Construct First, Design Later – A Hands-On Learning Experience in Reinforced Concrete

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Abstract

"Construct First, Design Later." This is the premise of "Civil Engineering Practices – Field Engineering," a summer course for newly declared civil and environmental engineering majors at the United States Air Force Academy's Department of Civil and Environmental Engineering. No other activity during this program captures the premise better then the Concrete Beam Design, Construction, and Testing Event. The event is targeted to a student audience educated in elementary structural analysis but without any formal instruction in reinforced concrete design; however, it offers avenues of instruction for any level student. In a period of less than 3 hours and armed with only a pencil, calculator, and their basic knowledge of how loads affect members under flexure, students are given a fixed amount of concrete and reinforcing steel, and asked to employ these resources to design and construct the strongest beam possible to resist mid-point loading. One week later, students load the beam and watch as it progresses through failure. This hands-on tool bridges the gap between the field and the classroom as the students bring their hands-on experiences to their design courses.

The Importance of Hands-On Experience to the Classroom

A strong desire to provide incoming students with practical experience in the field of civil and environmental engineering led the United States Air Force Academy's Department of Civil and Environmental Engineering to develop and offer CE 351, "Civil Engineering Practices – Field Engineering." This summer course, required for newly declared civil and environmental engineering majors, maintains the motto: "Construct First, Design Later." The department recognized the importance of hands-on experiences to the success of academic programs and provides three weeks of summer academic instruction devoted to hands-on construction activities as an introduction to the curriculum.

Structural engineering, which is often considered one of the more theoretical and abstract of the civil engineering disciplines, warrants increased hands-on activities to help bridge the gap between design theory and the actual behavior and construction practices students encounter (Morreau 1990). This paper discusses one particular activity within our summer program devoted to introducing students to structural engineering through the design, construction, and testing of a full-sized reinforced concrete beam at the Air Force Academy's Field Engineering and Readiness Laboratory.

Civil Engineering Practices – Field Engineering

CE 351, Civil Engineering Practices – Field Engineering is an introductory course for civil and environmental engineers at the Air Force Academy. All Civil and Environmental Engineering majors take this course prior to their junior year. Civil Engineering Practices – Field Engineering is commonly referred to as "FERL" because the course is held at the Academy's Field Engineering and Readiness Laboratory (FERL). This laboratory covers 50 acres of land on the Academy and is used by the department's Geotechnical, Environmental, Construction, and Structures divisions. This unique three-week block of instruction provides the opportunity for our program to introduce practical construction experience to students through 22 hands-on construction activities (Table 1).

Wood Frame Building Construction I (Framing)	Roadway Development and Geotechnical Activities
Wood Frame Building Construction II (Utilities)	***Concrete Beam Design, Construction and Testing***
Wood Frame Building Construction III (Finishes)	Water Treatment Plant/Wastewater Treatment Plant Field Trips
Steel Fabrication Shop Field Trip	Open Channel Flow
Small-Scale Steel Bridge Construction	Three Reservoir Activity
Concrete Mix Design	Introduction to Surveying
Concrete Placement and Finishing	Surveying: Autolevel
Concrete and Asphalt Plant Field Trips	Surveying: Global Positioning System
Materials Testing Laboratory	Surveying: Total Station
Power Production Operations	Water Sampling
Heavy Equipment Operations	Sprinkler System

Table 1. Civil Engineering Practices – Field Engineering Course Activities

These activities, including the Concrete Beam Design, Construction, and Testing event, provide a foundation for design and theory in the 148-credit hour civil or environmental engineering curriculum. Hands-on activities in the course were developed to support typical lecture-based courses within the civil and environmental majors. These activities also supplement traditional laboratory exercises that students experience in their civil and environmental engineering courses. Figure 1 below illustrates how the field engineering course provides baseline experiences for the major's courses which follow (Pocock et al 2000).

The Concrete Beam Design, Construction and Testing activity is especially beneficial to students taking our course in Concrete Design, required by every civil engineering major. As shown in Figure 1, Concrete Design is a technical design course that directly supports our civil engineering capstone course.

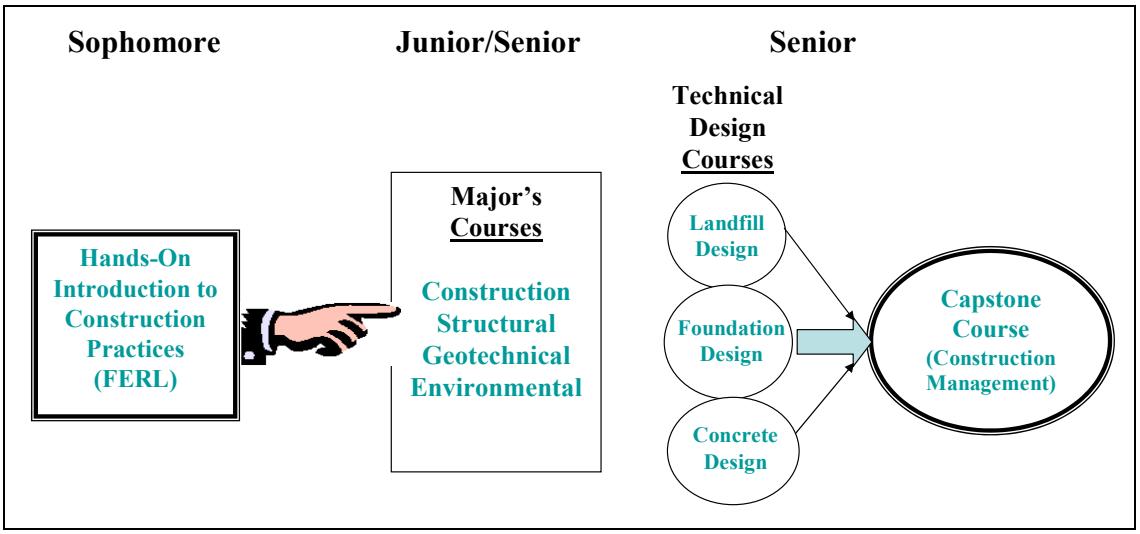

Figure 1. Integration of Construction Experiences throughout the Curriculum

The Concrete Beam Design, Construction, and Testing activity is one of the more prominent of the FERL activities, and truly no other activity during this program captures the "Construct First, Design Later" premise better. While other civil engineering programs have employed similar hands-on activities as part of reinforced concrete design courses (Schemmel 1998), the concrete beam activity is conducted *prior* to formal coursework. This promotes familiarity with the basics of reinforced concrete beam design, as well as detailed insight on actual construction methods and beam behavior under loading before to the students' formal instruction. Furthermore, the exposure to construction methods supplements construction management courses within the curriculum, including our capstone course. The capstone course is a construction management class that brings together the technical design courses through management topics in areas of cost estimating, contracting methods, and scheduling.

The Concrete Beam Design, Construction, and Testing Event at the US Air Force Academy

Since the students who are taking Civil Engineering Practices – Field Engineering are between their sophomore and junior years at the Air Force Academy, the hands-on concrete beam activity is targeted to a student audience educated in elementary structural analysis, but without any formal instruction in reinforced concrete design. In a period of less than three hours and armed with only a pencil, calculator, and their basic knowledge of how loads affect members under flexure, students are tasked to design and construct the strongest beam possible to resist mid-point loading. Although the premise of the activity is a simple one, it provides an educator vast avenues of discussion and instructional points for students of any skill level. The students are given a fixed amount of concrete and reinforcing steel to design and construct their beams. One week later, students load the beam and watch as it progresses through failure. In addition to the many construction practices experienced by the students in this event, loading the concrete beam to failure provides many valuable lessons akin to those used in failure case studies (Delatte 2000). The concrete beam activity allows students to make use of concepts observed in the field

when they eventually tackle the more abstract design and behavior theory in their design courses. The three general instructional categories of the activity reside in the title: Design, Construction, and Testing. The passages below give a broad account of how the event is conducted, followed by some example teaching points that may be introduced during each phase.

Design of the Concrete Beam – The Pressure of a Deadline

A typical class size of about 16-20 students is broken up into four groups of 4-5 students, which is the minimum number of people needed to construct the beam in the allotted time (about 3 hours). Following an introduction outlining the objectives and rules of engagement for the activity, the groups are given only 15 minutes to design a 16-foot long beam. The students are informed that the beam will be simply supported across a 15-foot span and subjected to a concentrated load placed at its mid-span. One-half cubic yard of concrete and three 16-foot long pieces of No. 4 steel reinforcing bar (rebar) are available for their design. Given the fixed volume of concrete and beam length, the students must select an appropriate width and height for the cross-section. A minimum width of 6 inches is specified to promote stability and safety during testing. A maximum width of 18 inches ensures that the beam will not overhang the supports and potentially become unsafe. At this point in their education, most students understand a taller and narrower beam is more effective; thus, widths commonly range from 6-inches to 10-inches.

Once the dimensions of the cross-section for the beam are established, the students choose a rebar configuration (Figure 2). The students are informed they may cut or bend the rebar to any configuration they desire, or they can even choose not to use any reinforcement at all.

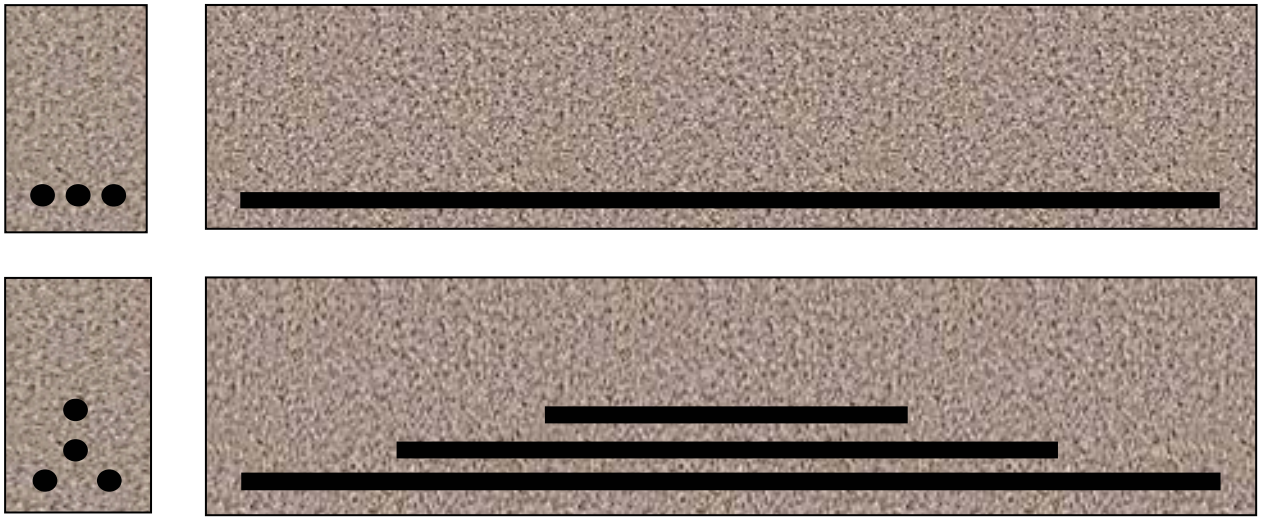

Figure 2. Example Beam Cross-Sections Illustrating Student Steel Reinforcement Configurations

Following the period allowed for design, the student configurations are quickly reviewed and approved by the instructor, who only checks for compliance with width standards and verifies the entire volume of concrete is accounted for in the cross-sectional dimensions. In some instances, it may be difficult at this point to suppress a smile indicating the inner excitement of a student beam design that is sure to give the class a great example of catastrophic failure. Once designs are approved, the students spend the rest of the session constructing their beams.

Construction of the Concrete Beam – Field Practices and Safety

As the first step in construction, the groups erect the formwork for their beam and gain an understanding of the benefits of using prefabricated concrete forms. Specifying a 16-foot long beam simplifies erecting the formwork because it is a multiple of both the 8-foot standard length of plywood sheets and the reusable concrete forms utilized in the program. One beam requires only four 2' x 8' panels to create the side-walls of the formwork and two 2'x2' panels to form the ends. Once one side-wall is joined with the two end panels, the remaining side-wall is adjusted to accommodate the width of the beam that the students have specified (Figure 3).

Figure 3. Students Erecting Forms for the Concrete Beam

To aid in clean-up after the forms are stripped from the cured beams, the inside of the forms are lined with plastic. The students are reminded that although this is not a common industry

practice, it does avoid messy form oil and minimizes the need to remove concrete from the forms (as a result of using plastic, the beams sometime have a "wrinkled" appearance). Careful attention is placed on laterally securing the formwork with wood blocking and pipe clamps. As the formwork nears completion, 2-3 members of each group begin fabricating their selected rebar configuration. After cutting and bending the rebar, students use tie wire and scrap rebar to maintain the bar spacing and depth specified in their designs. Finally, marks are made on the inside of the formwork to indicate the proper depth of the beam when placing the concrete.

Figure 4. Students Placing Concrete into Forms

Following assembly, the students are ready to place the concrete in the forms. The concrete is delivered to the job site via a ready mix truck. Students are introduced to concrete truck operations and the slump test. Two test cylinders are cast and subsequently tested in the laboratory to determine the compressive strength of the concrete. The students direct the concrete truck chute, use shovels and trowels to place the concrete (Figure 4), and are instructed in the purpose and techniques of vibration to ensure proper concrete consolidation. The top of the beam is finished at the proper depth using hand trowels. Before the finishing is completed, two rectangular "stirrups" are placed into the concrete along the top to allow a forklift to lift the beam onto the loading frame.

Testing the Beam - Behavior of Reinforced Concrete

The beams and concrete cylinders are allowed to cure for 7 days before they are tested. The concrete cylinders are tested in the laboratory to determine the compressive strength of the concrete to be used for calculating the theoretical strength of each beam. After the forms are

stripped, the beams are placed across a simply-supported span on the testing apparatus, which consists of a steel-frame structure with a clear span between pedestals of 15-feet (Figure 5). The loading is a simple, hand-operated hydraulic jack (fitted with a pressure gage) that is positioned on top of the beam to provide the mid-point loading. Prior to testing, the jack is calibrated in order to correlate gage pressures and applied load. A chart correlating jack pressure readings to load is used during the test to measure the actual loads applied to the beam.

Figure 5. Hydraulic Jack Used to Apply Load to Beam

Students steadily increase the load on their beam by operating the jack. They observe the behavior of the beam from initial load to failure by monitoring load (via gage pressure readings), deflection, and by observing the formation of cracks. Failure is not defined by achieving a prescribed deflection, but rather by the maximum load that can be applied. By having the four small groups accomplish this activity in the same session, the competition between the groups to produce the best design fuels the creative spirits and also provides a variety of beam designs. During testing, all groups observe the performance of each other's beams, and the variety of failures that occur provide excellent teaching opportunities to discuss how the different parameters affect behavior.

Instructional Points of the Hands-On Activity

As stated previously, there are aspects of this activity suited for students of all skill levels. The instructional lessons can be grouped in three broad categories that correspond to the three phases of the event: design, construction, and behavior during testing. Although there are a number of instructional points that can be covered during the activity, this paper will only elaborate on a few key examples. An outline of instructional points that are typically addressed during the activity is provided below (Table 2).

Design of Reinforced Concrete Beams	Concrete Construction Practices and Safety	Behavior of Reinforced Concrete
Aspect Ratio	Formwork Erection	Shear-Moment Interaction
Reinforcement Location	Rebar Placement	Stress-Strain Distribution
Rebar Spacing	Quality Control	Cracking Load/Moment
Constructability	Concrete Truck Movements	Crack Progression (Flexural)
Stirrups	Slump Tests	Crack Progression (Shear)
Cover	Concrete Workability	Local Crushing
Concrete Mix Design	Field Cylinder Samples	Bond Failure
Engineering Ethics	Placement Techniques	Ductility
	Concrete Vibration	Cure Time
	Protective Equipment	Predicted vs. Actual Strength
		Public Safety

Table 2. Example Instructional Points for the Hands-On Activity

During the design phase, the students depend on their own recollection of elementary structural analysis to select the cross-sectional dimensions and configurations of the steel reinforcement. The most effective cross-section would likely resemble the top cross-section previously shown in Figure 2, which is narrower than it is deep and places all three pieces of rebar in a single layer near the bottom. Even if the students select a configuration similar to this, they are probably unaware of the importance of concrete cover and proper spacing of the reinforcement. Students often construct a beam with a rebar configuration that does not allow the concrete to fully consolidate around the reinforcing bars, no matter how much vibration is introduced. This is a powerful instructional point when they place their beams on the loading platform and see the reinforcing steel "looking back" at them through the bottom of the beam. Additionally, this is an opportunity to mention the ethical responsibilities of an engineer due to potentially disastrous consequences of a poor design.

A frequently overlooked part of design, and very important instructional point, is constructability. Although the most efficient cross-section may specify a 6-inch wide beam, the students may find it difficult to work within such a small space to achieve their rebar configuration. Additionally, intricate rebar configurations the students may think are ingenious can prove to be extremely difficult to construct in the field. An unawareness of this highlights a problem that is typical of most engineering students (Schemmel 1998) and young engineers - not

considering the constructability of components during design. By addressing typical constructability issues during this activity, the students will be more likely to consider them during their design courses. They are also likely have a better understanding of the purpose of code limitations on items such as cover and bar spacing.

Another key point during construction is quality control. This can extend to any number of tasks during construction, but the easiest one to point out is placing the rebar in the exact location specified in the design. The students quickly find that placing rebar in the designed configuration is difficult, let alone making sure it stays in that same position while placing concrete around it. Frequently, the student's rebar will drop below its intended position or they will not fully consolidate the concrete in portions of their beam. Of course, lack of proper consolidation is easily observed when the formwork is stripped and rebar is visible through honeycombed voids.

Safety is paramount during all phases of construction and testing. The students are required at all times to wear the proper personal protective equipment, such as eye protection, work gloves, hardhats, and foot protection in the form of either steel-toed boots or toe-caps. Hearing protection is required during the use of equipment, and spotters are used during the testing of the beams to ensure that observers are not in an unsafe location. On hot summer days, it is of equal importance to emphasize the use of sunscreen and staying hydrated. While the students may feel like their hands are being held, this is the opportunity to point out that all the precautions listed above are a very real and important aspect of the job-site safety.

Figure 6. Concrete Beam Loaded to Failure

Testing is the most exciting of the phases and also provides the most opportunity to bridge the gap between theory and actual behavior. Here, the instructor has a visual aid available that is better than any chalkboard—the full sized beam itself. Using chalk or even a marker pen, the flexural and shear stress distributions can be drawn full-size on the side of the beam. As the loads increases and small cracks start to develop, the marker can be used to highlight their location and to mark the progression as the load increases. Because the beams are typically designed without any stirrups for shear reinforcement, flexural cracks frequently develop into shear cracks very early in the test and eventually lead to shear failures (Figure 6). Using the flexural and shear stress distributions for reference, many students that struggled with the concept of principal stresses during their mechanics of materials course begin to understand that cracks form at angles dictated by the interaction between the moment and shear.

Another key instructional point during testing is the ability of a reinforced concrete beam to exhibit ductile behavior. A properly designed concrete beam is under-reinforced so that the steel yields before the concrete crushes (MacGregor 1998). In doing so, the beam undergoes large deflections that give the occupants in or near a structure warning that the beam may be close to failure. Emphasizing public safety, our instructors affectionately like to call this "runnin' room," indicating that if you see a beam deflecting excessively and bits of concrete falling off, you will have time to run. Students also find it amazing that after loading the beam to significant levels that many would consider as "failure," the pressure in the hydraulic jack can be released and the beam will spring back towards its original shape. This is behavior that students would usually expect from an elastic material, but not from concrete, which they typically consider to be brittle regardless of the presence of reinforcement. All of these instructional points give the students a better appreciation for reinforced concrete as a versatile structural material and provide an experience they will remember well past their formal instruction in the area of reinforced-concrete design.

Results

The use of hands-on activities in our introductory Civil Engineering Practices – Field Engineering course has enhanced the students' undergraduate experience. Based on program-level feedback from our Air Force Program Review Committee, graduate and supervisor surveys, former faculty conferences, and internal feedback from our students it is clear that our efforts to bring construction experience into the curriculum have been successful. For example, one former senior faculty member stated, "I believe the increased emphasis on construction is good; eventually the success of the design is in the construction of the project" (Kuennen & Pocock 2002).

The response from students has also been remarkably positive. The department has recently solicited feedback from students as they were completing their degrees. Through focus groups and feedback sessions targeting, respectively, 20% and 65% of our civil engineering majors, students have consistently identified hands-on experiences, field trips, and our civil engineering practices-field engineering course as positive aspects of the two programs.

Though no control groups exist to demonstrate the impact of the FERL concrete beam activity on the concrete design course, initial surveys have been positive. All 56 Civil Engineering majors enrolled in the Academy's concrete design course in the fall of 2002 were asked to rate the effectiveness of this FERL activity to help them understand the course material. A range from 1 to 4 was available, with 1 indicating that the course was "Very Ineffective," to a 4 representing that the course was "Very Effective." The average response was a 3.4, demonstrating that the activity significantly helped them visualize the concepts of design, constructability, and behavior of reinforced concrete.

Conclusions

A hands-on activity in the design, construction, and testing of reinforced concrete beams promotes increased understanding of many aspects of concrete structural members. Each of the twenty-two activities in the U.S. Air Force Academy's course, Civil Engineering Practices – Field Engineering, provides students with the opportunity to gain practical knowledge not available in the classroom. This practical knowledge is especially evident in the Concrete Beam Design, Construction, and Testing activity, where students construct and test a concrete beam of their own design. Students gain significant understanding of constructability issues, safety, and structural behavior prior to entering a formal course in designing reinforced concrete. By actually constructing their own designs and observing how their beams perform from initial load to failure, the students will have a greater ability to visualize the concepts presented later during their formal reinforced-concrete design course…hence the premise, "Construct First, Design Later."

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Biography

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