Enhancing Student’s Understanding of Key Engineering Concepts Through the Use of Civil Engineering Toys in the Classroom.

Assistant Professor Tonya Emerson

Civil Engineering, California State University, Chico, CA 95929-0930

I. Abstract

Assisting students in developing a solid understanding of the many conceptual ideas presented in our undergraduate engineering courses is a significant task. In one key course, Mechanics of Materials, the abstract and sometimes intangible ideas of stress and strain, and what causes them, continue to be a great source of confusion for our engineering students. To effectively teach these conceptual ideas, we need to instruct the students with a variety of teaching styles and tools. One set of tools that enhance theoretical models is visual demonstrations. Providing visual demonstrations along with the theoretical models creates an environment for improved student understanding. The present paper presents a collection of models, props and toys that are currently being utilized in a Mechanics of Materials class to demonstrate the main principles of the course. Topics supported by the visual aids and discussed herein include, but are not limited to: bending, torsion, shear center, shear flow, shear developed from transverse loading, normal stress, compression and tension, Saint-Venant’s Principle, development of combined stresses, the effects of geometric properties such as the 2nd Moment of Area, I, thin-walled pressure vessels and buckling.

II. Introduction

Educational research repeatedly shows a variety of learning styles exist among our university students. A number of learning style models have been developed to categorize student’s preferred methods of learning including: the Myers-Briggs Type Indicator, the Herrmann Brain Dominance Instrument, the Productivity Environmental Preference Survey, and the Felder-Silverman Learning Style Inventory. However, regardless of which model is used to identify engineering student’s learning styles, a constant trait emerges; students learn differently. Kramer-Koehler, et. al. of Polytechnic University in Brooklyn, New York published the results of preferred learning style assessments of 144 undergraduates entering this science and engineering university in the fall of 1993 and an additional 196 students entering in 1994. Using the Myers-Briggs Type Indicator method, they found considerable variation among the students. Of the 16 possible learning style types specified by Myers-Briggs, no type gained more than 17% of sample population, although there was a tendency toward Thinker and Sensor types vs. Feeler and Intuitive styles. This research further shows a difference in gender learning styles, with a significantly larger number of Thinkers and Extroverts among the females than among the males. Of additional interest, less than 44% of the 340 students tested demonstrated preferred learning styles generally associated with an engineering or research scientist profile.
Additional research has been completed which shows students learn best if taught by methods which match their style of learning. Mismatched instruction tends to significantly impact student scores\(^6\). With this in mind, consider research completed by Allen, et. al.\(^7\), who evaluated 319 engineering students at San Jose State University, CA, using the Felder-Silverman Learning Styles Inventory. Their results found that around 60% of the students showed strong preferences towards visual learning with only 5% strongly preferring verbal styles; an interesting statistic in light of the fact that the typical engineering course is taught with a lecture only format.

Since it would be impossible to identically match ones teaching style to every student’s learning style, Felder recommends teaching in a manner that incorporates a number of methods\(^8\). In [8], he offers strategies for presenting course information in a range of styles. Many of these strategies focus on the use of visual aids/demonstrations to supplement the lecture. Using visual demonstrations not only provides students with additional modes of learning but also gives the instructor a useful tool for generating discussion and student interest. The following paper describes a collection of models, props and toys that are currently being utilized in a Mechanics of Materials class to demonstrate the main principles of the course. These toys are useful for starting short group exercises during class to generate student discussion and problem solving. The following collection is far from complete and I look forward to discussions with, and additional teaching ideas from, other instructors of this topic.

The paper is presented in the following format; the first half of the paper endeavors only to describe each civil engineering toy and the second portion of the paper outlines the different mechanics of materials topics that can be supplemented with these visual aids. This format was chosen in an attempt to make this paper a useful resource for instructors looking for methods to improve the visual demonstrations for a specific topic in their mechanics courses.

III. Civil Engineering Toys

The following are descriptions of a number of toys used in teaching civil engineering. They are presented in no specific order.

The Foam Beam

Probably the most useful and versatile tool, the foam beam, is not something new. In fact, I first saw this as a student myself and found it very informative. While these beams can be purchased from makers of academic visual aids, it is easily created using high-density foam cut to the desired shape and then marked with a grid pattern. The author has found the foam pads designed for kneeling that are sold at most hardware and gardening stores work quite well and can be cut by hand or on a table saw. This is a much less expensive option, which allows the instructor to have a number of these beams for student use. The beam cross-section can be a simple prismatic rectangle or the cross-section can contain notches or holes along the
beam’s length. (Figure 1.) Be sure the grid pattern has a line that coincides with the beam neutral axis and enough elements in the height of the beam to fully demonstrate tension and compression due to bending.

Beams of Wood Lath

Another common but under utilized tool is a length of wood lath or even the common yardstick. By itself, the single length of wood lath, or a yardstick, can be used to demonstrate a number of concepts. However, it can also be combined in threes for additional uses. (Figure 2.) The built-up beam contains 3 layers of wood lath glued together to create a rectangular built-up beam of three times the thickness of a single wood lath member. The wood I-beam combines three wood lath members to form the strong I-beam shape of the same cross-sectional area as the built-up beam.

Circular Foam Beam

A simple length of foam pipe insulation with a self-adhesive closure makes an easily deformable circular shaft cross-section. (Figure 3.) As the foam is black, white paint can be used to draw gridlines on the surface. Thick insulation with a small opening provides a sturdier, longer lasting toy.

The Beam Shear Model

Dr. Leonard Herrmann of the UC Davis, Civil and Environmental Engineering Department faculty, developed a model based on an idea from an early E. P. Popov mechanics of materials textbook which allows students to take apart a cross-section of a wide-flange beam and trace the shear path through the member. (Figure 4.) The section is taken along the length of a beam that has a changing moment along the length. The model includes the distribution of the normal stress caused by the bending, with magnitude of stress varying between the section’s ends due to the change in moment and therefore the change in stress along the length. The top half of the beam separates from the bottom half to show a horizontal shear component is necessary in the web for
the beam to be in equilibrium. The top flange of the beam also separates from the web to illustrate how shear develops in the top of the web and in the flange. The flange also separates into two pieces along the length to further demonstrate shear flow.

Shear Center Model

This is a simple toy of plywood and PVC pipe. The plywood forms a base that a column of PVC pipe is attached to using a screw-on flange plate. At the top of the column a 90° elbow joint is used to attach a cantilevered beam of PVC pipe to the model. The cantilevered beam is cut along most of its length to form a C shaped cross-section. A wooden dowel, oriented along the axis of symmetry of the C shaped cross-section, is attached at the free end of the beam. (Figure 5.)

Combined Stress Model

This model is similar to the Shear Center Model, in that it uses the same cantilevered column and beam system. However, in the combined stress model, a thinner cross-section of PVC is used for the column to make the system more flexible. The outer surface of the column is covered with a section of foam pipe insulation, which moves easily with the deforming column. Gridlines are drawn on the insulation. Rods may also be inserted into the foam at gridline intersections to increase the visual effect of this model. (Figure 6.)

Photo-Elastic Beam

The photo-elastic beam utilizes the concept of photoelasticity to create an effective visual representation of stresses in a loaded member. Using light polarized by polarizing lenses, the effect of a transparent beam’s stresses can be viewed as optical patterns of brightly colored bands. (Figure 7.) While the actual stress-state of the photo-elastic beam can be determined using the principles of photoelasticity, the model can also be used to visually demonstrate the flow of stress through a beam. Rectangular prismatic beams, tapered beams and notched beams can all be used with this system. The shown system, the Stress-Opticon, is sold by VISHAY Research and Education. This system can be placed on an overhead, which makes it quite useful in both large and small classrooms.

Other Toys
These remaining toys require no description as they common items that an engineering professor can easily come by:

- Balloons
- Paper Clips
- Rubber Bands
- Tensile Test Specimens of a Ductile Metal
- Silly Putty or Hand Putty

IV. Methodologies For Incorporating The Toys

The following are suggestions of ways to use the above civil engineering toys to support and compliment a verbal explanation. By no means are these assumed to be the only applications of these toys or the only toys available. These are simply ones currently in use by the author.

Axial Strain and Deformation

The foam beam is a powerful tool for demonstrating the deformation a member experiences under axial loading. The beam’s material is easy to deform in both tension and compression and the grid markings allow students to visually see the change in length of each element in the grid.

Saint-Venant’s Principle

The idea that the concentrated effects of a point load are negligible once you move a small distance, typically the larger of the two cross-sectional dimensions, away from the point of application is sometimes hard for students to believe. Using a foam beam covered with a grid pattern, students can work in groups to determine for themselves at what approximate depth the concentrated effects of the load diminish. (Figure 8.) The photo-elastic beam can also be used to provide a very vivid and colorful demonstration of this effect.

Deformation Due to Torsion

The angle of twist and how it varies along the length of a torsion bar can be difficult for students to visualize especially if two or more torques are applied that can cause the sign of the angle of twist to change. The use of the circular foam beam gives students the opportunity apply torque loads to a circular cross-section and see the effects on the beams deformation through the deformation of the grid pattern. Two or more students can work together to apply multiple loadings and observe the effects. (Figure 9.)

The grid pattern also demonstrates three important concepts. First, the grid demonstrates that plane sections remain plane in a circular member subjected to a torque. A simply twisting of the
rectangular foam beam shows this does not hold true for all cross-sections under torsional loading. Second, the longitudinal lines of the grid pattern demonstrate the angle of twist remains constant between points of torsional moment applications on the circular cross-section. Finally, the deformed shape of a stress block under shear stress is easily seen in the grid pattern to aid with shear strain discussions.

Bending Stresses

For demonstrating the distribution of bending stresses through a cross-section, the foam beam and the photo-elastic beam are again invaluable. The foam beam readily shows the transition from tensile stresses to compressive stresses in a beam in bending. (Figure 10.) The foam beam can be used simply as a visual aid for a lecture, or it can be used as a tool for student self-learning. After defining only a convention for positive and negative bending directions, allow students to work in groups for a few minutes with their own foam beams and determine for themselves where they think the maximum tensile stress and maximum compressive stress occur in a beam in pure bending. Further, have them postulate what is occurring at the neutral axis. The same exercise can be completed with the photo-elastic beam. If the beam is placed on an overhead projector, students can still work in teams to answer the same questions. However, my experience has found the students are more involved and quicker to come to the correct solutions with the foam beam. I find the photo-elastic beam provides an excellent supplement to the foam beam and is very useful in reinforcing the idea that Saint-Venant’s Principle is applicable to practically all loading conditions. (Figure 7.)

The foam beam also allows the instructor to demonstrate the validity of the assumptions of Bernoulli-Euler beam theory. The gridlines, which are perpendicular to the beams longitudinal axis, should stay straight during bending of the beam and should remain basically perpendicular to the neutral axis. The latter observation will of course improve with longer, more slender, foam beams. This will support the assumption that plane sections remain plane and perpendicular to the neutral axis during bending.

2\textsuperscript{nd} Moment of Area, I

The 2\textsuperscript{nd} Moment of Area, or the Moment of Inertia as it is commonly referred to in Mechanics of Material texts, is unfortunately nothing more than a mathematical property to many students. However, it is important for them to grasp the physical meaning of this important property to succeed in a mechanics course. Both the foam beam and the beam of a single wood lath (or yardstick) easily demonstrate the idea of a strong and weak axis and the importance of the distribution of a cross-section’s area with respect to the neutral axis. In an attempt to push students to the next level, I use the built-up rectangular beam and the built-up I beam created from the same area of wood lath. Students are required to guess which cross-section will provide more resistance to bending and about which axes. They are encouraged to test their hypothesis by trying to bend the two beam shapes and by calculating the actual moments of inertia of each beam.
Shear Developed From Transverse Loading

We know that a beam in bending develops horizontal shear forces but this is quite difficult for many students to visualize. The wood lath beams become a useful toy to demonstrate how this shear force develops. If you bend the built-up rectangular beam along its weak axes, the glue holds the ends together not allowing the planes to slip past each other. However, if you bend a stack of three single lath beams also oriented along the weak axes, which are not glued together, the students can see the ends sliding past each other as the beam is bent. The glue in the built-up member resists this sliding causing a shearing stress. While a number of engineering text books have drawings depicting this same idea, student understandings is enhanced when they can personally observe a physical demonstration or actually try it themselves. This demonstration can be done with any number of materials including plastic rulers or foam beams.

In addition to the wood lath beams, the beam shear model developed at UC Davis is an invaluable tool. This beam is especially useful in deriving the transverse shear formula \( \tau = \frac{VQ}{It} \) in the method illustrated in R.C. Hibbeler’s Mechanics of Materials text as it allows students to see the need for the transverse shear to keep the cross-section in equilibrium. (Figure 11.) Further, the model is ideal for describing the transition from \( \tau_{xy} \) to \( \tau_{xz} \) at the web/flange intersection.

Shear Flow

Following the path of the shear flow can be a difficult task for students. Again the beam shear model is a valuable tool. With the shear flow path plainly marked on the beam, students can remove individual sections of the beam to consider the contributions to the shear and, hopefully, develop a clearer understanding of its path. (Figure 4.)

Shear Center

Understanding the behavior of a beam when its geometry is such that the shape’s shear center does not coincide with the geometric centroid can be difficult. Particularly, the direction of twist can be
confusing for many students. Consider a simple half-pipe shape with the opening to the left of the vertical axis (Figure 5). If a cantilevered beam of this geometry were loaded with a downward point load at its free end acting though the centroid, most textbooks will point out that the beam will twist and, correctly, draw the shear flow at the point of load application in a clockwise direction. To resist this shear flow, students are then told the shear center is to the right of the cross-section, which in turn causes a clockwise moment. How does a clockwise moment resist what the shear flow pattern indicates is also a clockwise rotation? Having a simple shear center model as the one described earlier in this paper, allows the students to see the initial rotation of the cantilevered beam when loaded through the centroid is actually counterclockwise. (Figure 12.) Allowing students to work in small groups for a few minutes with a diagram of the loaded beam and the shear center model at their disposal, typically leads to the students determining on their own why the beam initially rotates in a counterclockwise direction and why the shear center occurs to the right of the cross-section. Recommending the students determine the beam’s reactions and draw a shear diagram will typically accelerate this self-discovery phase.

Combined Loadings and Stresses

Any instructor, who has taught a mechanics of materials course, even one time, might agree that combined stresses can be a very illusive topic for many students. It can seem that students either grasp this concept or they don’t and all attempts at examples and explanations are ineffectual when they are unable to visualize what is happening. However, for any student continuing in a structural or mechanical design type curriculum an understanding of this topic is paramount. Dr. Joel Arthur of CSU Chico and I, after many discussions, have developed a model that we believe will assists those students who simply are unable to ‘see’ this concept. The combined stress model allows students to visually see the effects of a combined loading on a fixed-free cantilevered column supporting a cantilevered beam. When the beam is loaded, the grid pattern on the flexible foam surrounding the column will compress, stretch, or twist in response to the applied loads on the beam (Figure 13.) The wooden dowels can be used to exaggerate the effects of the loading.

Buckling

Within buckling, my personal experiences have identified two areas that cause students the most difficulty: strong axis vs. weak axis buckling and the effective length concepts. The single wood lath member is very useful to remind students of something they already know. There is a significant disparity between the strength required to bend a ruler about the axes parallel and perpendicular to the smallest cross-sectional dimension. Further, access to different lengths of wood lath members can
enhance a student’s understanding of the effects of length on a column’s critical buckling capacity.

The foam beam also finds a use in buckling, allowing the instructor to model the effective lengths of different support conditions. (Figure 14.) Since the foam beam is easily deformed, it provides a straightforward method to model the effective lengths of most end conditions including: pinned-pinned, fixed-free, and fixed-fixed. With the help of a student, the effects of lateral bracing along the column length can also be shown.

Thin-Walled Pressure Vessels and Plane Stress

Long slender balloons are an inexpensive, but functional, model for cylindrical pressure vessels. Students are visually aware that the balloon’s resistance to deformation is much greater in the radial direction than the longitudinal. A stress block drawn on the balloon’s surface adds to the illustration of the directions of the principal stresses in the vessel. Circular balloons are identically useful for spherical pressure vessels. As a balloon’s skin easily deforms under any loading out of the plane of the skin, the point that negligible or no stress is developed out of the skin’s plane can be illustrated. In addition, since the balloon’s skin visually becomes thinner, students are shown that strain will still develop out of a plane in the plane stress condition. The plane stress condition is also effectively demonstrated by standing on the top of an empty aluminum can and then crushing it by slightly tapping the side with your other foot.

Elasticity, Plasticity and Permanent Deformation

Rubber bands and paperclips are simple but useful tools when introducing the ideas of elasticity, plasticity and permanent set. I have yet to see a student who was able to completely remove the bend from a paperclip. Fatigue is also easily demonstrated with a paperclip. Silly putty is also a simple toy for introducing the idea of plastic deformation and necking.

Tresca (Maximum Shear Stress) Yield Criteria

For many students, the idea that ductile materials fail in shear is difficult to accept, which means the need to check the maximum shear stress criteria is not apparent. Tensile test specimens with 45° failure surfaces are an excellent reinforcement to this concept. Narrow aluminum samples provide excellent surfaces.

Stress Transformation

Many of my students simply don’t understand the need to look at stresses along a different orientation. To address this issue, I have drawn elements at different orientations on the backside of the foam beam. (Figure 15.) When the beam is axially loaded, elements oriented along the longitudinal axis simply compress or stretch. However, elements rotated off of the longitudinal axis will distort due to shear. This
becomes a useful illustration to show that shear does exist on axes inclined from the longitudinal axis.

V. Conclusion

Presented herein is a collection of toys developed over a period of four years of teaching mechanics of materials laboratories and lectures. Initial courses were taught with little to no visual aids and I immediately discovered that many of the topics in the course were quite difficult to explain by words only and even more difficult for students to grasp. By no means do I suggest that this collection is complete or dormant in its evolution.

Of the toys, the foam beam has by far been the most successful, as it has proved useful for the largest number of concepts. In addition, the foam beam is introduced as a visual aid practically at the onset of the course, immediately showing students there are physical and visual representations of the course’s concepts. This early exposure, along with the continued exposure during the class, to visual illustrations appears to increase the likelihood of students trying to relate, on their own, the course concepts to physical realities.

Student response to these toys has been very positive as expressed in their student evaluations. For example, one student wrote, “I appreciate the demos and visuals that were given during class. It helped tie our theoretical ideas to a more ‘actual’ real world experience. It contributed greatly because it allowed greater understanding of physical and tangible concepts compared to just theoretical”. In addition, the toys definitely generate more discussion between students and between students and myself. More and more students will linger after class to have more ‘toy’ time or simply stop by during office hours to play with the models. Among the students, the foam beam, the photo-elastic beam and the shear beam model are the definite favorites for helping to illustrate ideas. It should be noted, that I only recently developed the combined stress toy but I anticipate its popularity will rate among the top.

I have found that a strong collection of visual aids for a course with both theoretical and abstract content is an indispensable tool for enhancing student understanding. With the exception of the photo-elastic beam, all the toys shown in this paper were developed from scrap lumber and plywood and foam and PVC pipe found at hardware stores. This paper was written with the hope that additional discussion could be generated to determine what toys other professors are successfully using in their mechanics courses. A natural progression from this paper would be the development of a resource where instructors can both share and gather ideas for improving the presentation of mechanics of materials topics.

VI. References


TONYA EMERSON. Professor Emerson, a licensed P.E., has recently joined the Civil Engineering faculty at California State University, Chico. Previously, she was at UC Davis completing her Ph.D. in Structural Mechanics, where she participated in the year long Program of College Teaching. She received a Master’s in Structural Engineering from Stanford and a Bachelor’s in Architectural Engineering from Cal Poly, San Luis Obispo.