Active Learning Demonstrations in Engineering Mechanics

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Abstract

Theoretical teaching of introductory strength of materials concepts has been enhanced with a series of simple demonstrations. The demonstrations take advantage of low cost, readily available materials including PVC pipe and a luggage scale. These materials offer students relatable and scalable concept examples. While they do not replace the need for typical industrial examples or theoretical teaching; they offer a quick option to boost student engagement and comprehension. While further investigation is still needed, preliminary student feedback suggests the demonstrations have provided an effective and enjoyable source of learning.

Introduction

Concrete everyday examples have been shown to increase both student engagement and concept retention.[3, 5, 7] McKeachie states "To link what is in your head with what is in the students' heads, you need to use examples that relate the subject to the students' experience and knowledge."[5] Unfortunately, students often lack familiarity with typical "Strength of Materials" textbook industry examples. Due to their large scale, building familiarity through classroom demonstrations of textbook examples also proves difficult.

To bridge the gap between student experiences and industry examples, a series of classroom demonstrations has been developed using low cost materials including PVC pipe and a luggage scale. Turning to PVC pipe as a structural member has allowed for quick and simple demonstrations. These demonstrations enhance the learning experience by engaging students with both visual displacements and tactile forces which are difficult to achieve with more rigid industrial materials. These demonstrations add credibility to theory which ultimately help students break down pre-existing mental models and rebuild them with new concepts.[3]

Three separate demonstrations have been developed to expose fundamental engineering mechanics concepts. First, an archery bow constructed from PVC pipe is used to reinforce understanding of bending and combined normal stress calculations. In this demonstration, load measurements with the luggage scale are substantiated with stress calculations. Next, a length of PVC pipe is used to demonstrate column buckling. Buckling analytical calculations are verified with luggage scale buckling load measurement. The last demonstration reveals the effects of cross-section shape on torsional rigidity of equal length PVC pipes.

Turning to lower strength and lower cost materials can simultaneously decrease barriers while increasing impact to student learning. Student surveys upon completion of the course support this assertion by indicating a high level of satisfaction and effectiveness with the demonstrations.

Course Description and Demonstration Implementation

The demonstrations were implemented in an introductory three credit Mechanical Engineering Technology Strength of Materials course. The only engineering pre-requisites for the course included Statics and Engineering Materials; therefore, this course is a student's first exposure to engineering mechanics. The course textbook is Mott's "Applied Strength of Materials".[6] This textbook already provides some excellent chapter activity suggestions. These activities can be supplemented with the demonstrations provided in this paper.

The archery bow was used to demonstrate bending stress in chapter 7 and also combined stresses in chapter 10. The buckling demonstration was carried out while covering chapter 11, "Columns". Finally, the demonstration of cross-section effect on torsional rigidity was applied to chapter 4, "Torsional Shear Stress and Torsional Deformation". The method of instruction for each demonstration follows below.

Method of Instruction

<u>Bending Stress and Combined Normal Stress in a PVC Archery Bow</u>. This demonstration combines force measurement using a luggage scale with stress calculation in a PVC archery bow (see Figure 1). The archery bow was created from ¾ inch schedule 40 PVC pipe by heating small sections of the 48 inch length of pipe with a heat gun until the material was pliable enough to form each curve to match a template. A number of internet tutorials exist for creating variations of this bow.[4] This exercise offers students a tactile feel for load versus deflection that can be related back to stress level. It also delivers a visual indication of bow deflection along with force vector directions produced by tension in the bow string. Finally, analytical methods are used in combination with measured loads to add credibility to theory and further impact student learning.

Figure 1. Bending & Combined Normal Stress in an Archery Bow

Students immediately notice this example is very different in appearance than typical textbook problems. The use of unexpectedness is a known strategy in gaining and holding audience attention.[3] As the PVC archery bow is presented, the following problem is posed to the students: "A piece of ¾ inch schedule 40 PVC pipe was used to make this archery bow. Let's determine a reasonable load on the draw string and then calculate the stress in the handle." After a number of students experiment by pulling on the draw string with the luggage scale, they arrive at what feels like a reasonable load, let's say 20 lbs. The students then hold the bow by the handle against the whiteboard and apply this load to the string. The displaced condition of the bow is traced around the bow on the white board for further analysis (Figure 2).

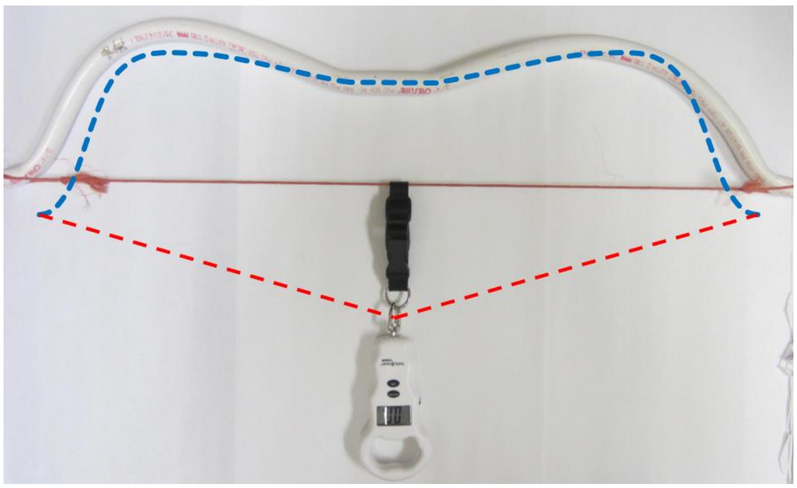

Figure 2. Displaced Bow Sketch Overlaying the Original Bow

Next, static force analysis is performed by creating a free body diagram with the sketch of the displaced bow (Figure 3). This particular luggage scale also has a tape measure which is used to add some dimensions to the sketch. These dimensions are used to drive the static force analysis and ultimately determine the forces and moment in the handle of the bow (Figure 4).

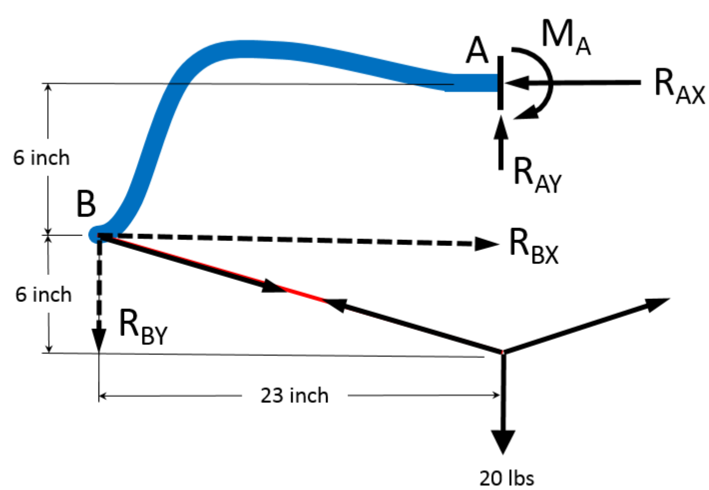

Figure 3. Free Body Diagram of the Displaced Bow

$$\textit{For the bow string}:$$
$$\sum F_Y = 0:\ 2R_{By} = 20\ lbs \therefore R_{By} = 10\ lbs$$
$$R_{Bx} = \frac{23}{6}F_{yA} = \frac{23}{6}(10\ lbs) = 38.33\ lbs$$

$$\textit{For the bow}:$$
$$\sum F_y = 0:\ R_{Ay} - R_{By} = 0 \therefore\ R_{Ay} = R_{By} = 10\ lbs$$
$$\sum F_x = 0:\ R_{Bx} - R_{Ax} = 0 \therefore R_{Ax} = R_{Bx} = 38.33\ lbs$$
$$\sum M = 0:\ (23\ in)R_{By} + (6\ in)R_{Bx} - M_A = 0$$
$$M_A = (23\ in)(10\ lbs) + (6\ in)(38.33\ lbs) = 460.0\ lb.in$$

Figure 4. Force Analysis of a Displaced Bow

Stress analysis can then be performed on the bow handle using the outputs from the force analysis. The forces generate a combined stress state with both bending stress and direct normal compressive stresses at the handle. Geometry properties of the pipe cross-section are required for the calculation and are readily available from numerous sources (Table 1)[1]. The maximum stress is a compressive stress at the base of the handle and is calculated in Figure 5. The PVC pipe's tensile strength (7450 psi)[2] and flexural strength (14450 psi)[2] can then be shared with the class to offer a quick reality check to the calculations. If time permits, there is opportunity for deeper learning with continued discussion around PVC material properties and why both tensile and flexural strength are reported.

Table 1. Cross Section Geometry Properties for ¾ Inch Schedule 40 PVC pipe[1]

O.D. (Outer Diameter):	1.050 inch
I.D. (Inner Diameter):	0.804 inch
A (Area):	0.358 in^2
I (Moment of Inertia):	0.0392 in^4

$$\sigma = -\frac{F}{A} - \frac{Mc}{I} = -\frac{R_{Ax}}{A} - \frac{M_A c}{I} = -\frac{(38.33\ lbs)}{(0.358\ in^2)} - \frac{(460\ lb.in)(1.050\ in)/2}{(0.0392\ in^4)}$$

$$\sigma = -107.1\ psi - 6161\ psi \approx -6270\ psi\ or\ 6270\ psi\ compression$$

Figure 5. Stress Analysis of a Displaced Bow

<u>Critical buckling load for a length of PVC pipe.</u> This demonstration involves using a luggage scale to measure the critical buckling load for a length of PVC pipe after determining the expected value from theoretical calculations (Figure 6). A 45.5 inch long piece of ½ inch Schedule 40 PVC pipe was used for this demonstration; however, any size pipe that can generate a reasonable buckling

load (10 to 50 lbs.) would be an acceptable substitute. The geometry properties and material strength necessary in performing buckling calculations are once again readily available from multiple sources and are listed in Table 2.[1,2]

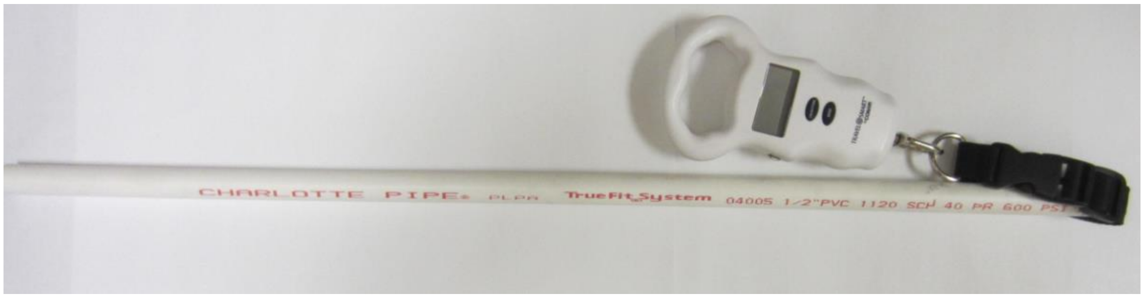

Figure 6. ½" PVC Pipe and Luggage Scale for Buckling Demonstration

Table 2. Geometry and Material Properties for ½ Inch Schedule 40 PVC pipe[1,2]

r (radius of gyration):	0.258 inch
A (Area):	0.270 in^2
E (Elastic Modulus):	400 000 psi
$S_y \approx S_u$ (Yield Strength):	7450 psi

This demonstration begins with calculation and concludes with measurement in an attempt to add context and credibility to theory for maximum learning impact. The class is presented with the piece of PVC pipe which instantly adds some authenticity to this example over previous textbook examples. To add further context, it is explained to the class: "Suppose we wanted to use this pipe to make a cane for your grandmother who is no longer very steady on her feet. Could we trust it to support her?" Discussion of the expected load and necessary safety factor compels students to care about the outcome. Generating a sense of caring has been shown to increase both engagement and retention of information.[3]

Following these lead-in discussions, the official demonstration can begin. Theoretical calculations follow the same method as earlier textbook example problems. It is noted that the pinned-pinned end fixity conditions may not provide a perfect idealization, but it is chosen because it results in the appropriate bending mode shape. The calculations begin by comparing the pipe's slenderness ratio with the material's column constant. This confirms the pipe is indeed a long column and requires the use of Euler's formula to determine the critical buckling load (Figure 7).

$Slenderness\ Ratio\ and\ Column\ Constant$:

$$SR = \frac{KL}{r} = \frac{(1)(45.5\ inch)}{(0.258\ in^2)} = 176.4$$

$$C_c = \sqrt{\frac{2\pi^2 E}{S_y}} = \sqrt{\frac{2\pi^2(400\ 000\ psi)}{(7450\ psi)}} = 32.55$$

$$SR \gg C_c \therefore use\ Euler's\ Buckling\ Formula$$

$Euler\ Critical\ Buckling\ Load$:

$$P_{cr} = \frac{\pi^2 EA}{(L_e/r)^2} = \frac{\pi^2(400\ 000\ psi)(0.270\ in^2)}{(176.4)^2} = 34.2\ lbs$$

Figure 7. Critical Buckling Load Calculation

Upon completion of the critical buckling load calculation, students are asked if the load seems reasonable. The pipe is passed around to let students get a feel for the applied force necessary to generate the buckling mode. Further discussion concerning the use of the pipe as a walking cane will naturally arise. This should be encouraged as students attempt to apply these theoretical concepts to a real world example.

The luggage scale surfaces only after this discussion so that the buckling load can be measured for further validation. The measurement will be close to the calculated load, but the difference in values offers additional opportunity for discussion and deeper learning. End fixity, loading conditions, material properties, and even subjectivity in measuring the critical buckling load all provide possible sources of error.

Cross-Section Effect on Torsional Rigidity. This demonstration is simply a tactile exercise for students to gain a relative understanding of the effect of cross-section on stiffness of a torsional member. As shown in Figure 8, three 18 inch lengths of 2 inch schedule 40 PVC pipe are used for the demonstration. One of the pipe cross-sections (bottom) was left circular to demonstrate the most efficient use of area in a torsional cross-section. A second section (center) was flattened to provide a rounded rectangular cross-section. This was created using a heat gun to soften the material until it could be flattened into this form. The final section (top) was left circular, but split down the center to demonstrate the effect of a discontinuous cross-section. Holes were drilled in the ends of each length of pipe so that ½ inch schedule 40 PVC pipe could be placed in each end and used as handles for twisting each section.

Figure 8. Cross-Section Effect on Torsional Rigidity

The textbook treatment of structural members loaded in torsional shear focuses mostly on solid and hollow circular cross-sections. This applies to a large percentage of applications including most shafts, axles, pipes, and tubes; however, it is important that students understand the effects of using other types of cross-sections to carry torsional loads for applications such as machine frames, auto bodies, or even consumer product structures. The analysis of stiffness and strength of non-circular cross-sections varies for each case, but it is possible to gain a quick sense of the effect of cross-section modification with this demonstration. With the introduction of non-circular cross-sections in torsion, students can try to twist each of the example sections to experience the resulting effects. It is important to note that each of the pieces differ only in cross-sectional shape and share the same material, length, and cross-sectional area. The closed circular section is notably the stiffest section, but the closed rectangular section maintains a comparable tactile feel. On the other hand, the open circular section results in a dramatic decrease in torsional stiffness. This can be related back to the use of tubular members in most machine and auto body structures. While it is tempting to design with open cross-sections produced by high volume manufacturing processes such as sheet metal stamping and injection molding, torsional stiffness is increased dramatically by finding ways to close these sections.

Assessment

Near the end of the course, students completed an anonymous survey regarding the class demonstrations. A Likert-type scale was used to rate students' agreement with three statements about each demonstration. These basic statements were only intended to assess whether or not the examples warranted continued use in future classes. These statements included:

A) "This demonstration made class more interesting and enjoyable."
B) "This demonstration helped me better understand concepts from this chapter."
C) "This demonstration is worth repeating in future Strength of Materials classes."

16 of the 20 students in the class completed the survey. Figure 9 displays the results of the survey with the average rating for each of the three questions within each demonstration. There was strong agreement with all three questions and all three demonstrations. The ratings were further reinforced with a few general comments from the survey. One student commented "the demonstrations were all very helpful. Great visuals made the class more interesting." These results suggests the demonstrations have provided an effective and enjoyable source of learning.

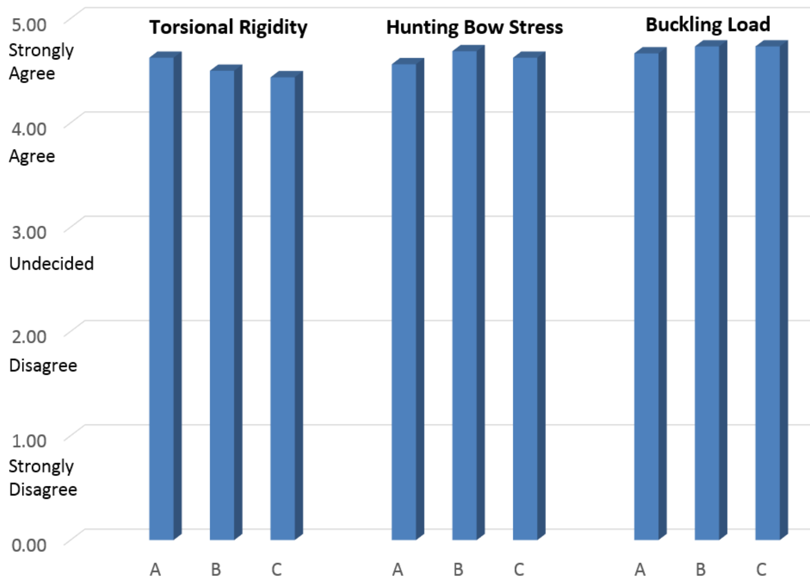

Figure 9. Demonstration Survey Results

Conclusions

This series of demonstrations offers an effective approach to bolstering theoretical teaching of engineering mechanics concepts in an undergraduate strength of materials course. While the demonstrations do not replace the need for theoretical teaching with typical industry examples, they can help bridge the gap between students' current experiences and textbook examples. This can be especially useful in courses with limited lab exercises.

Some initial success confirmed by feedback in student surveys supports continued experimentation with this series of demonstrations. Specifically, the torsional rigidity demonstration could be further improved by providing a connection to a real-world example in combination with analysis and measurement techniques similar to the other demonstrations. Additional demonstrations and examples could also be developed using these same materials and tools to support other course concepts. The simplicity, low cost, and quick execution of these demonstrations increase their appeal as a teaching aid; however, further evaluation is necessary to properly assess their overall effectiveness on student learning.

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