Designing Experiments in a Civil Engineering Curriculum

Allen C. Estes and J. Ledlie Klosky
United States Military Academy

Introduction

As all ABET-accredited institutions become more familiar with the Engineering Criteria (EC) 2000[1] on which their accreditations depend, it is important for various institutions to share information on how they are meeting these new requirements. The new accreditation philosophy requires institutions to define their own missions and objectives and to develop a process of assessment and continued improvement. The emphasis is on demonstrating how the educational objectives and outcomes are being met. Many outcomes have been specifically prescribed in the now-famous criterion 3 (a-k) requirements. One of the most controversial among civil engineers has been criterion 3b which requires engineering programs to "demonstrate that graduates have an ability to design and conduct experiments, analyze and interpret data." While most civil engineering programs conduct experiments, many have struggled with demonstrating that their students can design an experiment. This paper describes three instances where the students design experiments as part of the Civil Engineering program at the United States Military Academy.

Beam Bending Laboratory

The earliest opportunity for students to design an experiment occurs in the Mechanics of Materials course. Student will have already conducted a simple tension test and pure torsion test on specimens under controlled conditions using prescribed methods in previous laboratory experiences. The objective of the beam-bending lab is for the students to demonstrate the validity of the elastic bending stress equation. Students are given a bucket of parts and told to design their experiment. The parts include an instrumented beam, weights, clamps, measuring devices, and assorted spare parts. Students are asked to design a scale for the measurement of mass using these pieces. They define the beam support conditions, make all necessary measurements, attach the strain gage leads to a strain indicator and apply the weights. Assuming elastic behavior, the students can use the strain readings to compute stress and compare the results to the elastic bending equation. They can then use the device they built in a competition with the other lab groups for the determination of the unknown mass of an object. There is no approved solution and there are a variety of ways to conduct the experiment properly.

In designing this laboratory exercise, we had two principal objectives; first, to reinforce the fundamentals of beams in bending, to include the application of the shear and moment diagrams and confirmation of the flexure equation, and second, to expose students to conceiving, designing and executing an experiment. To add punch to the process, it was decided that some competition between the design teams would be beneficial. It was thus decided that the lab exercise would take the form of a scale-building competition, where each team would attempt to build a scale for determining the mass of an object. At the end of the process, there are two winners, one in the uncalibrated (first-shot) category, and one in the calibrated category.

To accomplish true experimental design, it is probably necessary to use more than a single lab session, and the design and execution of the experiment should include significant preparation prior to arriving in the lab. For our beams-in-bending exercise, the process looks like this:

- Students are introduced to the theoretical basics of beams in bending in class and through the text. They are also taught the basics of strain gages.
- As soon as they are familiar with the concepts of moment diagrams and the flexure equation, they are told about the upcoming laboratory exercise, shown the equipment, and are given a problem set which includes designing a scale using the provided beam and other equipment.
- In a meeting with their teacher, the students go over their proposed design, and the teacher provides guidance. The problem set is then reworked to reflect changes which come out of this meeting.
- The day of the lab, the students set up their apparatus and are then given an object with an unknown mass and asked to measure the mass of the object based on their computations alone.
- Various objects of known mass are then provided to the students, and they are given the opportunity to calibrate their scales. When they are satisfied with their calibration efforts, they are asked to reweigh the unknown mass and provide an updated prediction of its mass.
- The true mass of the unknown object is revealed, and recognition in the form of gag prizes is distributed.

Background The students need to know three basic things before beginning the design process. First, they need to understand shear and moment diagrams and the difference between simply supported and cantilevered beams. Second, the flexure equation should be introduced:

$$\sigma = \frac{Mc}{I}$$

Last, the students need to know what a strain gage is and how it works. This is an excellent opportunity to introduce students to the basics of electronic instrumentation, including precision and the difficulties of converting analog voltages to digital (numeric) readings.

Equipment. The principal equipment required is shown in Figure 1. Most of the items shown are very low cost, with the exception of the strain gage reader. The total cost per lab set-up with the equipment shown was less than $2k, with most of that cost being the strain gage reader. It is worth noting that the best setup of the equipment as far as accuracy is a cantilever beam, requiring only the instrumented bar, a single clamp and the bucket and string as a mass holder. The rest of the included material (tape, triangle, roller, cylinder, etc) is included to provide opportunities for the student to develop alternative solutions. The shapes are machined from UHDPE, which is quite durable, easy to machine and inexpensive.

Figure 1: Equipment for Beams in Bending Laboratory

Student Design. Once the student teams have the background training and an inventory of the available equipment, the problem becomes quite open ended. The task is stated fairly simply: Given this equipment and your knowledge of beams in bending, design and build a device for finding the mass of an unknown object. They can choose the orientation of the beam (strong or weak direction), support conditions, means of assuring repeatability and other details. Further, their supporting computations, completed before coming into the lab and confirmed during a meeting with their instructor, can completely define the expected strains according to theory. The students should also predict the likely precision and sources of error *prior* to arriving for the lab, something that they are usually called on to do after a laboratory exercise is complete.

During the laboratory period itself, the student teams gain key knowledge. First, they see the effectiveness (or lack thereof) of their respective designs, and they observe the conclusions reached by other teams. Second, they confirm the validity of the flexure equation and Hooke's Law as a by-product of the basic exercise. Last, they gain familiarity with the most basic of all electronic instruments, the strain gage. Set in an atmosphere of friendly competition, these lessons evolve naturally from the exercise, and the students gain knowledge not only of the physical phenomenon demonstrated, but also of the basics of the engineering design process.

Concrete Shear Capacity Experiment

Another opportunity to design an experiment occurs in the Design of Reinforced Concrete course. Students conduct an experiment where they verify the moment capacity and deflection equations for a reinforced concrete beam. Students construct the reinforcing cage, mix the concrete, test the concrete and cast the concrete beam to be tested. The beam is deliberately designed to fail in moment in the center of the beam using a three-point bending configuration. As a final portion of their laboratory report, the students are required to design an experiment using the same materials and equipment that would verify the shear capacity equations for reinforced concrete. The exercise involves defining the support conditions, prescribing the loading method, and designing a beam that will fail in shear.

Background. The Design of Reinforced Concrete Structures (CE483) is a 3.5 credit hour course comprised of 48 lessons. The laboratory program consists of eight two-hour lab periods (0.5 hours) that meet in addition to the 40 regular class sessions (55 minutes each, 3.0 credit hours). Table 1 summarizes the content of the CE 483 laboratory program. Estes and Sibert[2] provide a more detailed description of the lab experiences as well as the challenges, benefits, and assessment of the program.

Lab	Description of Activities
1	Discuss material properties of concrete and its components; prepare ingredients for concrete batch using absolute volume mix design.
2	Mix 1.55 cubic feet of concrete in portable mixers; perform slump, air content, and unit weight tests; place concrete in test cylinders and beam mold.
3	Perform uniaxial tension test on steel reinforcement; construct rebar cage consisting of longitudinal steel and stirrups.
4	Crush three 4”x8” cylinders to obtain average concrete strength, crush 6”x12” cylinder with embedded strain gage to obtain stress-strain curve and modulus of elasticity; break beam in 3 point load test to compute modulus of rupture.
5	Adjust mix design based on strength results and mix 1.75 cubic feet of concrete; perform slump, air content, and unit weight tests; place concrete in test cylinders and 4”x6”x86” beam mold.
6	Conduct non-destructive testing of concrete beam using Schmidt hammer, Windsor probe, and echo pulse velocity. Locate reinforcement using pachometer; obtain 2” cores samples from beam.
7	Observe beam loading demonstration; sulphur cap test cylinders; make theoretical calculations in preparation for final lab.
8	Crush three 4”x8” cylinders to obtain average concrete strength; load reinforced concrete beam to failure in 3 point load test.

Table 1: Summary of the CE483 Laboratory Program

The culmination of the lab program occurs in Lab 8 when the students load a 4” wide, 6” deep, and 86” long reinforced concrete beam to failure. By this time, the lab teams of 3 or 4 students have mixed and tested the concrete, tested the steel strength, built the reinforcing cage, measured all critical parameters, computed development lengths, allowed the concrete to cure, and computed the theoretical values for moment capacity, shear capacity, and deflections under certain loads.

Once they complete this final lab, the students are expected to:

- Compare the observed behavior of their reinforced concrete beam during the flexural test to their predictions of its behavior.
- Compare the actual flexural strength to the theoretical “nominal” strength of the concrete beam.
- Compare the pattern and location of cracks on the failed beam to the cracks shown in pictures in the textbook.
- Compare the actual deflection of the beam at 500 pounds (prior to the beam cracking) with the theoretical deflection value.
- Compare the actual deflection of the beam at 3000 pounds (after the beam cracks) with the theoretical deflection value.
- Compare the concrete strength determined from non-destructive tests (Lab 6) with the destructive tests from Lab 8.
- Construct a load-deformation diagram and use the information to answer questions regarding elastic behavior limits and appropriateness of load and resistance factors

Figure 2: Three-point Load Test on a Simply Supported Reinforced Concrete Beam

Equipment. The beam is loaded in a three-point bending configuration by a 400,000-pound capacity Forney uniaxial testing machine, shown in Figure 2. A load is applied at a constant rate until the beam either collapses or deflects to the point of touching the lower steel beam shown in Figure 2. A dial gage measures the midpoint deflection of the beam (Figure 3). The RC beam is simply-supported and contains two #3 longitudinal steel bars for flexural reinforcement. Stirrups composed of 10 gauge wire are spaced 2” apart to provide shear reinforcement. Two #2 bars in the top of the beam support the reinforcing cage. The top bars are cut-off in the middle to avoid having to account for compression steel in the analysis.

Students verified that the beam would fail due to excessive moment rather than shear. They superimposed the loading configuration on the beam as shown in Figure 4 and created shear and moment diagrams for the loading situation. They then verified theoretically that the beam would bear more than twice the load in shear as compared to moment under this loading configuration and that there was sufficient development length in the bars to ensure they would yield prior to pulling out of the concrete.

Figure 3: A Dial Gage is Attached to the Center of the Beam to Measure Deflections

Student Design. At the conclusion of the lab program, the students prepare a formal laboratory report that ties the entire lab program together and forces the students to evaluate, explain, synthesize, and analyze what they have done in the eight lab periods throughout the semester. The final requirement of the lab report is to design an experiment that will verify the theoretical equations for shear capacity of a reinforced and unreinforced concrete beam. To succeed, the beam must have a higher moment capacity than shear capacity. There is no approved solution and students have a combination of options that include changing the loading conditions, increasing the moment steel, reducing the shear capacity, altering the beam cross-section, or varying the concrete strength. They are constrained by ACI code[3] provisions that limit both the maximum stirrup spacing and the amount of longitudinal reinforcement that can be added. The students are also limited to using the materials and equipment on hand.

Designing an experiment is inherently difficult because students usually need a base of knowledge to be successful. The eight unified lab periods provided that knowledge. Conducting an experiment that verified the moment capacity of a beam under highly constrained and controlled conditions gave the students the tools to build on that experience and design a similar experiment on their own.

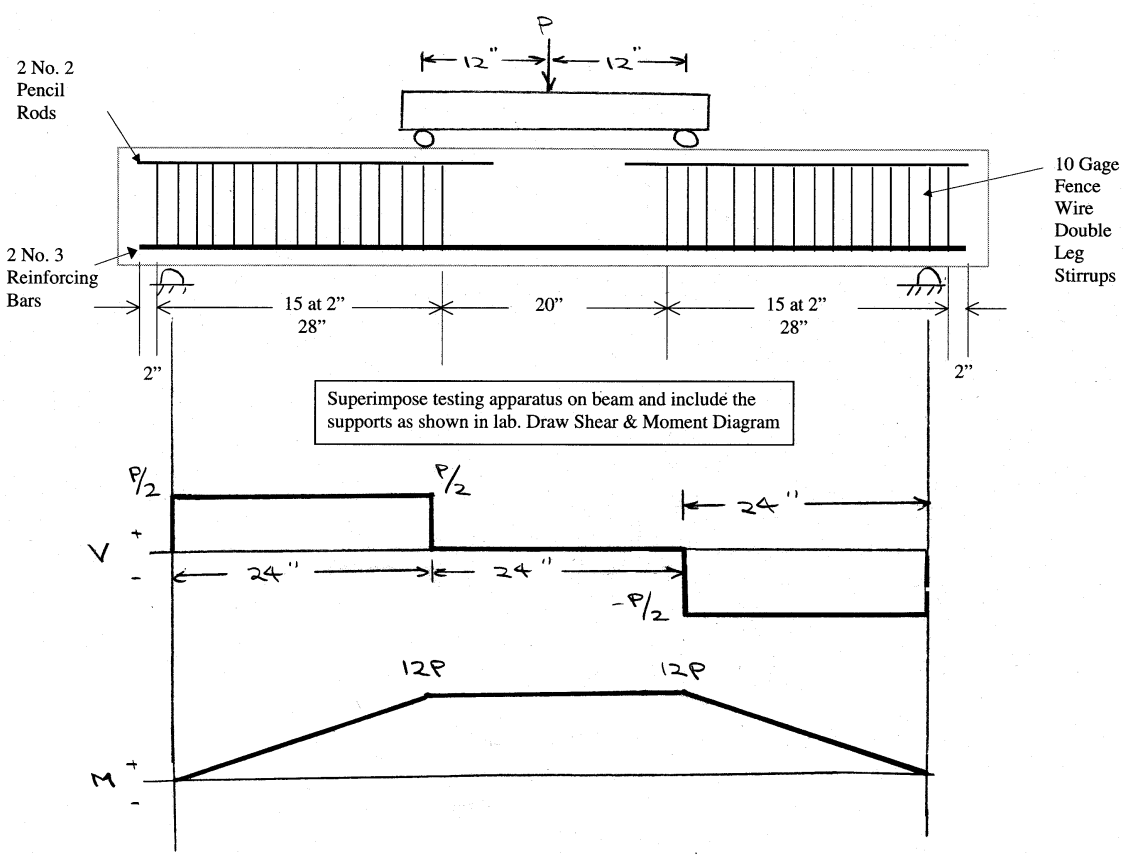

Figure 4: The Testing Apparatus Superimposed on the Concrete Beam and the Resulting Shear and Moment Diagrams.

Quality Control Plan

The final example is perhaps controversial because many will debate whether it qualifies as designing an experiment. In the Construction Management course, students are required to develop a Quality Control plan for a specific construction project. A Quality Control plan is a series of tests (usually following prescribed ASTM standards) that verify that the materials and methods are satisfactory and that the project will meet the required specifications. These tests require a comprehensive background in experimental procedure, conduct of physical measurements, documentation of strengths and deficiencies, critical analysis of data, and data interpretation as demonstrated by conclusions. Selecting the appropriate tests and their frequency *is* designing an experiment – probably the most realistic example of how a civil engineer designs experiments in the real world of professional practice.

Background. The Construction Management course (CE490) provides in-depth study of construction planning and management. The course covers life-cycle facility management to include planning, programming, design, bid, and construction. Major course topics include project scope definition, construction estimating (budget estimates and detailed estimates), scheduling (critical path networks, resource constraining), and management controls (progress reporting, payments, change-order control, project closeout) during construction. The quality control plan emerges during the lessons on quality control and quality assurance.

Student Design. Students are given a hypothetical construction project that is to be built according to a specific standard of quality. Students are asked to develop a plan (design an experiment) that will verify that sufficient quality has been achieved. The students, just like civil engineers in the field, will not be inventing specific new tests. It is not necessary. The American Society of Testing and Materials has already developed detailed tests (e.g., test methods for determining the compressive strength of concrete[4]) for most commonly occurring situations and the methods are clearly specified. The design of the experiment is knowing which tests to use, how many times they should be conducted, and when they should be scheduled to gain the most critical information. The quality control plan must complement the project schedule.

The quality control plan can be quite complex and is one level higher than designing a single experiment. If concrete is being placed on the site, the quality control plan schedules the appropriate number of slump tests, air content tests, test cylinder castings, curing inspections, and inspections of formwork construction and reinforcement location. When steel erection is part of the project, the plan must address inspection of welded and bolted connections, plumbing of the steel frame, anchor bolt tolerances, paint finishes, steel storage, and fireproofing. The placement of plumbing, electrical, mechanical, soil fill and asphalt paving requires quality control tests. The quality control plan is the most realistic example of the type of experiment that a civil engineer will encounter in day-to-day professional practice.

Conclusion

There are opportunities in a civil engineering curriculum to have students design an experiment. Student design is often difficult because they need a base of knowledge and a higher familiarity with laboratory equipment and experimental procedure than is required to simply conduct an experiment under controlled conditions according to prearranged procedures. The design of an experiment can be a good culminating experience for a particular course because it requires increased thought and understanding. The concept of designing an experiment in not necessarily confined to the traditional setting of a scientific laboratory – especially for civil engineers where the details of many field tests are clearly specified and standardized.

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ALLEN C. ESTES

Colonel Allen C. Estes is an Associate Professor and Civil Engineering Division Director at the United States Military Academy (USMA). He is a registered Professional Engineer in Virginia. COL Estes received a B.S. degree from USMA in 1978, M.S. degrees in Structural Engineering and in Construction Management from Stanford University in 1987 and a Ph.D. degree in Civil Engineering from the University of Colorado at Boulder in 1997.

J. LEDLIE KLOSKY

Dr. Led Klosky is an Assistant Professor in the Department of Civil and Mechanical Engineering at the United States Military Academy at West Point. He is a registered Professional Engineer in Maryland. Dr. Klosky received his B.S. and M.S. degrees in Civil Engineering from Virginia Polytechnic Institute in 1987 and 1988, respectively. He earned a Ph.D. degree in Civil Engineering from the University of Colorado at Boulder in 1997.