

Using a Realistic Hands-On Laboratory Program to Enhance a Reinforced Concrete Design Course

Allen C. Estes, David E. Sibert, and Christopher H. Conley
United States Military Academy

Abstract

Most engineering courses rely on a combination of basic engineering science theory and the use of laboratory-based empirical equations when the theory is not as easily understood. Students learn about the theory and the equations in the classroom, but the experience is far richer if these same students can verify these principles in the laboratory and see it for themselves. Effective laboratory experiences require money, time, equipment, materials and planning. They are more effective if they complement the material covered in the classroom. This paper describes the laboratory program associated with the undergraduate Design of Reinforced Concrete Structures course offered to cadets at the United States Military Academy.

The reinforced concrete course at West Point covers the topics one usually finds at the undergraduate level. These include properties of concrete and reinforcing steel, beam design, one-way slab design, bond stresses and development length, serviceability requirements, column design, and footing design. The hands-on laboratory program reinforces many of these topics and allows cadets to decide for themselves the validity of the theory and equations they use for design.

The lab program consists of eight two-hour sessions described in detail in the paper. By the completion of the course, the cadets have designed and mixed two batches of concrete, conducted quality control tests, assessed the concrete strength using destructive and non-destructive methods, constructed a steel reinforcing cage, and built and tested a reinforced concrete beam. In the process, they have verified the ACI code equations with respect to the tensile strength of concrete, Young's modulus for concrete, elastic range deflections, and the flexural capacity of an RC beam.

The final product is a formal laboratory report that ties the entire lab program together and forces the cadets to evaluate, explain, and analyze what they have done. The experience of working with the equipment, mixing the concrete, breaking the specimens and observing the ductility provided by the reinforcement could never be replicated in the classroom lecture environment.

Introduction

The Department of Civil and Mechanical Engineering at the United States Military Academy strives to bring its courses to life through interactive, hands-on classes. Interactive classroom discussion with physical models is the standard for courses taught in

support of a civil engineering major at West Point. Unfortunately, as the cadets approach their senior year, the structures that they analyze often dwarf the space available in the classroom. Additionally, while many of the design and analysis techniques are firmly based on the basic principles of the mechanics and strengths of materials, many of the equations used, especially for the design and analysis of reinforced concrete, are based on empirical relationships. Trying to find ways to give the cadets a physical understanding of such behavior becomes much more challenging.

The laboratory program that augments the United States Military Academy's Design of Reinforced Concrete Structures course offers the cadets just such an understanding. This paper will describe that laboratory program. The benefits of the program, the relationship of the laboratory's activities to the courses objectives, and the challenges of this specific program will be addressed.

Lab Program

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). These afternoon laboratory periods are spread throughout the semester at two-week intervals. Some cadets therefore will have days with a concrete class in the morning and a lab in the afternoon. The purpose of the laboratory program is to reinforce key learning objectives of the reinforced concrete course and help provide the cadets with a physical understanding of the theoretical concepts they are learning in the classroom. Table 1 lists the course objectives for CE483 and the degree to which these objectives are met in the classroom or the laboratory or both. Out of 19 course objectives, eight are attained by complementing the classroom and laboratory experiences.

The laboratory program uses standard (English) units. This is significant because the classroom portion of the course is taught in metric (SI) units and students purchase the metric version of the ACI code¹. Cadets are forced to become bi-lingual and thus become familiar with both the standard and metric ACI design equations. Additionally, the cadets are able to attach physical significance to the units in both systems of measurement.

Lab 1:

Cadets learn and use the absolute volume mix design method to proportion a concrete mixture. The objectives of this lab are fourfold:

- List the fundamental constituents of concrete and common admixtures.
- Explain how the properties of hardened concrete and steel reinforcing are relevant to the design of reinforced concrete structures.
- Predict the fresh and hardened properties of a concrete mix based upon its constituents.
- Design a concrete mixture to meet specifications.

Course Objective	Class	Lab
Explain the advantages and disadvantages of using reinforced concrete as a building material.	C	L
Describe the behavior of reinforced concrete members and structural systems.	C	L
Use ACI 318-99 and the ACI Strength Design methodology.	C	L
Analyze and design reinforced concrete beams with a rectangular cross-section.	C	L
Analyze and design slabs on grade	C	
Analyze and design one-way slabs.	C	
Analyze and design reinforced concrete T-beams.	C	
Analyze and design doubly-reinforced concrete beams.	C	
Calculate the development length of a reinforcing bar.	C	L
Calculate the deflection of a reinforced concrete beam and determine if the beam meets ACI deflection standards.	C	L
Model and analyze a statically indeterminate reinforced concrete frame.	C	
Analyze and design short reinforced concrete columns.	C	
Analyze and design reinforced concrete spread footings.	C	
Describe how individual structural elements are connected to develop a building design.	C	
Design a concrete mixture to achieve prescribed specifications.		L
Mix a batch of concrete and test the properties of the fresh concrete.		L
Determine the mechanical properties of hardened concrete through laboratory testing.		L
Describe the steps necessary to construct a RC structural component and the areas for concern regarding quality of construction.	C	L
Use <i>Mathcad</i> to solve engineering analysis and design problems.	C	L

Table 1: Relative Contribution of Classroom(C) and Laboratory(L) Lessons to Meeting Course Objectives

The cadets previously learned the procedures and methods of determining the specific gravity, absorption, moisture content, maximum size aggregate, fineness modulus and oven dry unit weight of aggregate samples in their Soil Mechanics class, a prerequisite for CE 483. Prior to this lab, the lab technicians performed these tests on the delivered aggregate samples. These concepts are reviewed and the cadets are given this data. Along with this material data and project specifications that include workability requirements, exposure conditions, nature of the structure, and concrete compressive strength requirements, cadets use the Portland Cement Association (PCA) absolute volume mix design² process to proportion a concrete mix to meet these requirements. After adjusting for moisture contents, they have the amount of cement, water, sand, gravel and, in some cases air entrainment, admixture needed to produce the 1.55 cubic feet of concrete they

will need in Lab 2. Samples of the aggregates and cement are available for cadets to touch. These samples are then used to batch a small, basic mix of concrete in plastic bags. This demonstrates the necessity of using the absolute volume mix design method, especially when predicting concrete yield. This past year, lightweight aggregate (an expanded shale) and silica fume were incorporated into the mix designs to illustrate some of the alternative constituents of concrete. Cadets use digital scales to weigh their ingredients and store the batched quantities for the next lab.

Lab 2:

The objectives of the second lab are to mix a sample batch of concrete and perform quality control tests to measure the properties of fresh concrete. Working in teams of two to four cadets (that they remain in throughout the semester), they use the mix design from the previous laboratory session. Two groups combine their components to share one of three six-cubic-foot mixers. Table 2 shows how the six groups are divided and the type of cement each used in their mix. After mixing according to specification³, the cadets perform a slump test⁴ (as shown in Figure 1), the unit weight test⁵, and an air entrainment test⁶. The cadets also learn how to adjust the properties of fresh concrete using chemical admixtures – mostly using a water-reducing admixture to improve workability.



Figure 1: Cadets perform a slump test to evaluate the workability of their concrete batch

Group	Mixer	Cement
1	1	Type I
2		
3	2	Type III
4		
5	3	Type I + 25% silica fume
6		

Table 2: Assignment of Lab Groups, Mixers and Types of Cement for CE483 Laboratory

Once the concrete is acceptable, the cadets prepare three 4" by 8" cylinders, one 6" by 12" cylinder with an embedded strain gage, and an unreinforced beam with dimensions 6" wide, 6" deep, and 24" long. After the concrete gains an initial set, the molds are stripped and the concrete specimens are placed in a curing tank.

Lab 3:

The objectives of the Lab 3 are to perform tension tests of standard reinforcing bars and to construct flexural and shear reinforcing for a reinforced concrete beam in accordance with ACI code provisions.

Each cadet group observes a uniaxial tension test on the same grade 60 reinforcing bars that will be used for the flexural steel in their upcoming reinforced concrete beam. The lab groups combine the data to obtain a reasonable estimate of the actual yield strength of the reinforcing steel. Cadets record load and deformation data points throughout the test and construct a stress-strain diagram for the steel to verify the yield stress, rupture stress, and modulus of elasticity. In the final lab report, cadets superimpose the stress-strain diagrams of steel and concrete in order to compare their respective properties of ductility, toughness, resilience, stiffness and strength.



Figure 2: Twelve Reinforcing Cages Ready to be Placed in Beam Molds

Cadets next construct reinforcing cages to accommodate a 4" wide by 6" deep by 86" long reinforced concrete beam. (Figure 3) The flexural reinforcement is two #3 grade 60 longitudinal reinforcing bars with ten-gauge wire spaced two inches apart to form grade 50 closed loop stirrups. The cage is completed with #2 bars at the top of the cage that are used to maintain the spacing and placement of the stirrups. To prevent the #2 bars from acting as compression steel, the middle section will be cut out while the concrete is being placed in the molds.

Lab 4:

In Lab 4, the cadets perform destructive tests on their concrete specimens and determine the mechanical properties of their first mix design. Specifically, the objectives of this lab are:

- Conduct compressive strength testing of concrete cylinders.
- Determine the static modulus of elasticity for concrete in compression and the flexural strength (modulus of rupture) of the concrete.
- Compare measured values of the modulus of elasticity and modulus of rupture to those predicted by the ACI Code provisions.
- Compare the compressive strength of the batched concrete to the required compressive strength, and then modify the mix proportions to meet slump and compressive strength specifications.



Figure 3: A 4"x8" Concrete Specimen Being Tested For Compressive Strength



Figure 4: The Embedded Strain Gage Can Be Observed in the Crushed 6" by 12" Concrete Specimen

The students crush three 4" x 8" cylinders (Figure 3) in a 400,000-pound capacity Forney uniaxial testing machine in accordance with ASTM C 39-94⁷. The compressive strength of the concrete is determined from the average load value from the three tests divided by the area of the concrete cylinder. Because the concrete has not cured for the full 28 days, cadets use established predictive equations⁸ to extrapolate what the concrete strength should be at 28 days. To determine the concrete's modulus of elasticity, the cadets

recorded strain readings from the strain gage embedded in the 6" x 12" cylinder (Figure 4) while it was loaded in compression. Readings were taken at uniform load intervals in order to develop a stress-strain curve for the concrete. The modulus of elasticity from the stress-strain curve was then compared to the modulus predicted by the ACI code.

At a second station, cadets loaded the 6" by 6" by 24" beam to failure in a third point bending test⁹ to determine the modulus of rupture which represents the tensile strength of the concrete. Instructors emphasize the brittle nature of the failure and have the cadets compare this experimental value to the ACI code value. Finally, the cadets assess the strength and workability obtained from their initial batch of concrete, adjust their mix design accordingly, and weigh a new batch of concrete components for Lab 5.

Lab 5:

The objectives for Lab 5 are the same as Lab 2 as the cadets mix, test, and place their final batch of concrete. They prepare concrete for more 4" by 8" cylinders and a 4" wide, 6" deep and 86" long beam mold that contains the rebar cage constructed in Lab 3. An electric concrete vibrator is used to consolidate the concrete. (Figure 5) The forms are stripped a day after placing the concrete, and once again the specimens and beams are placed in a water tank to allow complete curing.

Lab 6:

After allowing the specimens to cure for 14 days, the cadets perform non-destructive testing during Lab 6 to estimate the mechanical properties of the concrete. The cadets use several non-destructive methods to determine the compressive strength of the concrete in their 86" beam. These methods included using the rebound (Schmidt) hammer (Figure 6) and the Windsor Probe (Figure 7). Additionally, the cadets use a digital pachometer (Figure 8) to confirm the size and location of reinforcing bars, and a pulse ultrasonic digital tester for determining the condition of the concrete. Finally, the cadets use a coring drill to remove a two-inch core sample from their beam for compressive testing. The non-destructive data is extrapolated to a 28 day strength and the results using the various techniques are compared.

Lab 7:

Lab 7 is mostly preparatory work for the final lab (Lab 8) where cadets will load their reinforced concrete beams to failure. During Lab 7, cadets observe a flexural bending test demonstration on a reinforced concrete beam. The beam is set up in a third point loading configuration similar to that used for the determining the modulus of rupture, but on a larger scale (Figure 9). 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 9. A dial gage measures the midpoint deflection of the beam. (Figure 10)



Figure 5: An Electric Vibrator is Used to Consolidate the Concrete



Figure 6: A Schmidt Rebound Hammer Tests the Concrete Strength



Figure 7: A Cadet Fires a Windsor Probe Into the Concrete Beam



Figure 8: A Pachometer is Used to Determine the Location of the Steel Reinforcement



Figure 9: The Test Set-Up For The Reinforced Concrete Beam



Figure 10: A Dial Gage Records the Deflection at the Center of the Beam



Figure 11 : A Sulphur Cap is Applied to the Concrete Test Specimen



Figure 12: Cadets Identify the Crack Pattern on the RC Beam

After the demonstration, the cadets prepare their beam for a similar test during lab 8. They must apply their knowledge of concrete behavior, properties, and design to predict failure loads, deflections, and cracking patterns. As part of their preparatory work, the cadets calculate the shear strength, development lengths and flexural strength of their reinforced concrete beam using the data from the earlier labs. They verify that a moment failure is the controlling failure mode. In addition, the cadets prepare their concrete cylinders for compressive testing by applying sulphur caps (Figure 11).

Lab 8:

Finally, in lab 8, the cadets load their beam to failure in a third point bending test identical to the one they observed in lab 7 (Figure 9). In addition, they determine the current compressive strength of the beam's concrete (f'_c) through uniaxial compression tests on their concrete cylinders. Using this strength, they refine the strength predictions they calculated during lab 7. Once they complete these tests, the cadets 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 (Figure 12) 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

Finally, the cadets carry their destroyed beam to the concrete saw and depart with a souvenir sample of their beam. (Figure 13)



Figure 13: A Concrete Saw Cuts a Slice of Beam for the Cadets to Keep as a Souvenir

At the conclusion of the lab program, the cadets prepare a formal laboratory report that ties the entire lab program together and forces the cadets to evaluate, explain, analyze, and synthesize what they have done. The final requirement of the lab report is to design an experiment using all of the same materials and equipment that will verify the theoretical equations for shear capacity of a reinforced and unreinforced concrete beam. Many realize that the experience of working with the equipment, mixing the concrete, breaking the specimens and observing the ductility provided by the reinforcement could never have been replicated in the classroom lecture environment.

Benefits

The laboratory program benefited the students by giving them a hands-on application of key principles of reinforced concrete design. The purpose of and variability in strength reduction factors became apparent to the cadets in Labs 4 and 8. The cadets witnessed the sudden compression failure of an unreinforced concrete beam during the modulus of rupture test in Lab 4. Later, they saw the ductile tensile failure of a reinforced concrete beam. During these labs, more than one cadet expressed his newfound acceptance that anything made of concrete could actually be thought of as ductile. (Figure 14)



Figure 14: Cadets Observe That Reinforced Concrete Behavior Can Be Quite Ductile

Cadets developed a full appreciation of the inherent variability of concrete strength and that mix design is not an exact science. Adjustments in mix design may or may not have the desired effect and mix design is a trial and error, statistically-oriented process. Concrete cylinders made from the exact same batch of concrete may have very different breaking strengths. Non-destructive testing methods can give vastly different results. Quality control tests such as slump and air-content can vary.

Cadets gained insight into concrete constructability issues that only come from experience. Such tasks as building forms, meeting spacing tolerances, providing adequate cover, bending rebar, finishing concrete cannot be appreciated from a textbook. Cadets learned that if concrete is not properly vibrated and consolidated, there will be voids. Concrete is heavy.

The lab program adds realism to the theoretical equations and principles from the textbook. How flexure and shear cracks form becomes readily apparent to the cadets during Lab 8. The lab also validates the elastic flexure equation and its underlying assumptions. Through the execution of the lab, the cadets also gained an appreciation of the significance of the reinforced concrete beam design assumptions. Finally, cadets are able to fully appreciate the behavior of a reinforced concrete beam as a result of their experience in the final lab. While not a course objective, the laboratory program also gives the cadets hands on experience with a material that most will face in their professional future as US Army engineer officers and civil engineers.

Challenges

Several issues constrained the scope of the concrete laboratory program. The most inescapable of these constraints was time. The laboratory program was conducted, as previously stated, during eight laboratory sessions of two hours each. Some tasks do not fit nicely into a two-hour window and the highly regimented nature of the cadet schedule prevents taking more. One solution was extensive assistance from lab technicians, who performed the majority of time and labor-intensive tasks that do not directly support the learning objectives. The lab technicians stripped molds, bent and cut rebar, and cored additional samples as required. This allowed the instructors and cadets to focus on those key tasks and events that highlighted the course objectives.

Another challenge was that concrete has to cure sufficiently before it can be tested. It required careful planning to provide meaningful laboratory experiences during the period that concrete was gaining its minimum acceptable strength. Maintaining a constant moisture content in our aggregate was a concern as well, as the aggregate was tested, weighed, and mixed over a significant period of time.

Laboratory programs can be expensive. The fixed costs include testing machines, curing tanks, a collection basin (fresh concrete is environmentally hazardous), mixers, beam forms, vibrators, scales, aggregate bins, coring drill, concrete saw and lots of hand tools. The variable costs are not as high because sand, cement, gravel, and reinforcing steel are fairly inexpensive. The strain gages that are embedded in the concrete cylinders however are over \$40 each. The annual cost (once all the equipment is on-hand) of conducting the lab program described herein for a class of 55 students is approximately \$5000.

Assessment

The reinforced concrete laboratory program was successful in reinforcing many key learning objectives of the design of reinforced concrete course. All students do not necessarily appreciate lab experiences because they take time, tend to be more work, and expose the world as imperfect. In course-end surveys over the past two years, the response to the question that asked the extent to which the laboratory experience contributed to their learning has been fairly consistent. Table 3 shows a positive reaction, but not a glowing endorsement.

To what extent has the laboratory experience in CE 483 contributed to your understanding of the course material?		
Rating	2000	2001
Excellent	26%	16%
Good	38%	47%
Satisfactory	25%	29%
Marginal	7%	4%
Unsatisfactory	4%	4%

Table 3: Results of Course-End Survey For Past Two Years

It is harder to get students to prepare for a lab experience than it is for a classroom exercise. There was a tendency for students to arrive unprepared for labs. Many felt a general expectation that someone would explain everything on site. Because of the cost of equipment, the scarcity of time, and the emphasis on safety, the students knew that the instructor would not let them stray too far. Also, because the students were in assigned groups, they expected that someone in the group would be able to figure it out. One solution is well-structured pre-lab homework that is collected prior to the start of class and graded rigorously.

The final laboratory report is absolutely essential to the concrete lab program. Otherwise, the eight labs appear to be unrelated exercises and the students will treat them as such. A final lab report prevents them from discarding their data and forces the students to reflect and combine the results from different lab sessions to reach a coherent conclusion and overall understanding.

Conclusion

The combination of a reinforced concrete design course with a comprehensive laboratory program allows the fullest understanding of several fundamental reinforced concrete design concepts. By giving the cadets an opportunity to reinforce their theoretical study of the mechanics of reinforced concrete behavior with experimental experience, the cadets gained a better grasp the key concepts of reinforced concrete design. This inclusion of physical, hands-on models as part of an interactive classroom experience gives the cadets the best opportunity to fully appreciate the topic. When the laboratory program is conducted concurrently with the design course, a synergistic effect allows the benefits of the two courses to exceed the combined individual benefits of each program experienced sequentially. Lab programs represent a huge investment in time, money and preparation, but the benefits are substantial.

Bibliography

1. American Concrete Institute. *Building Code Requirements for Structural Concrete (318M-99) and Commentary (318RM-99)*, Farmington Hills, Michigan, 1999.
2. Kosmatka, S.H. and Panarese, W.C. *Design and Control of Concrete Mixtures*, 13th Ed. Portland Cement Association, Skokie, Illinois, 1994.

3. American Society For Testing and Materials. *Making and Curing Concrete Test Specimens in the Laboratory*, Designation C 192-90a, ASTM, Philadelphia, PA.
4. American Society For Testing and Materials. *Slump of Hydraulic Cement Concrete*, Designation C 143-90a, ASTM, Philadelphia, PA.
5. American Society For Testing and Materials. *Unit Weight, Yield, and Air Content (Gravimetric) of Concrete*, Designation C 138-92, ASTM, Philadelphia, PA.
6. American Society For Testing and Materials. *Air Content of Freshly Placed Concrete by the Pressure Method*, Designation C 231-91b, ASTM, Philadelphia, PA.
7. American Society For Testing and Materials. *Compressive Strength of Cylindrical Concrete Specimens*, Designation C 39-93a, ASTM, Philadelphia, PA.
8. McGregor, J.G. *Reinforced Concrete Mechanics and Design*, 3rd Ed. Upper Saddle River: Prentice-Hall, 1997.
9. American Society For Testing and Materials. *Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*, Designation C 78-94, ASTM, Philadelphia, PA.

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.

DAVID E. SIBERT

Captain David E. Sibert is an Instructor in the Department of Civil and Mechanical Engineering at the United States Military Academy (USMA). He is a registered Professional Engineer in Virginia. CPT Sibert received a B.S. degree from USMA in 1991, an M.S. degree in Engineering Management from the University of Missouri at Rolla in 1996 and an M.S. in Structural Engineering from Virginia Polytechnic Institute in 2000.

CHRISTOPHER H. CONLEY

Dr. Christopher H. Conley is an Associate Professor in the Department of Civil and Mechanical Engineering at the United States Military Academy (USMA). Dr. Conley received a B.S. degree from University of Massachusetts in 1978, an M.S. degree in Structural Engineering from Cornell University in 1980 and a Ph.D. in Structural Engineering from Cornell University in 1983.