices for Mobile Hands-On Learning in Electrical Engineering," ASEE/IEEE Frontiers in Education Conference, Oklahoma City, OK, Oct 23-26, 2013.

[7] A. Lanterman, M. Giardino, B. Ferri, J. Michaels, W. Hunt, and A. Ferri, "Embedding Low-Cost, Portable Experiments into a Lecture-Based Signals and Systems Course," Proceedings of the 2014 American Control Conference, Portland, OR, June 4-6, 2014.

[8] B.H. Ferri, A.A. Ferri, D.M. Majerich, and A.G. Madden, "Effects of In-Class Hands-On Laboratories in a Large Enrollment, Multiple Section Blended Linear Circuits Course," *Advances in Engineering Education*, Vol 5, No. 3, 2016.

[9] B.H. Ferri and A.A. Ferri, "A Controls Approach to Improve Classroom Learning Using Cognitive Learning Theory and Course Analytics," Proceedings of the 2016 American Controls Conference, Boston, MA, July 6-8, 2016.

[10] B.H. Ferri, J. Harris, and A.A. Ferri, "Three Models for Blending Classes in a Multi-Section Course," in *Blended Learning in Practice: A Guide for Practitioners and Researchers*, edited by Ashok K. Goel, Rob Kadel, Amanda Madden, and Lauren Margulieux: MIT Press, 2019

[11] B.J. Goodno, and J.M. Gere, *Mechanics of Materials.* 9th Edition, Boston, MA: Cengage Learning, 2018.

[12] Canvas learning platform, Instructure, Inc., Salt Lake City, UT. [Online]. Available: http://www.instructure.com.

[13] Piazza social question and answering application. [Online]. Available: http://piazza.com.

[14] Matlab, MathWorks, Inc., Natick, MA. [Online]. Available: http://www.mathworks.com.

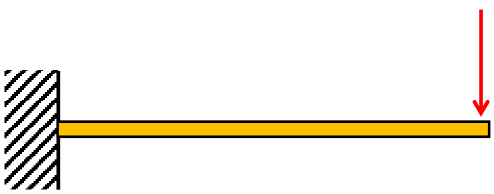
[15] LabVIEW, National Instruments, Austin, TX. [Online]. Available: http://www.ni.com.

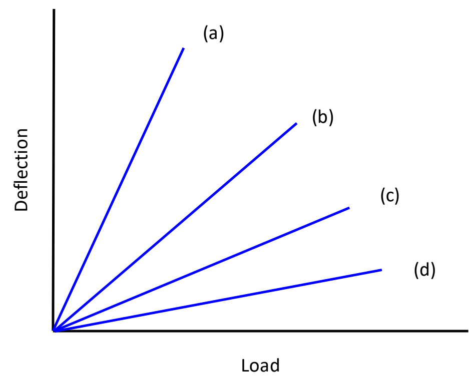
## Appendix A: Beam Bending Concept Inventory

**Beam Bending Concept Inventory (correct answers are highlighted in red)**

| Material | E (GPa) | Yield Strength (MPa) | Ultimate Strength (MPa) |
|---|---|---|---|
| Steel | 200 | 250 | 400 |
| Aluminum | 69 | 95 | 110 |
| Wood | 10 | 85 | 85 |
| Acrylic | 3.2 | 68 | 70 |

**Questions 1 – 4 pertain to the cantilever beam figure and deflection-load curve shown below.**






1. Four cantilever beams of identical length and cross-sectional geometry are loaded at the tip by small, identical point loads. The figure shows the tip deflection as the load is increased. Which line corresponds to Steel? (refer to the table of material properties above)

(a) (b) (c) **(d)** (e) not possible to tell

2. Which material would have the greatest stress at the root (clamp location)?

(a) Steel
(b) Aluminum
(c) Wood
(d) Acrylic
**(e) Same for all materials**

3. Which material would have the lowest strain at the root (clamp location)?

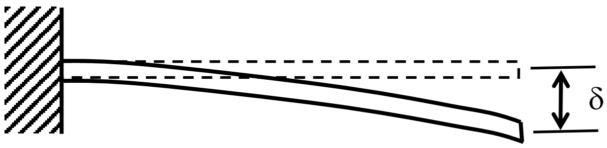
**(a) Steel**
(b) Aluminum
(c) Wood
(d) Acrylic

(e) Same for all materials

4. For the same tip load, which material would be most likely to yield?

(a) Steel
(b) Aluminum
(c) Wood
**(d) Acrylic**
(e) Same probability for all materials

**Questions 5 and 6 pertain to the prescribed displacement condition shown below**



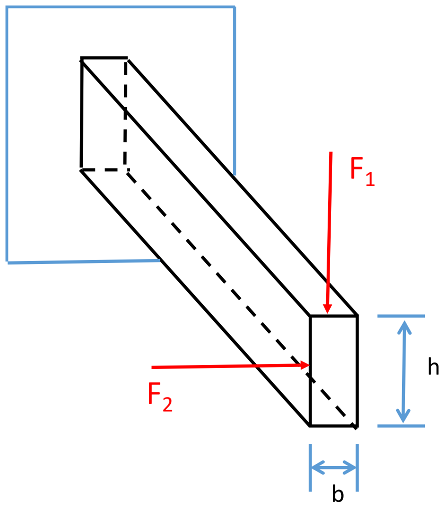

5. Imagine that all beams are given tip deflections of the same amount. Which beam would have the highest stress at the root?

**(a) Steel**
(b) Aluminum
(c) Wood
(d) Acrylic
(e) Same for all materials

6. Imagine, again that all beams are given the same tip displacement. Which beam would have the greatest strain at the root?

(a) Steel
(b) Aluminum
(c) Wood
(d) Acrylic
**(e) Same for all materials**

**Questions 7 – 10 pertain to the figure below**




7. A cantilever beam with a rectangular cross section is loaded in one of two possible ways. $F_1$ is aligned with the larger cross-sectional edge and $F_2$is aligned with the shorter cross-sectional edge. Both $F_1$ and $F_2$ have the same magnitude. Which loading will result in the greatest deflection of the tip?

(a) $F_1$ **(b) $F_2$** (c ) The deflections will be the same (d) Not possible to tell

8. Which loading will result in the greatest stress at the beam root (clamping location)?

(a) $F_1$ **(b) $F_2$** (c ) The stresses will be the same (d) Not possible to tell

9. If the ratio of h to b is 2 to 1, then the displacements resulting from $F_1$ and $F_2$ will have the ratio of:

(a) 2 to 1

(b) 1 to 2

**(c ) 1 to 4**

(d) 4 to 1

10. If $F_1$ were applied alone, the deflection in the horizontal direction would be:

**(a) zero**

(b) infinite

(c ) non-zero but finite

(d) Depends on if the load is applied on the centerline of the beam