Simple Demonstrations in Basic Mechanics Courses

Richard Kunz[1]

Abstract – At Mercer University, as at many engineering schools, the basic mechanics courses of Statics, Dynamics, and Mechanics of Materials are taught in a traditional lecture format with no laboratory component. Students are typically exposed to abstract concepts such as forces, moments, rigid body kinematics, stress, kinematics of deformation, strain, and stress-strain transformations through sketches, mathematical derivations, and equations. They often struggle with connecting the mathematical representation of these concepts with the physical world and with their own intuition. Supplementing mathematical demonstrations with videos, computer animations, hands-on activities, and physical demonstrations have been shown to be effective in connecting abstract concepts with physical reality. In this paper, several simple physical demonstrations are described that have been successful in illuminating difficult concepts in basic mechanics courses.

Keywords: Statics, dynamics, mechanics of materials, classroom demonstrations

INTRODUCTION

The fundamental mechanics courses of Statics, Dynamics, and Mechanics of Materials, typically taught in the sophomore or early junior year, form the foundations for mechanical engineering students' subsequent study in machine design, vibrations, solid mechanics, and dynamics of machinery. It is critical that basic concepts of equilibrium, stress, and kinematics of deformation and of motion become second nature. These basic courses are often taught in a traditional lecture format with no laboratory component, so that students are typically exposed to abstract concepts such as forces, moments, rigid body kinematics, stress, kinematics of deformation, strain, and stress-strain transformations through sketches, mathematical derivations, and equations. They often struggle with connecting the mathematical representation of these concepts with the physical world and with their own intuition.

Engineering educators have recognized the difficulties that our students face and have sought to augment traditional chalkboard lectures with supplementary material to give physical meaning to abstract concepts. Computer animations, videos, team projects, hands-on activities, and in-class demonstrations have all been effectively used to move important fundamental concepts from the abstract to the real.

It has long been recognized that learning is enhanced by breaking up the traditional chalkboard lecture with supplementary material. Computer animations [1,2] are available for classrooms that are wired and can be effective in helping students to visualize difficult concepts. On the other hand, today's students are accustomed to sophisticated computer graphics; unless really well done, animations can seem cartoonish and lacking in reality. Especially for students of mechanical engineering, demonstrations using physical artifacts are an effective way to achieve an understanding of physical concepts. Advocates have shown that carefully chosen demonstrations can be used effectively at all stages of the learning process to motivate topics in engineering, create links between mathematical models and physical behavior, and reinforce analytical developments [3]. In a previous paper [4], the author advocated the use of artifacts derived from industry to form a link not only to the physical world but also to the world of engineering practice. A group of engineering educators at West Point [5, 6] has been active in developing and assessing physical demonstrations in undergraduate mechanics courses and has partnered with McGraw-Hill to create a web resource for sharing the use of physical models with the education community (www.handsonmechanics.com) [7]. All of the above have reported favorable reactions from student surveys and

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responses during the demonstrations. In fact, the observation has been made that in subsequent semesters, the strongest student recollections have often been of the demonstrations, not of the underlying equations [6].

In devising in-class demonstrations, the instructor is constrained by time, space, cost, and complexity. Given the amount of material to be covered in these courses, devoting substantial parts of several class periods to supplemental demonstrations is difficult to justify. Furthermore, space is limited in most classrooms, and instructional budgets rarely support complex and elaborate equipment. In fact, the author's classroom experience has indicated that students tend to respond best to simple, brief physical demonstrations that illustrate concepts that are difficult to grasp otherwise. This perception is consistent with [8], in which demonstrations using highly stylized pieces of purchased equipment were compared with demonstrations constructed from spare parts with no concern for aesthetics. Although sample sizes were small, the authors found that the raw demos were superior to the more polished productions in all measured assessments of learning.

In this paper, several simple demonstrations are described. The equipment or props necessary for each are inexpensive and readily available around the house or in stores. A few require less than an hour in the workshop for fabrication and assembly. All are designed either to illustrate key concepts, or to give physical reality to results that may at first seem counter-intuitive.

STATICS AND SOLID MECHANICS

First-semester sophomore engineering students at Mercer typically take a three-semester-hour traditional lecture course in statics and solid mechanics. This, along with electrical fundamentals, is the first discipline-specific hard-core engineering course in the curriculum. The fundamental concepts of forces, moments, and equilibrium introduced in physics are applied to structural and mechanical systems, including internal force systems and concepts of stress, strain, and elasticity applied to bars under axial loading, torsion, bending and shear. The course has the potential to be very rewarding for the aspiring engineer: it provides the opportunity to finally apply the abstract concepts from calculus and physics to engineering systems. However, because of the lecture format of the course, students can miss the physical connection without some physical artifacts to provide grounding for the mathematics.

Kinematics of deformation in torsion and bending

Students often have difficulties in visualizing the kinematics of deformation in the fundamental conditions of bending and torsion even when supplemented by sketches and photographs. A simple foam "water noodle," purchased for a couple of dollars at a discount store, provides a visual demonstration of the essential kinematics Figure 1. It helps to draw a grid so that the essential features of the deformation can be clearly seen. In the case of bending, students' attention is drawn to the observation that plane sections remain plane, and longitudinal lines remain perpendicular to the rotated sections. Longitudinal lines near the bottom are stretched and those near the top are shortened. From there, it is not hard to conclude that longitudinal strain, and therefore stress, varies linearly with depth, and the flexure formula results. In the case of torsion, the shear deformation is clearly seen; plane sections remain plane for the circular section, and the basis for the torsion formula is obtained.

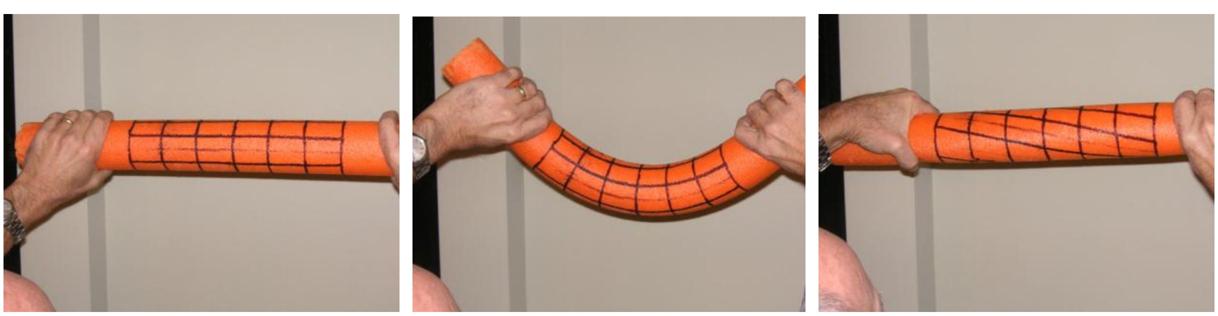

Figure 1. A water noodle is used to demonstrate flexural and torsional deformation.

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Illustration of the Parallel Axis Theorem with Sandwich Construction

In statics and introductory solid mechanics, the calculation of area moments of inertia using the parallel axis theorem finds application in the flexure formula for beams. Students are happy to use this approach to calculate area moments, but without a concrete example, they often don't make the connection to the physical implications to the design of beams. The significance for design can be dramatically illustrated by a simple sandwich structure. I am fortunate to have some samples of aluminum honeycomb and thin-gage aluminum sheet, Figure 2, but a similar demonstration can be made using stiff cardboard glued to a thin piece of foam to make a simple sandwich structure. By themselves, neither the face sheets nor the core exhibit significant stiffness or strength, but when bonded together, an extremely stiff and lightweight structure results. The demonstration is accompanied by a calculation in which a 0.040-in. thick rectangular beam is compared to a sandwich consisting of two 0.020-in face sheets separated by a 1-in thick core. The sandwich construction is shown to reduce the maximum bending stress by a factor of 75 and increase the flexural rigidity by a factor of 1875.

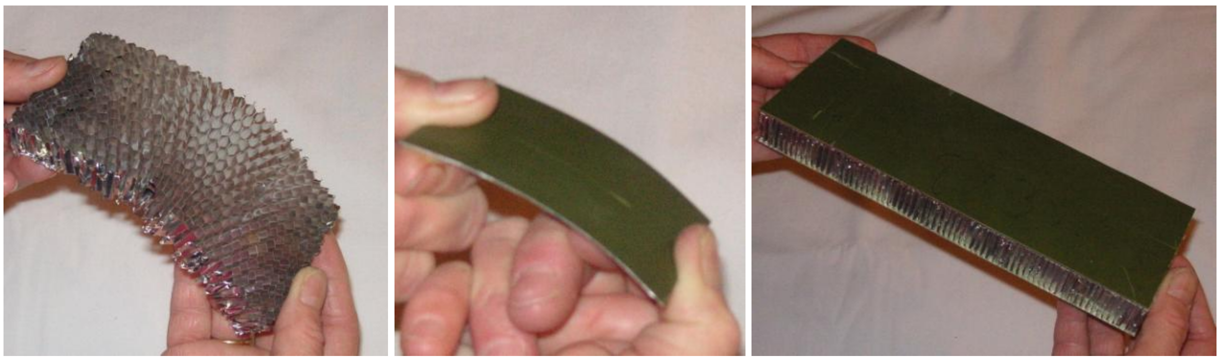

Figure 2. A simple sandwich structure illustrates the power of the parallel axis theorem in design for flexure

DYNAMICS

Dynamics at Mercer is typically taken in the second semester of the sophomore year. Even students who do well in statics often struggle in dynamics. Students who rely heavily on physical intuition typically find that their intuition lets them down in dynamics. Demonstrations that are able to show that bodies really behave the way the equations of kinematics and kinetics say they will are particularly effective.

Kinematics of Rolling

When a wheel rolls without slipping on a flat surface, the center of the wheel moves in a rectilinear path, while the point on the circumference that is instantaneously in contact with the surface has zero velocity. This leads to a simple relation between the angular velocity of the wheel and the velocity of its center. While the kinematics in this case are fairly simple, students sometimes have a difficult time in visualizing the motion of a point on the circumference. I use a hula-hoop with tape showing two diameters, so that the motion of the center and an edge point can be tracked during the motion.

Figure 3. A hula-hoop is used to demonstrate the kinematics of a rolling wheel.

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Once the idea of rolling has been established, it is applied to study at the motion of a spool that is being pulled by a cord wrapped around the inner circumference, Figure 4. When the cord is pulled off the top of the spool, as in the left-hand side of Figure 4, the speed of the center, v_C, is shown to be related to the speed at which the cord is pulled, v_o, by

$$v_C = \frac{R}{R+r} v_o$$

meaning that the center of the spool moves slower than the cord is pulled, so that the cord outside the spool keeps getting longer. Students generally are accepting of this result. On the other hand, when the cord is pulled from the bottom of the spool the speed of the center is shown to be

$$v_C = \frac{R}{R-r} v_o$$

meaning that, as the cord is pulled, the spool moves faster than the end of the cord, and eventually overtakes the hand pulling the cord. Students tend to be far more skeptical of this result; each term some even suggest that there must be some mistake in the result, and that the wheel will actually roll in the opposite direction.

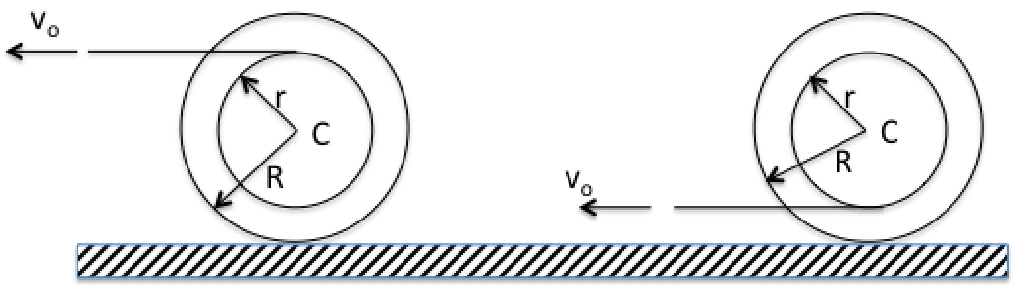

Figure 4. A rolling wheel is pulled by a cord wrapped around an inner spool.

To counteract this skepticism I fashioned a simple, albeit crude spool in my workshop from scrap plywood. When the predicted motion is demonstrated in the front of the classroom, students tend to believe what the kinematic analysis is telling them.

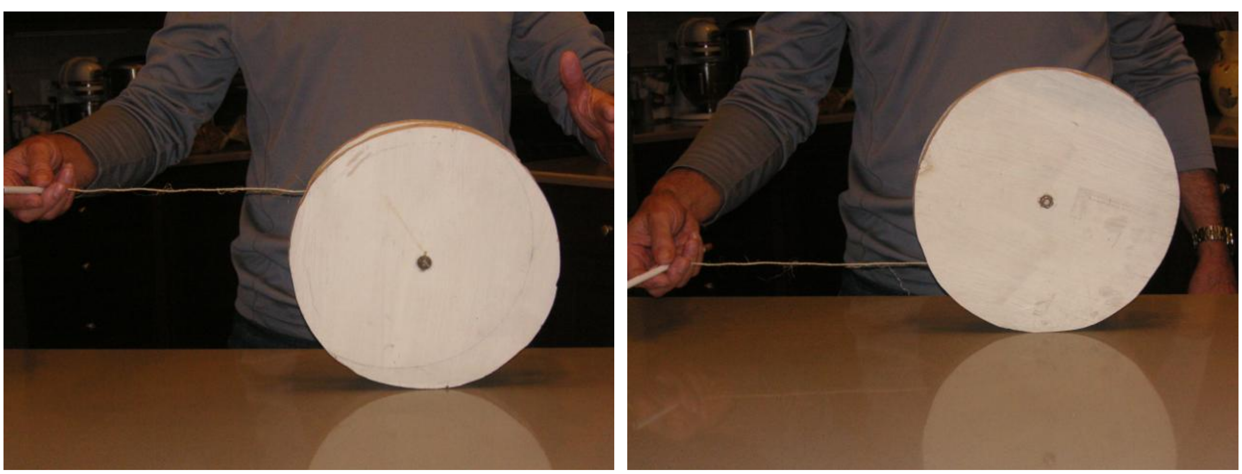

Figure 5. Demonstration of the rolling spool

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The Bouncing Hula Hoop

In analyzing the rolling motion of an unbalanced wheel (Figure 6) using the principle of rigid body kinetics, the normal force between the wheel and the surface on which it rolls is shown to be

$$N = mg + m\omega^2 d$$

(where m is the mass of the wheel, and ω its angular velocity) when the center of mass G is below the center of the wheel as in the left sketch of Figure 6. When G is above the center, the normal force is given by

$$N = mg - m\omega^2 d$$

as in the right sketch in Figure 6. This latter result implies that, if the wheel is rolling fast enough, the normal force can be made to be negative. Since this is not physically possible, the conclusion is that the wheel will lose contact with the surface, if it is rolling fast enough.

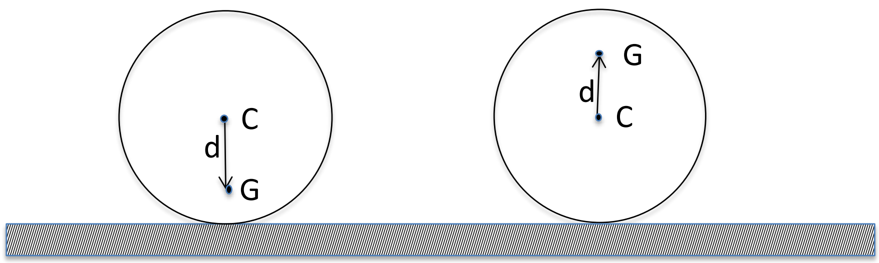

Figure 6. An unbalanced wheel rolls on a flat surface

To demonstrate that this can actually happen, I made in unbalanced wheel by taping two lacrosse balls inside the rim of my hula-hoop, Figure 7. When given a healthy shove, the hoop will hop when the lacrosse balls near the top of their path.

Figure 7. The unbalanced hula-hoop will hop if rolled fast enough.

The Returning Hula-Hoop

When a hula-hoop is cast away along the ground with backspin, it can be made to roll back to the sender. Initially there is sliding of the hoop on the surface, following by pure rolling. This can be easily shown (with some minimal practice) with the same hula-hoop used in demonstrations described previously. I ask the students what determines how much backspin is required to make the hoop return: mass, radius, radius of gyration, coefficient of friction. We then go through the analysis of the problem to find what are the important parameters. After going through the analysis, it turns out that, for a given hoop radius, the key parameter is the radius of gyration; that is, it is easier to get a hoop, which has a large radius of gyration, to return than a sphere, such as a bowling ball, which has a smaller radius of gyration.

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Figure 8. The hula-hoop will return if given enough backspin

MECHANICS OF MATERIALS

Mechanics of materials is taken during the first semester of the junior year. The course extends the basic solid mechanics covered in the statics course to include transformation of stress and strain, theories of failure, generalized Hooke's law, and energy methods.

Transformation of Strain

Students tend to have a difficult time grasping the physical significance of stress and strain transformation. Doing the calculations required to determine components of stress and strain in a rotated coordinate system, or to find principal stresses and strains, is not generally a problem. But understanding what it all means, and being able to visualize the effects is often lost in the computational minutia.

A simple demonstration using the water noodle described previously helps students visualize the transformation of strain. A square aligned with the noodle's axis is seen to deform into a rhombus under torsional deformation, Figure 9. On the other hand, a square aligned at 45° to the axis deforms into a rectangle under the same deformation, Figure 10.

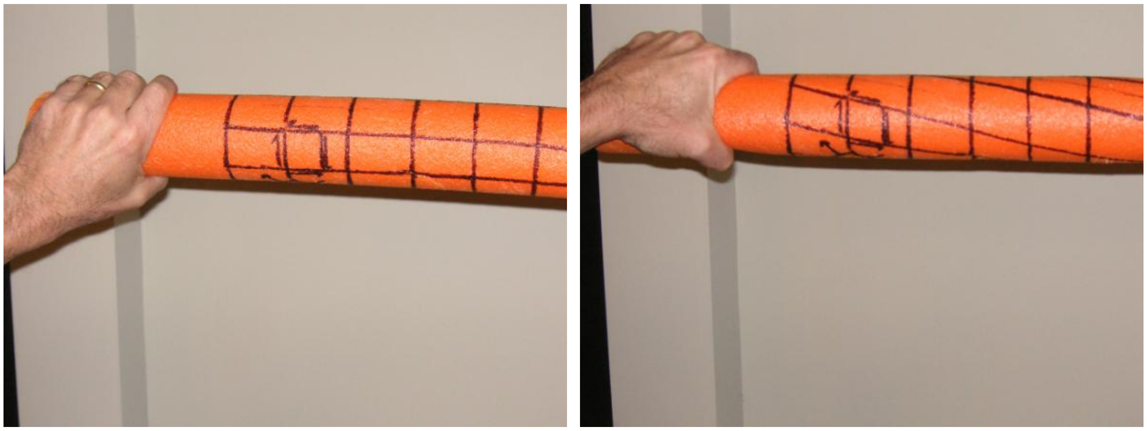

Figure 9. A square aligned with the axis of the bar deforms into a rhombus.

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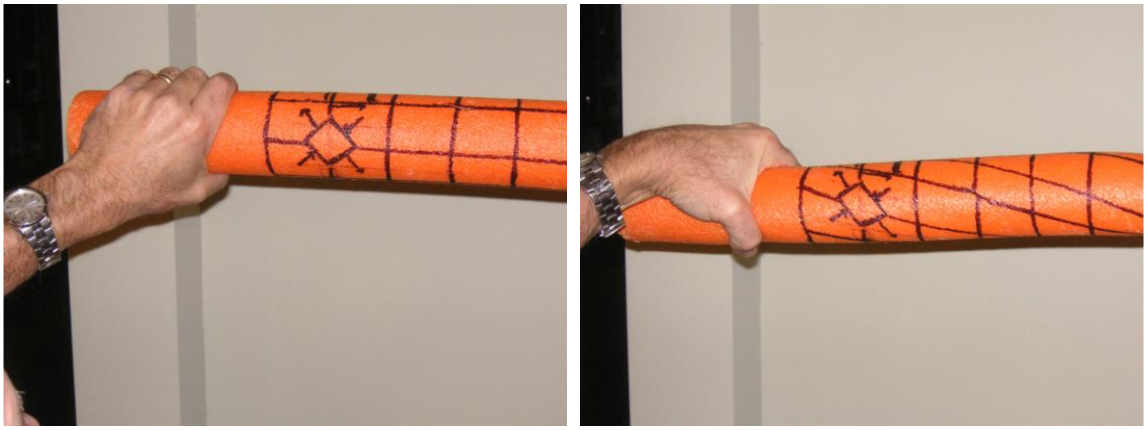

Figure 10. A square aligned at 45º deforms into a rectangle.

Tensile failure in bending and torsion

A couple of pieces of chalk serve to demonstrate both the concept of principal stress and of failure theories. Chalk is described as a brittle material that is weak in tension, implying that the Maximum Principal Stress theory of failure may apply. A piece of chalk is loaded in three-point bending, and fails in the plane of the cross-section, which is the plane of maximum principal stress, Figure 11.

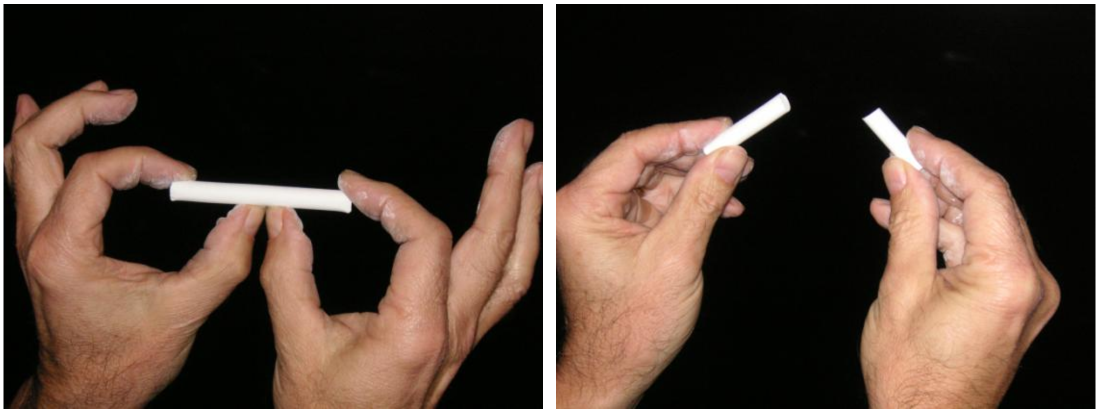

Figure 11. A piece of chalk loaded in three-point bending fails in the plane of the cross-section, which is a principal plane.

A second piece of chalk is loaded in torsion, and fails along a spiral surface at roughly 45º to the cross-sectional plane, Figure 12. For the pure shear induced by torsion, the 45º plane represents the plane of maximum principal stress.

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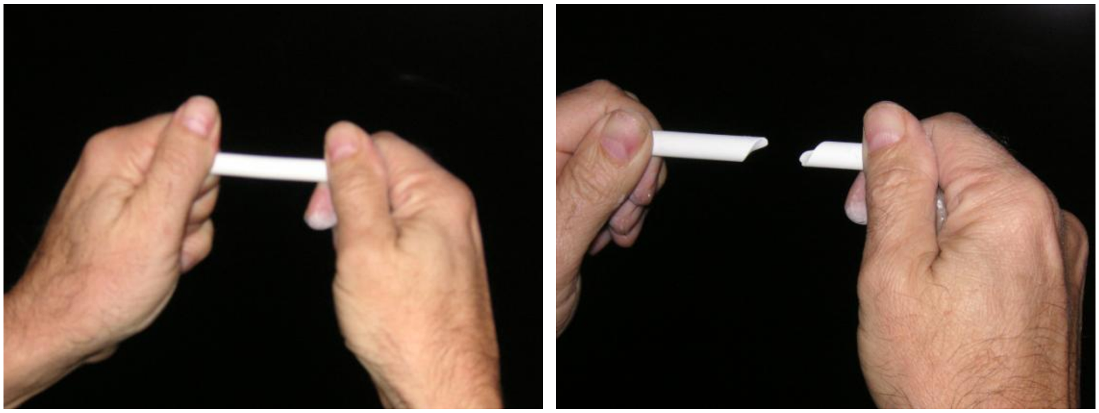

Figure 12. A piece of chalk loaded in torsion fails at 45° to the cross-section in the direction of maximum principal stress.

STUDENT REACTIONS AND CONCLUSIONS

The demonstrations described above all were made either out of materials available around the house or readily obtained at local discount stores. As should be clear from the appearance in the photographs, none requires a great deal of time or skill to make. As an example, I thought of the unbalanced hoop demonstration the evening before my 9:00 am Dynamics class. I already had the hula hoop (previously purchased for one of the other demonstrations), so all it took was a few minutes to identify suitable weights and find the duct tape, and about 20 minutes of practice to make sure I could get the hoop to hop. In fact I sometimes feel that making fun of my own lack of craftsmanship helps the students remember what they saw, what happened, and what it means.

No systematic student survey has been undertaken to formalize student reaction to the demonstrations. I have often passed former students as I head to class with my hula-hoop, and they invariably comment on what they recall is about to happen. Overall, student feedback has been positive. On several occasions, students have remarked to me that all they remember from a class is the demonstrations; I'm not entirely convinced that this is a good thing, but at least they remember something.

All of the demonstrations described fit easily within the budget and time constraints inherent in a lecture-based course. All are short enough that they can be conveniently inserted into a class at the most appropriate time to illustrate the concepts as they are introduced.

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