Benefits of a Cost Effective Structural Lab

Matthew K. Swenty, Ph.D., P.E.[1] and David W. Johnstone, Ph.D., P.E.[2]

Abstract – The Civil Engineering curriculum at the Virginia Military Institute (VMI) has traditionally included labs for many core courses. Lacking from the list has been a lab covering basic structural engineering or mechanics principals. A variety of reasons have precluded this type of lab, however a recent compromise was made to include a new reinforced concrete lab series as part of an existing water resources' lab. The reinforced concrete lab fit within the existing schedule, specimens were constructed in storage space and outdoors, and testing was done by reusing existing equipment. The lab was cost effective and required a minimal amount of additional resources. The course was implemented during the spring semester of 2013 and the students reported it helped them understand many of the basic mechanics and structures principles. The lab successfully introduced relevant structural components within the current curriculum and overcame scheduling, space, and resource constraints.

Keywords: Laboratories, Demonstrations, Structural Engineering, Cross Discipline

INTRODUCTION

The Virginia Military Institute (VMI) is a four year undergraduate university awarding degrees in fourteen areas in engineering, science, and the arts. The student body, known as the Corp of Cadets, consists of approximately 1500 students who all live in military style living quarters called the barracks. The students are educated in a pseudo military environment on military studies, athletics, leadership, and academics. Three engineering majors are offered: Civil, Mechanical, and Electrical Engineering. Civil engineering has a current enrollment of approximately 240 students along with ten full time faculty and numerous support staff and part time faculty [1].

The Civil Engineering degree at VMI falls into the category of a broad based engineering education. Students start by taking introduction courses, surveying, statics, and solid mechanics. By their junior year they take core engineering classes in fluid dynamics, environmental engineering, structural theory, project management, Civil Engineering materials, soil mechanics, and transportation. Subsequent courses are also required in reinforced concrete and water resources typically in the second semester of that same year. Seven engineering electives remain along with a semester long cap stone course during their final year in college.

Along with each of these courses a series of labs are required. The broad based civil engineering degree has numerous labs because the VMI degree is very application oriented and hands on. Value is seen in having students perform experiments within lab settings. The introduction courses, surveying, soil mechanics, materials, water resources, and environmental engineering all have labs that students must take. Additional elective classes such as timber design and engineering geology also have required labs. All of these labs are taught in afternoon sections for approximately three hours. Not included are labs in construction, structures, and engineering mechanics.

LITERATURE REVIEW

Engineering laboratories have been a long standing tool used in undergraduate courses. This is especially true in engineering mechanics and structural engineering. Having "demonstration driven learning opportunit(ies)" allow the students to see the big picture in structural engineering concepts [2]. The labs allow students to physically set up

---

[1] Virginia Military Institute, 621 Nichols Hall, Lexington, VA 24450, swentymk@vmi.edu

[2] Virginia Military Institute, 619 Nichols Hall, Lexington, VA 24450, johnstonedw@vmi.edu

experiments and then sense (watch, hear, and touch) the results. This has been shown to help students understand concepts, get excited about the topic, and connect the theoretical with reality [3]. While there are applications where computer programs and simulations have taken the place of labs in recent years, many students still greatly benefit from the hands on experiences [4]. It is hard to simulate cracking in concrete, the heat generated in strained steel, or the excitement of taking a beam to failure.

For structural engineering the design course in reinforced concrete lends itself to demonstrations. A lab allows students to see the construction of beams or columns, the failure mechanisms, and how close the theories are to reality [5,6,7]. Tests on reinforced concrete behavior are very visual because of the cracking patterns and deflections. Additionally, failure case studies can be added to the lab to demonstrate how the topics apply to the real world [8]. Learning the failure modes will introduce students to forensics and help them in their careers when they see concrete deterioration, overstressed conditions, or demolition. This is particularly true for the students going into a military engineering career path. Some universities have added a lab into their standard course offerings to accomplish this goal and the value added has been well documented.

Many areas of Civil Engineering overlap one another. Labs can be used to demonstrate multiple principles through projects that are cross disciplinary. Schools have demonstrated this principle by combining courses in areas such as mechanics into a core body of knowledge. This allows the professors to focus on presenting the most important concepts into cohesive lessons [9]. Others have demonstrated undergraduate research components and instrumentation applications while using a reinforced concrete lab [10]. A reinforced concrete lab can be expanded to not only cover the failure modes of structural members but also the construction processes, scheduling, material design, and instrumentation of structures.

BACKGROUND

The structural engineering and mechanics faculty decided that adding a lab to their curriculum would be helpful to the students by providing visuals, allowing the students to be creative, and letting the students test the theoretical principles learned in class. The feeling was that the students miss out if they don’t have a lab in the solid mechanics, statics, structural theory, or structural design courses. The initial plan was to allow the students to build a series of reinforced concrete beams that could be cured and tested within the same semester. The lab would not be dedicated to only structures but to an array of engineering topics.

One of the major limitations of students at VMI, which is also a problem at many other institutions, is time [8]. This includes both time in the classroom and time available for study and extra curricularl activities. Many engineering programs are under pressure to keep total degree credits at a minimum in order to graduate students in four years. This trend of reducing engineering credits needed to earn an undergraduate degree continues [11]. Therefore, it isn’t easy to add an additional lab because it will add credits to the program thereby increasing the demand on student’s time and financial resources. This is compounded at a school like VMI which has limited academic hours in any given day from approximately 8 AM to 4 PM [12]. During academic hours, time is allotted for physical training, military coursework, and lunch. Evening classes, additional lab times, or shifting the schedule cannot be accomplished because it upsets the schedule of cadets at VMI. There isn’t enough academic time budgeted in a four year degree to easily add labs.

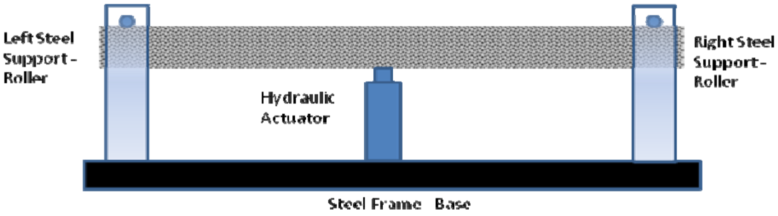
The second limitation faced by the professors was the availability of lab space. Because VMI is an undergraduate focused university, the teaching labs are highly utilized. The structures area does not have dedicated labs so they must share space with others such as the materials, water resources, or Mechanical Engineering mechanics labs. The other option, acquiring new lab space, was not a possibility at the time.

Due to these two limitations and a desire to implement this lab within the constraints, compromises were made. In the VMI curriculum the reinforced concrete course is traditionally offered in the spring semester at the same time the water resources course and lab are offered. The instructors for water resources were very willing to work their schedule such that they shared part of their lab time with the structures faculty. The decision was made to use four of the twelve weeks in the water resources lab for reinforced concrete labs. The nature of the reinforced concrete lab (building forms, placing concrete, and then curing concrete) leant itself to a shared schedule with breaks, sometimes for weeks, between labs. In fact, by alternating the labs, the lecture part of each course could be coordinated with the lab schedule to ensure the students had enough background information for the labs. In addition, to sharing their lab time, the water resources faculty provided approximately one third of their lab space for temporary storage of reinforced concrete parts. The space constraint for construction was overcome by being creative and making use of outdoor space and shared storage areas. A temporary testing area was found within a shared lab with the Mechanical Engineering Department. There was not a dedicated device to test beams or space to store the beams but there was space to maneuver, test, and remove the beams on specific lab days.

COST EFFECTIVENESS OF THE LAB

An additional goal of the lab was to use a limited amount of new materials and keep the cost as low as possible. The lab was new and therefore it would require resources that had not been budgeted. The goal was to be able to continue to offer this lab on a yearly basis without taxing the laboratory budget.

The first problem was to decide how to test the reinforced concrete beams. All else hinged on finding or creating an apparatus that could fail the beams safely and quickly. A survey was made of old testing equipment at VMI and a steel frame was found for doing an inverted test of an aluminum I-beam. The depth and width restrictions were approximately 8 in. and 12 in, respectively. The length could be adjusted by machining the frame but still had an upper limit of approximately 10 ft. The frame's material, connections, and capacity were all unknown, so conservative estimates had to be made. The connections were bolstered and a rudimentary dial gauge was added to measure deflections at mid-span. In addition, a small hand pump and 25 ton ram were found that could be used to load the frame. With a little machining and a few scrap materials, a basic frame was setup as shown in Figure 1. The frame was left in the shared lab so that it wouldn't interfere with other departments but was still readily available upon use.



a) Schematic of the testing frame.

b) Image of the frame in use.

Figure 1 – Beam testing frame.

Once a testing system was ascertained the beams had to be designed to fit both the dimensional and strength restrictions of the frame. This provided a very good lesson in practical engineering that could be shared with the students. The beam dimensions, 6 in. wide by 7.25 in. deep by 8 ft long, were chosen to fit the estimated capacity of the frame, fit within the geometry of the frame, and remain movable. The only lifting devices available were a one ton engine lift, a pallet jack, and students. The beams were designed with 4 ksi lightweight concrete and #3 and #4, Grade 60, reinforcing bars; all were available from a local ready mix plant. Six different beams were designed with differing amounts of rebar in order to create six different failure modes: shear, under reinforced, ACI minimum tension, typical tension, balanced, and over reinforced. The basic layout of the six beams is shown in Figure 2.

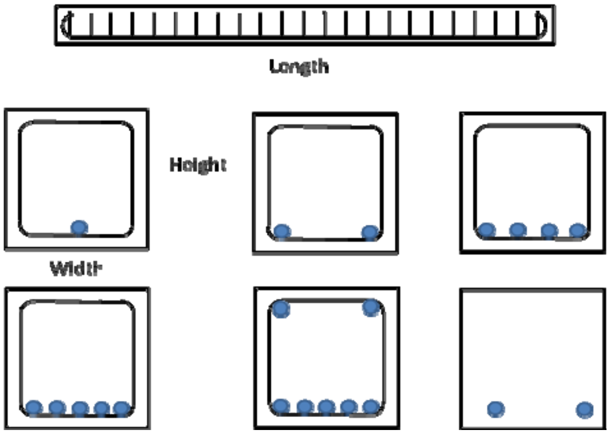


Figure 2 – Basic layout and cross sections of the six beams.

Once the beams were designed, the formwork and construction plans were formulated. All materials were available at a local lumber store and concrete ready mix plant as shown in Table 1. The sides of the formwork were made of 2 by 8's, the connections were made of 2 by 2's, and the base was made of ¾ in. plywood. The wood was screwed together with wood screws so that it could be disassembled, stored, and reassembled by future labs. The reinforcing bars were made of small sizes that are easier to bend and fit in the forms. A manual rebar bending tool was bought that would bend and cut the pieces of rebar. The total cost of these materials was approximately $1000 and the forms could be reused 5 or more times. The tools required an initial investment but should be useful for many years to come.

Table 1 – Materials needed to build six reinforced concrete beams.

Item	**Quantity**	**Approximate Cost ($)**	**Lifespan (Uses)**
2 x 8 Dimensional Lumber	15 – 10 ft Pieces	175.00	**5**
2 x 2 Dimensional Lumber	10 – 8 ft Pieces	35.00	**5**
2 x 4 Dimensional Lumber	6 – 8 ft Pieces	25.00	**5**
¾ in. Plywood	4 – 4 ft x 8 ft Sheets	120.00	**5**
1.5 in. Wood Screws	100	10.00	**5**
2.5 in. Wood Screws	200	10.00	**5**
#3 Grade 60 Rebar	15 – 20 ft Sections	125.00	**1**
#4 Grade 60 Rebar	10 – 20 ft Sections	100.00	**1**
Rebar Ties	1000	25.00	**1**
4 ksi Lightweight Concrete	1 yd3	150.00	**1**
Rebar Bending Tool	1	200.00	**25**
Rebar Tie Tools	6	30.00	**25**
TOTALS		**1,005.00**	

IMPLEMENTATION

The lab was implemented as a four part reinforced concrete lab with sub lessons on construction, materials, and statics. The first two parts of the lab were construction focused. During the first lab the students were required to help cut the wood, assemble the formwork, and measure tolerances. In the second lab they cut the rebar and bent the stirrups and longitudinal bars. The bars were assembled into a cage and then placed in the forms with chairs (Figure 3).

Figure 3 - Construction of the beams.

The third lab was focused on materials and construction. The students placed and cured the concrete for all six beams at once. Every student was involved and they were all given guidance but also allowed to get dirty and make mistakes. They were able to work with the ready mix truck driver, place the concrete, finish the surfaces, place burlap and plastic on top of the beams, and clean up the lab. A brief survey showed that less than half of the class had participated in similar activities, so this was very new to many of them. It wasn't a repeat of their materials lab were concrete was made for basic ASTM tests. This was a much larger scale concrete placement that required very careful coordination of each member in the class and team work (Figure 4).

Figure 4 – Placing and curing the beams.

The last lab was focused on statics and reinforced concrete behavior. The students removed the forms from the beams, placed them into the testing frame, and applied a center point load until failure. The original method to move the beams with an engine lift proved less than ideal due to obstacles in the labs. To overcome this problem, eight students lifted the approximately four hundred pound beams and placed them into the frame. Each end was tied down with a steel roller. Testing was done immediately after setting up the data acquisition equipment (Figure 5). Ultimate load and deflection were both measured at the middle of the beam. The beam was held with simple steel roller supports at each end. In addition to measuring maximum load versus displacement, the students mapped the crack patterns, filmed the entire experience, and observed overall behavior.

Figure 5- Setting up the test.

Upon finishing the tests, the beams were removed by the students and the failure modes were analyzed. Various methods of failure were induced which resulted in different crack patterns (Figure 6). The students mapped the crack patterns on each beam, compared them and then found what shear and moment caused the different failure modes. The last part of the analysis was to plot a load versus deflection curve and determine the first cracking load from the lab.

The post lab assignments focused on the reinforced concrete analysis and data analysis. The students were originally required to find the bending and shear strength of each beam based upon the designed properties. They were then required to reanalyze the beams with the actual material properties from the beam tests. After finalizing their two sets of theoretical calculations they compared the results to what was seen in the lab. A discussion followed comparing the behaviors, numerical results, and the factors of safety used in design.

Figure 6 – Various Failure Modes: Tension Controlled, Balanced, Doubly Reinforced

The students were required to submit a lab report prior to testing the beams and a follow up lab report after testing. The first lab report focused on the theoretical calculations for shear and bending strength and expected first cracking loads. The second lab report focused on formatting and analyzing the data from the lab, recalculating the shear and bending strength, and comparing the tested results to the first lab report.

RESULTS

Student Responses

Because the change in the lab schedule was not announced to the students, they had very few expectations. Having multiple labs was a surprise for nearly everyone but it appears to have been a positive experience for most. Discussions were recorded throughout the process to get their first impressions. An anonymous survey was provided to the entire class at the end of the semester and 25 of the 47 students enrolled took the survey. Five bonus points were added to their 100 point lab if they participated. No connection was made between how the students performed in the lab and what their final grade was in the class.

The first part of the survey asked the students how familiar they were with building structural concrete and writing lab reports prior to the class. The second part asked the students what gains they made after performing this lab. The survey results indicated the students had little experience building formwork or rebar cages, placing concrete, testing beams, acquiring data, or using lightweight concrete. The overall results indicated the lab significantly helped in their understanding. Another positive response was the lab helped them connect construction, material, and structural theories to the real world. The part they liked best in the lab was the instructional hands on approach, interaction with the instructors, and participation in the labs.

Based on the feedback it seemed nearly every student enjoyed at least one of the labs. Some were not as thrilled with the hands on construction aspects while others were fascinated with acquiring data and testing the beams. Interestingly, when asked which lab was their favorite, the students evenly split among all four labs. When asked what they would take with them, the comments focused on the construction processes and how hard it is to build theoretical designs.

A number of comments were given on how to improve the lab. Numerous people would have appreciated more labs to go over theoretical material. Because of the tight time frame, the classes were predominantly hands on without much theoretical instruction. The theoretical concepts were covered in the course lecture or individually out of class. Connecting the lab to the class proved to be a challenge for some.

In general, the students said they really enjoyed the visuals and hands on experience. Many even said they don't like structures but did enjoy learning more about how everything fits together in Civil Engineering. Some of the seniors said they missed having labs and they thought this was a really good, fun addition.

Professors Response

From the professors' perspective many things went right but there is room for improvement. There were three classes with enrollments of 19, 16, and 12, respectively. The larger two sections were big for the space constraints and it is recommended to keep the maximum numbers closer to 12. In general, most students were very involved but the lab was more effective and efficient in the smallest section. When constructing the beams in the first two labs it was better to have more oversight because so many of the students were inexperienced.

A small challenge occurred in the scheduling process. Because this lab was added to a water resources lab there were about a half dozen students who were not enrolled in reinforced concrete. They obviously didn't understand the theory but the lab was still useful because they could follow the construction, materials, and statics aspects of the lessons. Abbreviated lab reports were submitted, but they did not get to see the full theory behind the lab. The best way to fix this would be to require that both reinforced concrete and water resources be taken before or during this lab.

One suggestion is to add in additional lab periods or better coordinate the labs with the reinforced concrete curriculum. If the labs could be performed a few weeks later in the semester, then the students would have gone through more appropriate theoretical material in class that may have helped them better understand the labs. This is especially true if beam deflections are to be analyzed in future labs. The other option is to add a lab to go over the theoretical aspects in more detail at the beginning.

A comparison was made between actual material design properties and those obtained from standard ASTM compression and splitting cylinder tests. The actual concrete strength was much higher than designed creating major errors in the design strengths and final behavior. This demonstrated to the students the benefit of having factors of safety and minimum design strengths, so it was actually a good learning tool. However, the result was some of the failure modes, such as shear and compression, did not occur during testing.

The lab report involved looking at theoretical and measured bending and shear strengths for each beam and interpreting why they did not match. Differences were observed among the theoretical calculations, the calculations using actual material properties, and the observed values. This was an excellent demonstration of uncertainty in materials, design methods, and factors of safety.

One of the main problems that occurred ended up being a great learning experience for the students. The students were given the freedom to build the formwork, however most did not have the skill level to come close to ACI tolerances. This caused the beam dimensions to be a half inch or more off in places and the clear cover for the rebar to vary greatly. These problems became very apparent when the molds were removed from the beams. The class had many conversations appreciating the construction aspects and communication required to build a design.

Some of the most exciting comments and questions concerned the testing setup. The students were able to see what the infamous roller connection from statics class looks like, how a point load is applied to a beam, and how to acquire load and deflection data. A certain group of students were extremely interested in knowing more about data acquisition and how the systems worked. They also enjoyed seeing how a load is applied and thinking about the shear and moments in the beam.

Another benefit was the forensics aspect of the lab. The students had not been exposed to failure modes in a structure including deflections, crack patterns, and ultimate failure. Besides the obvious fun factor of breaking large beams with tens of thousands of pounds, the students had a better concept of how shear and flexure cracks occurred in concrete beams. Some people started to understand how you can inspect structures that are in distress or back calculate failure modes from broken beams. This was very relevant considering an above average number of graduates from VMI go into military engineering. Salvaging structures and preventing failures in high stress environments might require forensic skills.

Additional cost savings could have been realized in a number of areas. The reinforced concrete could have been made in house, however we had a local supplier who provided a standard 4000 psi lightweight concrete mix for a reasonable price. Bending the rebar could have been done with a more rudimentary method and wouldn't require a rebar bender. A couple of the beams could have been eliminated such as balanced and ACI minimum considering they demonstrate very similar failure modes as over-reinforced and tension controlled, respectively.

CONCLUSIONS

A cost effective and practical reinforced concrete lab was recently added to the VMI Civil Engineering curriculum. A series of beams were designed, built, tested, and reanalyzed. The students overwhelmingly enjoyed the lab, although for a wide variety of reasons. The cross disciplinary lab involved construction, materials, statics, and reinforced concrete topics which helped reach a very diverse student population. Nearly everyone found something that they enjoyed, from the construction aspect to the refined analysis and the materials testing. The class fit relatively well within the water resources lab and could fit very well with a few small adjustments to the schedule. The cost for the lab, while a little large the first time, should be relatively inexpensive as the setup is recycled for years to come. The goal to add a practical structures lab to the curriculum without adding a course or requiring a large budget was achieved.

REFERENCES

[1] Virginia Military Institute Web Site, “VMI Quick Facts,” http://www.vmi.edu/Content.aspx?id=10737420849, Accessed Nov. 30, 2013.

[2] Purasinghe, Rupa; Dusicka, Peter; Berman, Jeffrey W.; Bautista, Edgar; Noddings, Michael; Nguyen, Linda My Hanh; Aung, San Yu; Dam, Lang Anh, “Bringing Current Research to the Classroom Using the Linked Column Framed System in an Undergraduate Structures Lab,” ASEE Annual Conference and Exposition, Conference Proceedings, American Society for Engineering Education, 2011.

[3] Pong, Christopher; Le, Tim, “Development of hands-on experimentation experience for civil engineering design courses at San Francisco state university”, ASEE Annual Conference and Exposition, Conference Proceedings, American Society for Engineering Education, 2006.

[4] Ernst, Edward W., “Engineering Laboratories an Irreplaceable Learning Resource”, ASEE Annual Conference Proceedings, v 3, p 1402-1404, American Society for Engineering Education, 1985.

[5] LaFave, James M.; Stojadinovic, Bozidar; Wight, James K., “Lab Experiments for Reinforced Concrete Design Course”, Concrete International, v 18, n 12, p 59-62, American Concrete Institute, 1996.

[6] Roberts, Matthew W.; Thompson, M. Keith, “The DORC Factor: Engaging Students in Reinforced Concrete Design”, ASEE Annual Conference and Exposition, Conference Proceedings, p 4745-4756, American Society for Engineering Education, 2005.

[7] Rumsey, Nathan; Russell, Jonathan; Tarhini, Kassim, “Innovative Approach to Teaching Undergraduate Reinforced Concrete design”, Proceedings - Frontiers in Education Conference, FIE, p T1C1-T1C5, Institute of Electrical and Electronics Engineers Inc., 2010.

[8] Delatte, Norbert J., “Using Failure Case Studies in Civil Engineering Education”, Engineering, Proceedings of the Congress, p 430-440, ASCE, 2000.

[9] Wadzuk, Bridget; Dinehart, David; Glynn, Edward; Gross, Shawn; Hampton, Frank, “A Methodology for Curriculum Modification Applied to Civil Engineering Mechanics”, ASEE Annual Conference and Exposition, Conference Proceedings, American Society for Engineering Education, 2011.

[10] Mirmiran, Amir, “NDT and Instrumentation in an Undergraduate Concrete Lab”, ASEE Annual Conference Proceedings, p 4, American Society for Engineering Education, 1998.

[11] American Society of Civil Engineers – Raise the Bar, "Seeing the Future – Looking Back", http://www.raisethebarforengineering.org/seeing-future-looking-back-0, Accessed November 30, 2013.

[12] Virginia Military Institute Web Site, "General Order 1 – Schedule", http://www.vmi.edu/content.aspx?id=36119, Accessed November 30, 2013.

Matthew K. Swenty

Matt Swenty obtained his Bachelors and Masters degrees in Civil Engineering from Missouri S&T then worked as a bridge designer at the Missouri Department of Transportation. He returned to school at Virginia Tech to obtain his Ph.D. in Civil Engineering with a focus in structural engineering. Following graduate school he worked at the Turner-Fairbank Highway Research Center in McClean, Virginia on concrete bridge research before coming to the Virginia Military Institute. Matt teaches engineering mechanics and structural engineering courses at VMI and enjoys working with the students on undergraduate research projects and with the ASCE student chapter.

David W. Johnstone

Following undergraduate and master degrees from Youngstown State University, David W. Johnstone attended the University of Akron where he received his Ph.D. in civil engineering. During that time, he worked as a consulting engineer for Envital, Ltd. and taught part-time at Youngstown State. His research focuses on drinking water quality and disinfection. He is currently in his fifth year as an assistant professor in the CEE Department at the Virginia Military Institute. He serves as a member of AWWA, ASCE, and ASEE.