AC 2003-939: "SHOW ME THE MONEY!" USING PHYSICAL MODELS TO EXCITE STUDENT INTEREST IN MECHANICS

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Introduction

Students often have difficulty grasping the reality of what is being discussed in introductory courses in mechanics. For some students, especially those who are struggling, physical reality becomes mired in seemingly endless equations and the apparent mish-mash of theory and practical application. This should be prevented if at all possible, as mechanics is the first course in which students can participate in designs that include material type and geometry in a realistic way. One essential method for convincing students of the importance and truth of what you are teaching is to actually show them that truth up close. Students crave reality when confronting engineering topics for the first time. In a sense, students say "Show me the money!", or "Don't TELL me, SHOW me…".

This paper presents a number of simple, low-cost and rapid classroom demonstrations that enhance student understanding by allowing for the direct observation of physical phenomenon. Each of these demonstrations has been thoroughly classroom-tested, and comments on the use of each demonstration are presented. Demonstrations of stress transformation, shear stress, pressure, and load visualization are presented and practical advice on the use and misuse of classroom demonstrations is offered. Student feedback is also presented, and consistently points to the effectiveness of hands-on demonstrations in driving home key points in mechanics.

Conversion of Force and Stress

Objective: To clearly show the relationship between force, area and stress, while simultaneously demonstrating a key mechanical concept; the pressurized cylinder and piston system.

Equipment: The equipment required for this demonstration is shown in Figure 1. While somewhat more costly and complex than the other systems presented in this paper, the total cost for materials is still less than $250. Some machining is also required. The device consists of a 3 ft acrylic tube having an inside diameter of 3 in, capped at each end with a threaded PVC cap. The top cap has a hole for the pushrod, and the bottom cap has an access port to which a 15 psi pressure gage and bleeder valve is attached. Additionally, the top of the half-inch pushrod is fitted with a load platform. The bottom of the pushrod is fitted with a soft rubber wiper. Initially, a tight-fitting reinforced hard-rubber wiper was contemplated, but the friction from the wiper-cylinder interface was too large and ruined the demonstration. The relatively light friction from the soft rubber wiper should be balanced with the weight of the platform and pushrod assembly, so that the weight added to the platform during the demonstration directly converts to the pressure seen on the gage. A portable scale with a capacity of about 100 lbs is also useful, and a calibrated bathroom scale will serve this purpose nicely.

Procedure: Place the demonstrator atop a sturdy desk or table where it can be seen well by everyone in the room, with the pressure gage facing the students. Pick two students to help you out with the demonstration. Have them pick up student textbooks for use as the load, making sure the students donating books write their names on the inside cover or can otherwise identify their textbook. While this is going on, open the bleeder valve and lift the piston to near the top of its stroke. This is a good time to explain to the students how the device works and how air pressure, a stress, will support the textbooks on the platform, a force, and how those are related. We typically do not get into a deep discussion about piston friction, as this tends to obscure the key point of the demonstration.

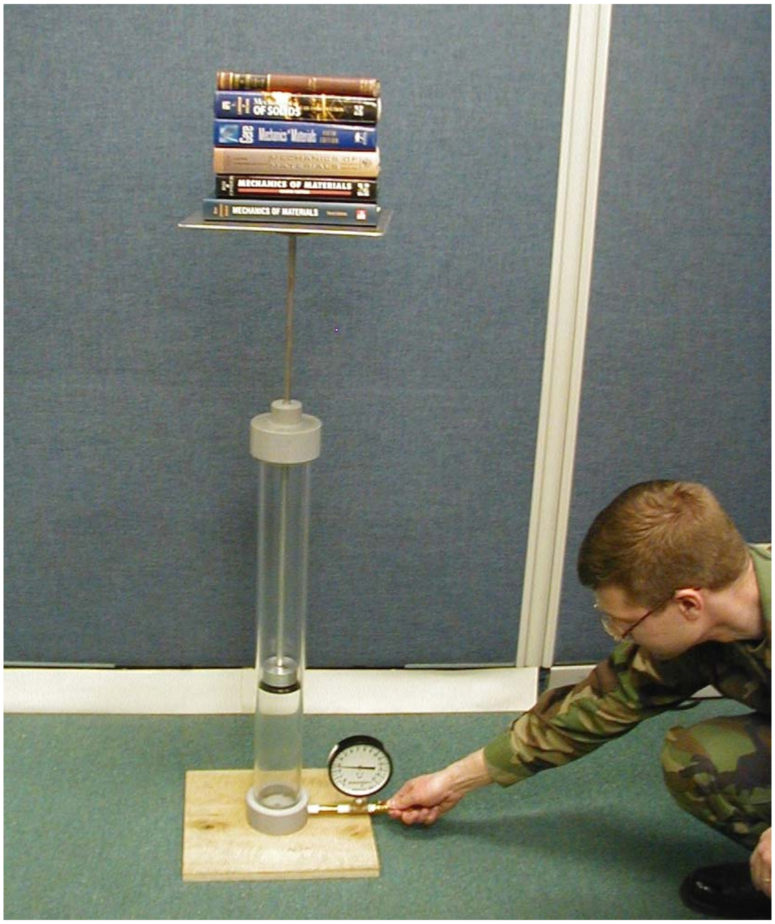

Figure 1: The Stress Demonstrator
(Shown here on the ground. Recommend elevated use for student visibility)

The textbooks are then weighed, and the students are told the diameter of the cylinder and given an opportunity to compute the expected stress reading on the pressure gage. Once a general consensus on the expected stress level is reached, the books are placed on the loading platform by one student, and the instructor slowly opens the bleeder until a constant, slow downward motion is observed. The second volunteer then reads the pressure gage, which should remain constant (with the bleeder open) until the device “bottoms out”.

Observations: The observed pressure value corresponds to the weight of the books divided by the internal area of the cylinder. It is necessary to read the gage while the piston is in motion because of differences between static and kinetic friction. The device DOES NOT produce reliable or even correct results in the at-rest position. This demonstration also provides a direct connection between something many students understand well (pressure) and something they are just learning (stress).

Shear Demonstrator

Objective: To illustrate the difference between shear and normal stress, to show the effect of double versus single shear, and to provide a simple exercise in the conversion of force to stress.

Equipment: Our first attempt, which did not work out, was a wooden shear device, shown in Figure 2, combined with a simple spring scale. The demonstrator was constructed from plywood and poplar, and provided for both single and double shear in a variety of sample diameters. This device worked very well for the first semester of use. However, because of differences in wood types, the poplar pull-board expanded significantly during the summer, and by fall was wedged tight in the internal channel. The pull board was extracted with repeated impact loadings and planed down to fit in the channel. Despite these efforts, the device would not provide consistent results, most likely due to a poor fit of parts, and a noticeable growth of the holes near the shear plane. In essence, the device wore out due to the poor wear characteristics of the wood. It is possible that this problem could have been avoided by constructing the device out of harder woods, but that is by no means certain.

A second prototype of the shear device was then constructed out of acrylic, and this much cleaner-looking device is also shown in Figure 2. We found that shearing a single strand of spaghetti worked well, while shearing multiple strands was chancier because all the strands don’t necessarily act together, and progressive rather than group failure can occur, skewing results. Further, we had to try multiple spaghetti brands to arrive at one which had a suitably thin and consistent diameter. Angel hair pasta seemed to work best, but constant cross-sectional area is the key to success. The behavior of a particular brand should be tested before trying this sort of device in class. It is also worth noting that we attempted to use an electronic fishing scale as a load readout, but the update rate was far too slow to allow for an accurate reading. A spring scale is recommended, preferably with a max load indicator.

Machining the acrylic parts proved to be a challenging process, since acrylic sheet tends to be highly variable in thickness (±0.070 in!) and has to be cut down and squared prior to use. The bottom line is that if repeatable, predictable results are desired, a high-precision device is probably required. In general, the authors recommend a tolerance of no more than plus or minus two thousandths.

Procedure: The use of the device is very straightforward. The students are shown both parts, then a single strand of spaghetti is failed in single shear and the load recorded. Then, a single strand is placed in the double-shear part of the demonstrator, and failed with the load recorded. If desired, the students can measure the diameter of the spaghetti with a micrometer

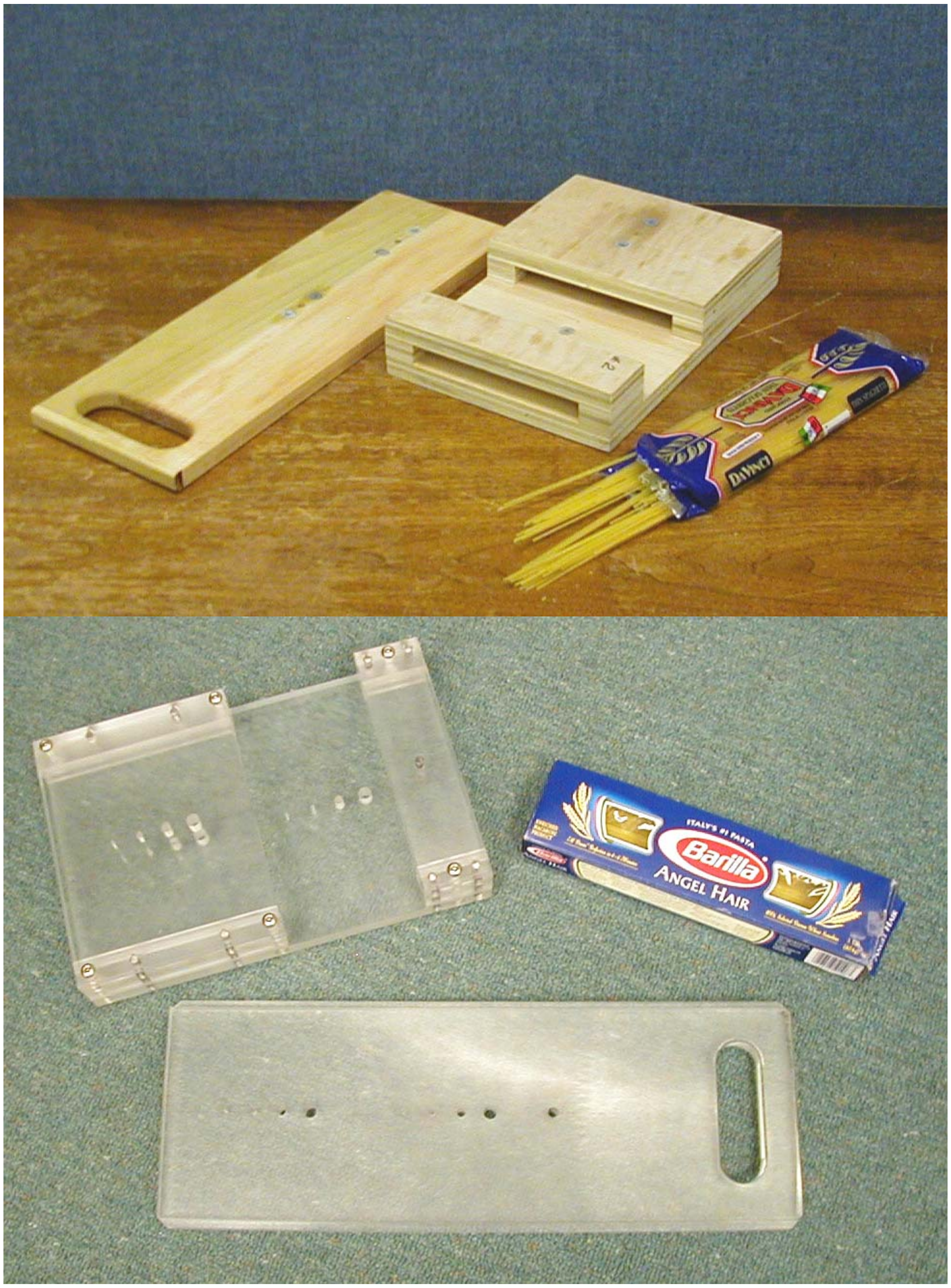

Figure 2: Shear Demonstrators. Above: Wooden, Below: Acrylic

(preferably good to 0.0001”) and compute the shear stress at failure for both samples, which should be roughly the same.

Observations: The observed load to fail the specimens in double shear should be twice that observed in single shear, but the computed failure stress remains the same. Multiple strands of spaghetti do not work well, and care should be taken in selecting a suitable brand of pasta. Students enjoy this demonstration, and it helps to physically reinforce the key concepts of shear strength and shear connections.

Statically Indeterminate Systems; "The Compression Cadet"

Objective: Demonstrate the key concepts related to the solution of statically indeterminate problems.

Equipment: Figure 3 shows the equipment required for this demonstration. The total cost for the materials is approximately $30. The apparatus consists of an eight-foot long 2x4, a hardhat with a steel bracket attached, a bungee strap, and a weight. Make a three-quarter inch hole at one end of the 2x4 for a ten-inch long pin, and another three-quarter inch hole approximately six-feet along the 2x4 where the hardhat will attach. Place two j- hooks, one about three-feet from the pinned end, and the other on the far end of the 2x4. Use a one to two-foot piece of surgical tubing or bungee cord hung from a ceiling or other convenient point and attached to the middle J-hook.

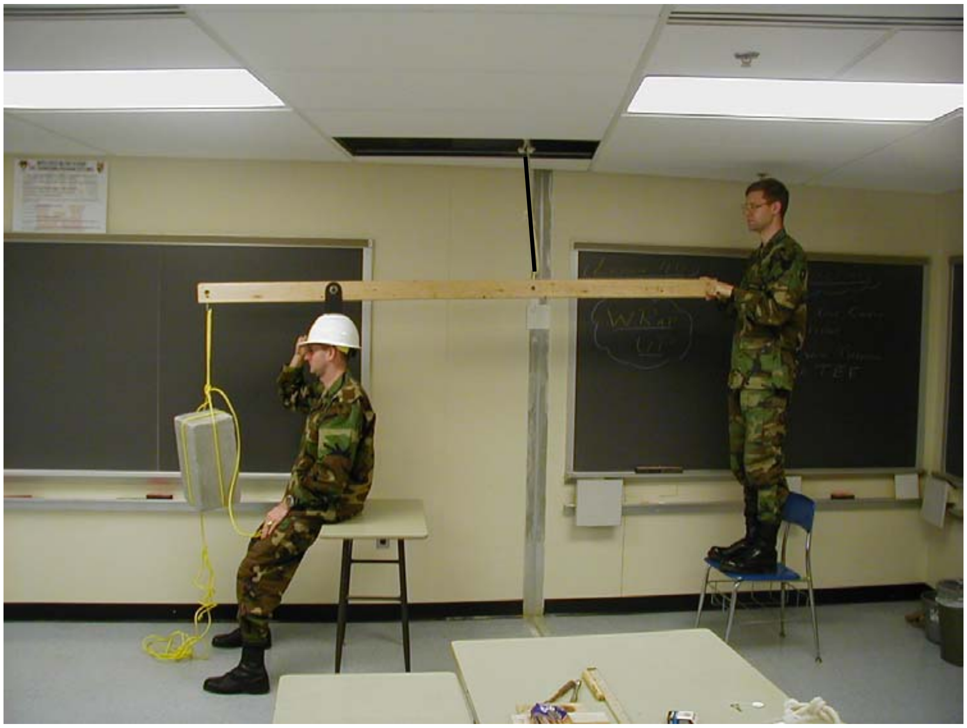

Figure 3: Demonstration of Statically Indeterminate Systems; "The Compression Cadet"

For the hardhat support, we used a U-shaped bracket made out of sheet metal that had a two-inch wide opening and was three inches wide and six inches tall. We made a 5/16 inch hole in the top of the hardhat and bolted the bracket onto the hardhat, and then pinned the bracket to the 2x4 about six feet from the pin end. Any object between about five and twenty-five pounds can be used as a weight, depending on the strength and tolerance of the student. We have used a piece of light weight concrete (heavy) or a bucket of water (light) for the weight.

Procedure: Two students are needed to participate in the demonstration. Have one student stand on a chair and hold on to the pin. Ask the student what motion a pin allows and what motion it prevents. Attach the bungee cord to a support in the ceiling, and hook in on to the first j-hook. The second student puts on the hardhat attached to the 2x4 as shown in Figure 3.

Now add the weight at the end. Lightweight concrete has worked best, because it looks impressive, while weighting less than 20 pounds. Be careful not to have too heavy a weight, or the student wearing the hardhat might be injured. Have the student wearing the hardhat squat down several inches to allow for observable deformation of the bungee.

Observations: The students should observe that the bungee cord is in tension, the student wearing the hardhat is in compression, and that there is a compatibility relationship between the deformation of the bungee cord and the student wearing the hardhat. Point out that this is a statically indeterminate problem.

Stress Transformation

Objective: To show first-hand how a simple change in orientation can change the observed effects of the stress at a point.

Equipment: A big book with identical squares drawn 45 degrees offset, as shown in Figure 4. Catalogs available from various machine-tool suppliers work well, and the cost of this demonstrator is thus very minimal. The key is that the book MUST have a stiff binding, not a soft paper binding such as that found in telephone directories. The stiff board on the binding maintains page alignment.

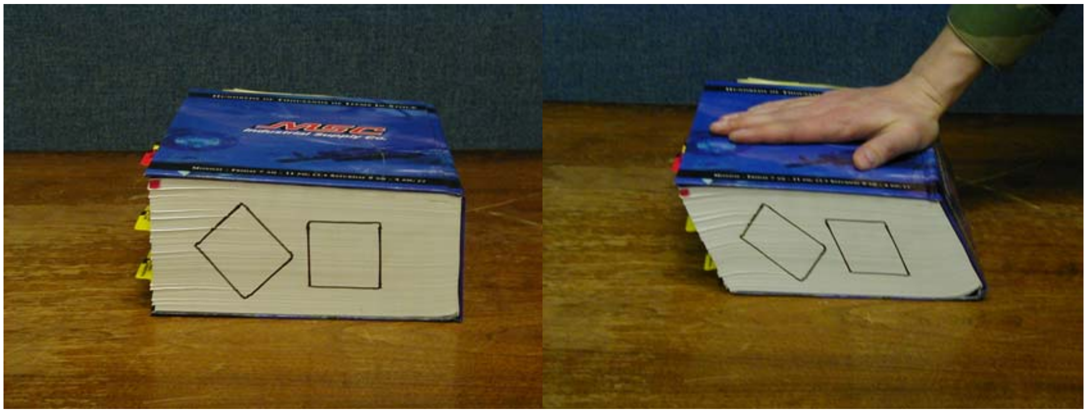

Figure 4: Demonstration of Stress Transformation

Procedure: Place the book on the desktop and point out to the students that there are two identical squares. Be sure to call attention to the 90 degree corners in both squares. Then, place the book in shear by pushing on the top parallel to the desk.

Observations: The student should observe that the two squares have deformed quite differently. The unrotated square shows clear shear deformation, but little or no normal deformation. This block is oriented to show the planes of maximum shear. The corners are no longer oriented at 90 degrees. Conversely, the square which began offset 45 degrees has undergone no shear whatsoever, but has experienced significant normal deformation. This block contains the two principal planes. This effect is shown in Figure 4. The clear implication is that despite having identical states of stress, the observer sees different effects depending on the orientation of the reference frame. This is the essence of stress transformation.

Buckling with Various End Conditions

Objective: Demonstrate the effects of end conditions and effective length on the critical load that causes column buckling.

Equipment: This equipment was developed by others, and has been in use in the Department of Civil and Mechanical Engineering at USMA for many years. A 30-inch long by 1/8-inch thick by 2-inch wide piece of acrylic is mounted in the hardwood (we used poplar) frame shown in Figure 5 below. Cut the movable end blocks with a notch in the center of one side, and a slot the same width as the acrylic column cut in the other side. If the slot is cut too wide, you will not get good results for the fixed connections. The end blocks are attached to the frame with wooden dowels, which rest in slotted holes in the frame. The holes must be slotted so the end block can slide down freely as weights are added on top of the block. A small board with two dowels is mounted on a hinge at the mid-point of the columns. A set of several small weights is also needed.

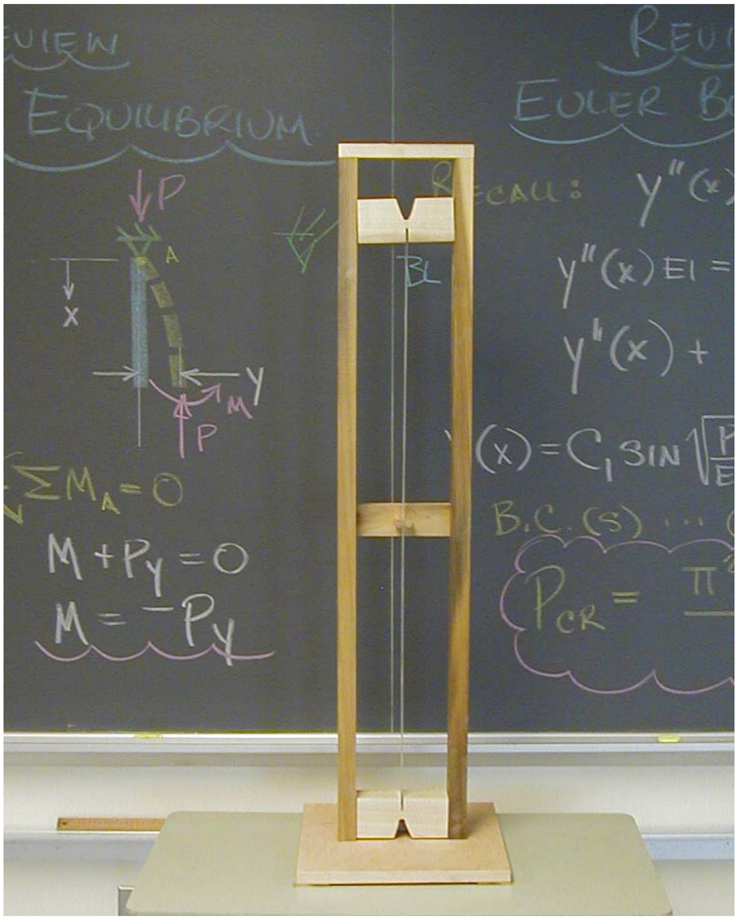

Figure 5: The Buckling Demonstrator

Procedure: Place the acrylic column in the pin-pin ends, with the lateral-restraint board in the center flipped down. Add weight to the top until the column buckles. Record the weight. Now rotate one of the ends, so the acrylic is held in a pin-fix configuration. Add weight until the column buckles and record the weight. Repeat with fix-fix end conditions. Now flip up the lateral-restraint board in the center, so the dowels are holding each side of the sample, demonstrating the effects of changing the effective length of the column. Be sure to include the weight of the top end block in your computation.

Observations: As long as the slot in the end-block holds the acrylic tight, and small weight increments are used, the demonstration will fairly accurately determine the Effective Length Factor, k, in the Euler Buckling Equation. The demonstration will also show the result of changing the effective length, and can be used to physically verify the Euler Buckling Equation.

The Strain Demonstrator That Wouldn't

Objective: The basic idea of this demonstration was to illustrate the effect of length on deformation, and thereby lead the students towards an understanding of strain and elastic stiffness, *E*.

Equipment: Two strands of surgical tubing, one long and one short, where produced. Both had ropes tied to the ends to facilitate gripping the tubes. Additionally, a spring scale was used to apply the load and a measuring tape is required to measure length. A picture of the equipment is shown in Figure 6.

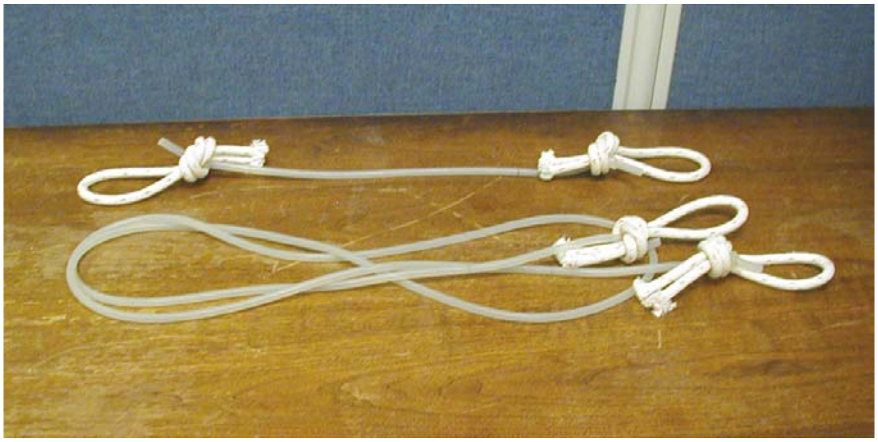

Figure 6: Two Chunks of Less-than-Useful Surgical Tubing

Procedure: No procedure that we attempted worked repeatedly. We put hash marks on the tubes, applied a load and measured the initial and final lengths of the portion of the tubing between the hash marks.

Observations: Surgical tubing is very odd, and is not a good material for this demonstration. The results obtained were not consistent, nor did the elastic behavior appear linear. After multiple testing attempts proved futile, we massively prestressed (yielded) the surgical tubing prior to loading, in the hopes of "pulling" the material into a more coherent molecular alignment. This did not work. It is still possible to use this set-up to demonstrate strain in a qualitative way, but quantitative measurements were not possible. This failure again points out the need for careful testing of demonstrations prior to classroom use. We are still searching for a material which is highly deformable, linearly elastic, non-hysteretic and cheap.

Hoisting a Tractor: Factor of Safety and the Effects of Material Type and Geometry

Objective: To introduce the concepts of design, factor of safety computation and use, and selection of material for use in design.

Equipment: A spool of 0.006 inch diameter (hair-thin) soft tempered copper wire, a rubber band, a scale, a round pointer or stick, and a toy tractor. Our toy weighs 4.3 pounds. We added metal weights to the inside of the toy until four strands of wire broke when we lifted the toy, and six strands worked. The general set-up is depicted in Figure 7.

Procedure: This is the lesson where we first introduce the students to the concept of design. We start the class by giving the students a scenario where, soon after graduating, they receive the task of designing the lift cable capable of hoisting a bulldozer (our toy) from a dock (instructor desk) onto a ship (student desk). The students are given two materials they can use for their lift cable, a rubber band or the very thin copper wire. We discuss reasons not to use the rubber – much lower ultimate strength so lots more material needed, stability of the dozer as its hoisted, lots of deformation (Does our crane even have enough reach to take all the stretch out a rubber cable?), and what happens if the rubber breaks? The students are led to the selection of copper wire rather than rubber. The next question that arises is if we use the copper wire, how much do we need? How safe are we when we use that much wire? Did we waste money by

Figure 7: Hoisting a Load with Very Thin Copper Wire

significantly over-designing the cable? At the beginning of the lesson, the students lack the tools to answer these simple questions in a quantitative way.

The students are then led through experimentally determining how much wire is required to lift the toy. Start with two strands of the copper wire wrapped around a smooth stick to simulate the crane. The smooth stick with multiple wraps is necessary to avoid kinking and thereby weakening the wire. The students are asked if they think this cable will work. Try lifting the dozer. The cable breaks. Repeat with four strands. The cable breaks. Try again with six strands. The cable works. Ask the students if this is the design they want to use. How safe is a six-strand cable? This leads into a discussion of the design equations and the factor of safety. The students are then introduced to ultimate stress, and the concept of factor of safety. This is done by first drawing a Free Body Diagram using the six-strand cable, and solving for the actual stress and thereby factor of safety. Discuss why this does or does not seem reasonable. Redesign the cable using a factor of safety the students pick. Emphasize that we must round up to the nearest whole number of strands.

Observations: This demonstration works very well to introduce the concept of design. We are able to discuss the impact of using different materials in our design, introduce material properties and talk about what a factor of safety is, why we need it, and typical values. The value of thorough testing before going into the classroom is obvious in this case, as it is essential that the results of the lifting "experiment" match the published values for ultimate strength of the copper, and that all the stress levels work out correctly. Further, having the cable work with just two strands would make much of the demonstration moot. This is the classic case of a very simple demonstration that must be carefully tested and prepared prior to going into the classroom.

Assessment

Lowman (1995) contends that demonstrations, which he calls lecture-demonstration classes, are essential in engineering and science courses. The authors of this paper couldn't agree more, and both anecdotal and statistical data support this contention. First, student response during the demonstrations is always strong, and inspires a high volume of questions, a clear sign of student engagement. Second, most of the demonstrations described here were put into use in the Fall of 2001, and were not used in the Fall of 2000. For the authors, who taught Mechanics both terms, semester-end survey questions related to visual connection showed a strong upward trend between the two semesters (see Figure 8). This is significant because the instructors, course content and student population composition remained fairly constant between those two terms. Third, in speaking with students in the semester following the Mechanics courses, most of the strongest recollections are of the physical demonstrations rather than equations or even general concepts. Speaking with former students follows a predictable path, when you remind the student of the demonstration, you get a strong recollection of the physical demonstration which usually leads to a recollection of the physical phenomenon.

Student comments also supported the use of demonstrations, though usually not in a direct way. In general, students were very positive about how the course related to real-world applications and physical understanding, which the demonstrations have a clear impact on. A few examples of positive student comments related to the use of demonstrations are as follows:

- "The instructor uses extremely effective learning tools in class, and they really helped me to better understand the material presented."
- "This has been my favorite class…(cut). Even though it was more work than any other class, it really stimulated my learning and excitement of being a Civil major."
- "Good visual aids"
- Q: Strengths of course. A: "The instructor demos and visual aids", "Practical applications", "Interesting material, vital to Civil and Mechanical majors", "Made difficult concepts easy and applicable"; "Relevance to practical applications/life"; "very practical material".

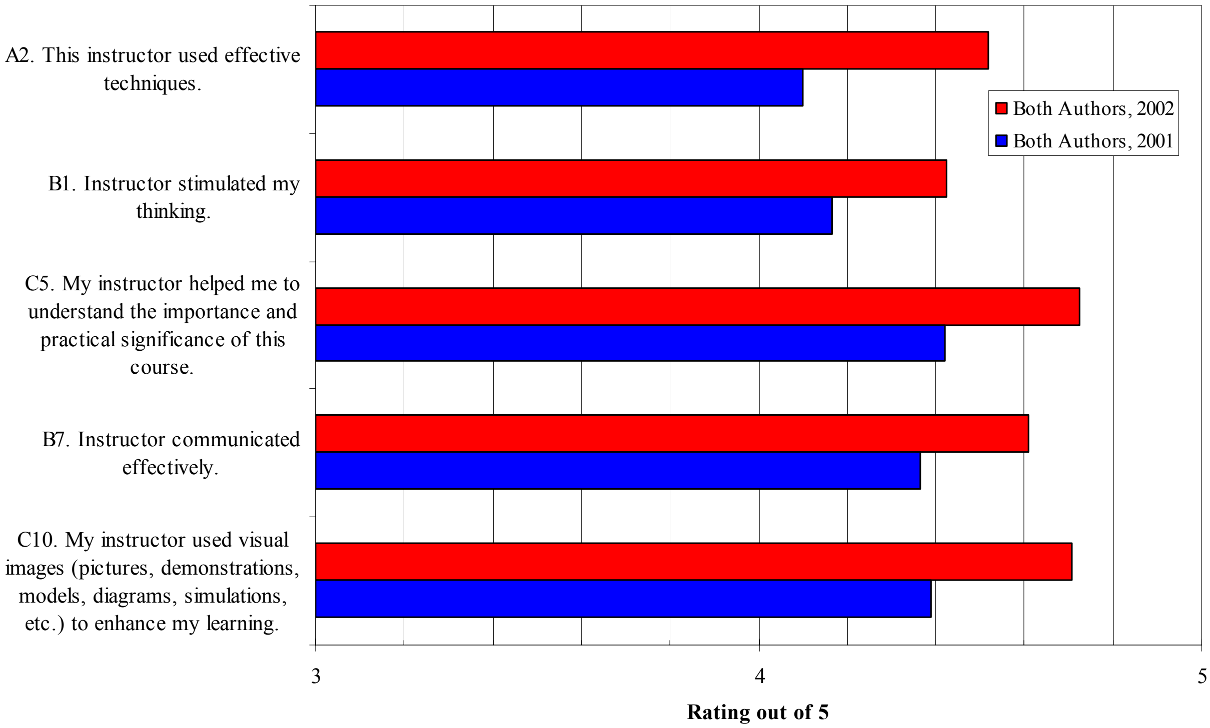

Figure 8: Assessment Data for Fall 2001 and Fall 2002

Conclusions

This paper presents a number of low-cost, effective classroom demonstrations in elementary mechanics. The reader is encouraged to both try out the demonstrations given here and to develop new demonstrations. Course-end assessment by students at West Point has consistently shown a highly positive student response to the demonstrations used, and they tend to form the core of what students recall even years later.

Acknowledgements

The authors wish to acknowledge the efforts of Colonel Steve Ressler, who had the original idea for the compression cadet. The rest of the demonstrations depicted are not his fault, so don't blame him.

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