Teaching Freshman Engineering Using Design Projects and Laboratory Exercises to Increase Retention

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Introduction

The primary goal of the freshman engineering course at Baylor University is to help students to appreciate the exciting career possibilities that a degree in engineering will provide them. Obviously this can be accomplished with descriptions of what engineers do, including interesting videos and speakers from industry; however, we believe that the best way for students to understand what engineers actually do is to give them the opportunity to practice engineering. The analogy to teaching swimming is appropriate. Teaching swimming with a textbook, excellent videos, and even presentations from Olympic swimmers cannot substitute for actually getting into the water. The challenge is to provide meaningful experiences of engineering practice to students with very limited technical backgrounds.

In this paper, we will share the approach that we are developing to allow our students to practice *real engineering* in their freshman engineering class and to allow them to make an informed decision on whether this is the best career choice for them. We will provide a detailed description of our two design-build-test projects as well as give a more cursory description of our laboratory experiences. Finally, we will document the increase in retention that is occurring as we continue to develop this approach.

Approach

We begin our class by defining engineers as "individuals who utilize their knowledge of science, mathematics and economics combined with experiments to solve technical problems that confront society." We have made a conscious decision to build our freshman engineering course around laboratory experiences and two design-build-test projects that will bring this definition to life.

We (the authors) began this journey of improvement by brainstorming laboratory experiences and design projects that might be feasible for freshmen engineering students and could provide an existential appreciation for how engineers "do what they do". From this larger group of possible activities, we then selected two design-build-test projects and four laboratory experiences. The design projects and laboratory experiences were selected to include both electrical and mechanical engineering topics, because this is the first engineering course for both majors. Furthermore, most of our freshman engineering students have not yet decided which discipline they will pursue as a major. The topics we currently cover include: (1) reverse engineering; (2) measurements and associated calculations to determine a drag coefficient; (3) digital computing (addition); (4) a resistance-capacitance (RC) circuit experiment; (5) solid state sensors; (6) a mini design-build-test project of a children's flashlight that will turn itself off in 30 seconds; and, finally, (7) a major design-build-test project of a truss bridge constructed of basswood.

Laboratory Experiences

The first laboratory experience is a reverse engineering exercise. The students disassemble a variety of consumer products, determine exactly how they function and then make suggestions on how the products might be improved. Products that are relatively easy to understand, such as an electric drill, are used. Many of the students have never done any tinkering and find this simple exercise extremely interesting.

The second laboratory experience involves the use of a tapped, hollow cylinder, oriented perpendicular to the air flow in a wind tunnel. Pressure is measured as a function of angle around the circumference of the hollow cylinder. The relationship of velocity to pressure is also derived by the professor to teach the students why the pressure varies in the way that it does. The students then calculate, using an Excel spreadsheet, the net force acting on the cylinder from which they can determine the drag coefficient. They come to appreciate that some phenomena in nature are easily predicted using calculations but are difficult to measure, while other phenomena are extremely difficult to calculate from first principles but are relatively simple to measure. The combination of measurements plus analysis based on physical laws is a particularly powerful tool.

We describe the field of *electrical* engineering as broadly divided into two camps: one dealing primarily with information, the other with power. We provide one laboratory experience in each.

The third laboratory experience addresses the manipulation of information by requiring students to analyze and then construct a simple digital circuit. At this point in their studies, the students have had only minimal exposure to Boolean algebra or logic gates and are unable to design circuits themselves. Therefore, the students are given a schematic representation of a logic circuit that will add three, one-bit binary numbers. Students analyze the circuit by completing a truth table to follow the "flow" of logic in the circuit. Then, integrated circuits containing discrete logic gates (NAND, XOR, etc.) are used to construct and test the circuit. Tactile inputs are provided with toggle switches, and outputs are visually indicated by LEDs. This is often the first circuit of any kind that the students have constructed. Although they usually begin with trepidation, the students rapidly gain confidence and complete the exercise with enthusiasm.

The fourth laboratory exercise focuses on the power storage and delivery aspects of electrical engineering. By means of preceding lectures, a water analogy has been drawn to assist the students' intuitive understanding. A long, transparent hose (representing a capacitor) is filled with water (representing electrical charge) and lifted by a professor to the top of a ladder (a "high" voltage). A small orifice (resistor) restricts the flow of water at the bottom of the hose, which is held steady and aimed by a student. When the ends of the hose are uncovered, the water squirts out and its trajectory is seen to decay exponentially (across the classroom). The students' attention is held by their fear of getting soaked.

Then an electric circuit is constructed perform do the same function. A six-volt battery is connected in parallel with a large (250,000 uF) capacitor and a flashlight lamp with approximately ten Ohms of resistance. When the battery is disconnected by means of a push button switch, the lamp slowly fades. Different values of lamp resistance and capacitors in parallel and batteries in series are tested. The concepts of exponential decay, time constants, and electrical energy storage are thus explored, and the way is paved for a flashlight design project (see below).

The fifth laboratory experience involves solid state sensors. The purpose of this laboratory is to introduce students to the amazing properties of solid state sensors and the crucial role they play in the control of many things, including computer controlled processes. The students measure the change in resistance with temperature for a thermister and are amazed to see the more than 1000% change in resistance as we go from ice water to boiling water. Mercury in a conventional thermometer, by comparison, changes only a few percent for the same change in temperature. Next, the students measure the change in resistance of a light sensor in the presence of light and in the dark, noting a 1300% change in resistance. This large change in resistance is used to build a simple circuit that can turn an LED on and off depending on whether our light sensor is covered or exposed to light, performing the function that they see with street lights each evening.

These laboratory experiences are essentially Montessori learning for college students, and the students love it. They really learn in a much more profound way when they can learn by doing rather than just by hearing.

Mini Design-Build-Test Project - A Child's Flashlight

Starting from the concepts learned in the circuit laboratory exercise, students are asked to design the circuitry for a child's flashlight that prolongs battery life by turning itself off when left unused. The design requires the lamp to completely fade out (as observed by eye) between 20 and 30 seconds after activation by a switch. The design is somewhat constrained in that students are only allowed to select from given values and styles of capacitors, batteries, switches, and lamps.

Students, working in small groups, first connect the components on a table top with wires and wire clips in order to prove their concept. In general, the circuit is realized by a parallel combination of a capacitor and lamp that together are in series with a battery and a switch. Following successful completion of this step, students create a single sided circuit board layout using the drawing features of Microsoft Word. The simplicity of the circuit does not warrant the learning curve required of more sophisticated layout software. Students draw a positive image of the circuit traces that are printed onto a special paper with a standard laser printer.

The paper is produced by Pulsar (http://www.dynaart.com/) and is known as the Toner Transfer System. The positive image of the circuit is placed face-down on a blank copper clad circuit board material, such as Fr4. The copper and paper are together fed through a laminator which adheres the toner onto the copper. After soaking in water for a few minutes, the paper comes free, and the circuit is etched with ferric chloride, a standard copper etchant. The toner provides an effective barrier to the etchant so that only the exposed copper is removed. Students can produce their first board in under two hours and subsequent iterations in twenty minutes. The assembly of the components is then performed by the students, including soldering. Finally the circuit is tested, and the students in each group fight over who gets to keep the circuit. This hands-on, start-to-finish approach helps demystify electric circuits, builds student confidence, and fuels curiosity for the tinkering deprived.

Major Design-Build-Test Project – Truss Bridge

The objective of this capstone experience is to pull together a complete design experience that incorporates essentially every feature of a real design project. We begin by teaching simple concepts from statics, specifically, summing forces acting at nodal points on a truss and requiring that they must sum to zero in the "x" and "y" direction. We do several simple truss problems for them to illustrate how the physics and mathematics allow one to predict the forces acting in each member. Then we use software, produced at Johns Hopkins University (JHU) and available for free on the Internet (http://www.jhu.edu/virtlab/bridge/bridge/htm), to make this process less tedious for more complex truss designs. The first problems we solve using the software are the same ones that we did with hand calculations to help the students learn that there is no magic in the program. The physics and mathematics in the computer program are identical to what they have been calculating by hand. Now the students can explore many different truss design options but cannot yet predict what loads their trusses will support. An example of a simple truss analyzed using this software is seen in Figure 1 below.

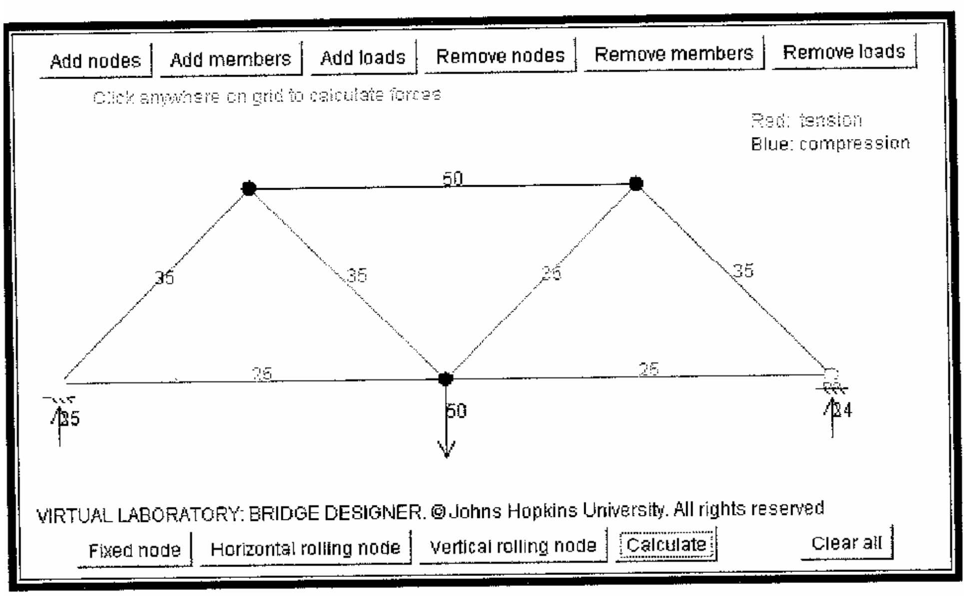

Figure 1. Truss Model Using Johns Hopkins University Bridge Designer

Our second step is to require the students to perform a literature survey and to read as much as they can about truss bridges in order to identify the various kinds of truss bridges and the

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rationale for the use of each. This provides them with some insight into the advantages and disadvantages of different designs for different applications.

The third step is to perform materials testing in the laboratory using an electromechanical MTS mechanical testing machine (MTS-QTEST 100, MTS Corp, Eden Prairie, MN). We test basswood specimens and various kinds of glue to determine the strength of the truss elements and the joints. The students enjoy this early exposure to sophisticated equipment that will be typical of what they might use later as engineers.

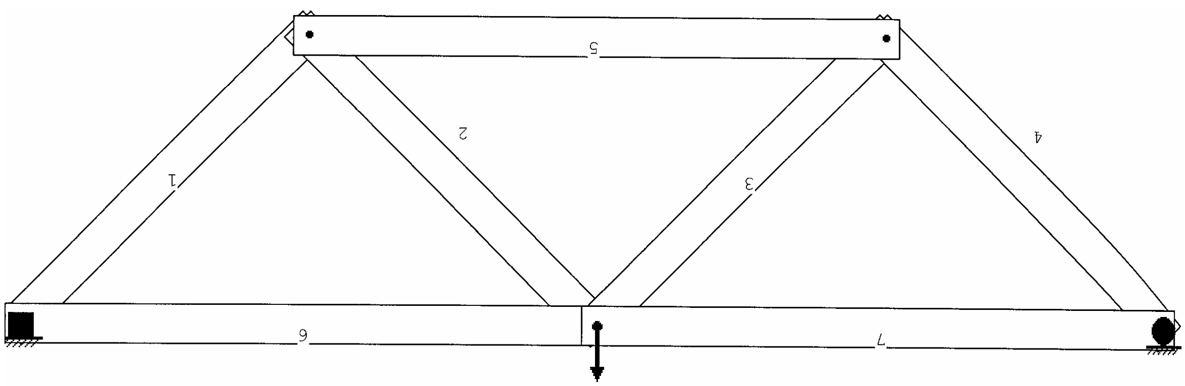

Figure 2. ModelSmart Model Truss Bridge

Breaking Load = 205.17 lbs.

Memb. no.	Matl. id	L (in)	Actual Force F(#)	M(in-#)	Ultimate Force Tu(#)	Cu(#)	Mu(in-#)		Eff. ratio
001	2BAL8D3	4.24	-151.07	2.84	662.5	428.4	45.8		0.41
002	2BAL8D3	4.24	148.37	0.94	662.5	428.4	45.8		0.24
003	2BAL8D3	4.24	147.10	1.82	662.5	428.4	45.8		0.26
004	2BAL8D3	4.24	-151.60	0.66	662.5	428.4	45.8		0.37
005	2BAL8D3	6.00	-210.92	1.16	662.5	214.2	45.8	<NG>	1.01
006	2BAL8D3	6.00	106.11	3.10	662.5	214.2	45.8		0.23
007	2BAL8D3	6.00	107.29	2.10	662.5	214.2	45.8		0.21

Structure Weight = 27.54 grams

Table 1. Actual forces (F (#)) and moments (M (in-#)) in elements from Figure 2 with ultimate allowable forces in tension (Tu (#)), compression (Cu (#)), and bending (Mu (in-#)) also indicated.

The fourth step is to shift our analysis from the JHU software to a commercial software package, ModelSmart. This software package incorporates the strengths for the different elements in tension, compression (buckling) and bending, assuming they are made of balsa wood. It also allows the user to choose between three element sizes to adjust the load bearing capacity as needed. The allowable truss members are all square, with dimensions of 0.125 inches, 0.187 inches, and 0.250 inches. The span for the truss bridge is specified to be 15 inches and the loading point(s) is varied from semester to semester to prevent students from copying the previous semester's winning design. Once the bridge design is completed and the element sizes are selected, the students can load their bridge to failure using the ModelSmart program in order to determine where the bridges will fail and at what load. The program's output also provides information about the loads and the maximum allowable loads on all elements at the time of failure, as seen in Figure 2 and Table 1. This guides and informs the students as they seek to improve their designs in a systematic manner by adjusting either the basic design or the sizes of the various elements with each iteration. The material properties in the program are for balsa wood, but one can easily use the ratio of the strength of basswood to balsa wood to adjust the predicted strength for their bridges.

Failure occurs (See Table 1) when an element is subjected to an actual force equal to an ultimate allowable force (see member with Eff. ratio > 1.00). Also, note that the ratios of forces in various elements are identical to the JHU model, within round off error, as they should be. Realistically, labor costs should also be included as well, but this issue will be addressed shortly.

The fifth step is to now have the students begin to work together in teams, combining their various ideas into a team design that uses the best features of their individual designs. We also incorporate economics into the project at this point by informing students that the team competition will be judged based on the load supported at failure divided by the mass of the bridge, representative of the cost of materials.

In step six, each team builds a prototype bridge that they test in compression on the MTS machine using displacement control. This permits the failure to occur one truss element at a time. The teams learn several things in this step. First, simple bridges are much easier to construct than more complex designs, and the quality of the construction is much easier to control when there are fewer elements in the bridge. Second, the students learn that the bridges in the computer program are perfect while the bridges that they build have real imperfections. For example, if the two trusses are not of exactly the same height, the applied load will be distributed in an uneven and unfavorable manner between the two trusses. The students also learn that computer programs do not necessarily take into account all of the important physics. It is sometimes the case that the bridges fail at the joints rather than within the truss elements and thus fail at lower loads than predicted. This is a very valuable concept for them to understand. While the computer program is extremely helpful during their design, it is no substitute for prototype testing. A much more complete mathematical model that also took into account joint failures (which were verified experimentally) would be necessary to get the final prediction with the model alone. Nevertheless, the quality of the bridges is improved by the use of the ModelSmart program.

In step seven, they apply what they learned in the prototype testing and make adjustments to their designs, often major adjustments. The final bridges are always simpler in design than the original bridges as the students learn the price that complexity brings to such a project during construction (not to mention labor costs, which do not figure in their bridge rating but do cost them in time to make their bridges).

Step eight is the actual contest in which we test all of the bridges and rank them as top third, middle third and lower third, with grades of A, B, and C assigned accordingly for this portion of the design project. Two interesting points were learned in this final testing. First, the final bridge strength to mass ratios improved on average 70% compared to the prototype bridges. Second, the ratio of the actual strengths to the predicted strengths was very nearly equal the ratio of the strength of the glued joints to the strength of the wood, as one might expect, since the failures, even with gusset plates, were in the joints. The winning design in our competition of eighteen teams is seen in Figure 3 below.

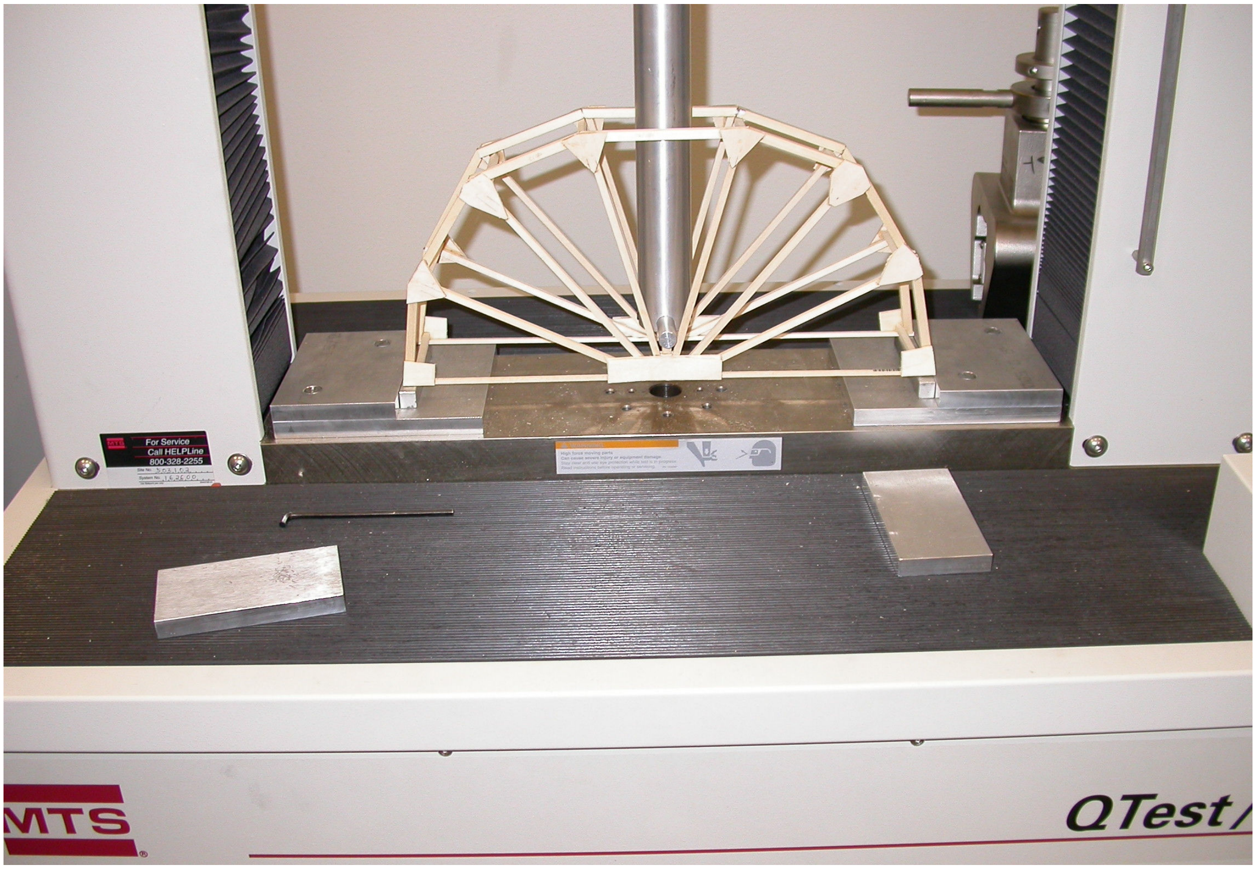

Figure 3. The winning bridge out of eighteen in the competition

We have carefully developed this project to provide as realistic a design experiment as we can for freshmen, given their limited tools at this stage of their education. The students put in the greatest effort in this part of the course and do so with almost no complaining as they seem to enjoy the experience very much. They learn the value of using physically based models to assist in their designs, assisted by the computer program, and they learn the limits of computer modeling. They see the necessity of materials testing and prototype testing as a part of the process. Finally, they come to appreciate the relationship between design and manufacturing and the bottom line of economics, strength to mass ratios in their case. Overall, it appears to be a very rewarding experience for the students.

Retention

One of the measures of the effectiveness of our freshman engineering course is retention. If we measure retention by the number of students who take our first engineering course but do not take the second engineering course, we can determine the percentage loss of our engineering students during the freshman year. We lost 33% in Fall 2002, 21% in the Spring 2003 and 14% in the Fall 2003 as we have continued to increase the experienced-based learning in this course. Interestingly enough, the course is more challenging intellectually and more time consuming than it was before. We are persuaded that it is not the amount of effort that frightens students out of engineering, but the large effort that is often required without sufficient vision to see the rewarding career that their effort will make possible. There is a Biblical proverb that says, ”Without a vision, the people perish”. We think this is especially true of engineering students. One way to provide such a vision is with very rich experience-based learning in their first engineering class.

Conclusion

We have designed a freshman engineering course on the premise that students must “do engineering” to get a meaningful picture of what a career as a professional engineer might be like. We want to motivate the students to work hard at engineering long enough to be able to discern whether this field interests them as a future career. The entire course is built around carefully chosen laboratory experiences that introduce students to experimental and analytical tools that engineers use. The students then utilize these tools in two design projects which they both build and test.

Improved retention of engineering students is a major goal of our introductory course, and it appears that we have made a good start toward achieving this goal. We will continue to monitor retention statistics throughout the students’ 4 year program.

Biographical Information

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Carolyn Skurla is an Assistant Professor in the Department of Engineering at Baylor University. She received her Ph.D. in Mechanical Engineering from Colorado State University. In addition to the freshman engineering course, Dr. Skurla teaches courses in materials engineering and biomaterials. Her research interests are in biomaterials and total joint replacements.

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Walter Bradley received his B.S. in Engineering Science and his Ph.D. in Materials Science and Engineering from the University of Texas (Austin). After 8 years at Colorado School of Mines and 24 years at Texas A&M University, Dr. Bradley is a Distinguished Professor of Engineering at Baylor University. His research interests include mechanical properties of materials.