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Research-Focused Design Capstone Project: Ultra High-Performance Concrete (Case Study)

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ABET Inc. requires the curriculum within an engineering program to include a culminating major engineering design experience that incorporates appropriate engineering standards and multiple constraints and is based on the knowledge and skills acquired in earlier course work. Many programs use a capstone design project or experience to fulfill this requirement. The paper outlines a case study on how the civil engineering program at the United States Air Force Academy uses a research centric project to serve as a valid culminating design experience, which some may view as an innovative approach. The case study within the paper outlines the project itself, the motivation for pursuing a research-centric capstone, a description of the overall capstone experience, and a justification for how the program feels the project meets the ABET requirements.

Introduction

The civil engineering program is one of six ABET accredited engineering programs at the United States Air Force Academy (USAFA). In addition to requiring students to achieve seven different student outcomes, Criterion 5 (Curriculum) of ABET states that the curriculum must include a culminating major engineering design experience that:

1) incorporates appropriate engineering standards and multiple constraints, and
2) is based on the knowledge and skills acquired in earlier course work.

The curriculum must also meet civil engineering program criteria that include designing a system, component, or process in at least two civil engineering contexts. ABET also defines engineering design as "a process of devising a system, component, or process to meet desired needs and specifications within constraints. It is an iterative, creative, decision-making process in which the basic sciences, mathematics, and engineering sciences are applied to convert resources into solutions [1]."

Howe and Wilbarger [2] conducted a survey of engineering capstone courses in the United States to gain an understanding of how they were structured. They had 444 programs respond to their survey, and they found that most capstone courses contained a mixture of classroom and project components, with an increase in both the variety and quantity of projects that were externally sourced through industry. Researching the types of activities that civil engineering programs are using for their capstone project reinforced those findings. Even when searching for "research-focused" capstones, the types of projects identified in the various articles are project-oriented and/or linked to industry. While the list is certainly not exhaustive, several examples are these types of capstone projects are described in [3] – [7]. Warner and O'Hern [8] describe how Howard University and Sandia National Laboratories have collaborated to develop research-focused projects that are appropriate for capstone design student teams. The students are exposed to a research environment and learn how to use their designs to perform experiments that can acquire high-quality data. As part of these problem-based learning projects, the students employ various Computer Aided Engineering (CAE) tools available as part of their design work, build apparatus, acquire data, and perform data analysis. The projects were focused on design, but led to an experimental apparatus that was tested, leading to students' experience with equipment such as data acquisition systems, high-speed cameras, image analysis, evaluation of experimental uncertainty, and comparing data with models. Two example projects were presented in their paper, one focused on development of an apparatus for testing flocculation of small particles, and another on developing a vibration test platform for experiments on bubbles under vibration. Zahraee [9] also described how the College of Technology (COT) at Purdue University Northwest (PNW) has pushed to increase engagement with local industry to both direct capstone projects for students and work as consultants for student-led capstone projects. Zahraee explains an initiative within the construction engineering and management technology program that takes the involvement with industry a step further by allowing students to use an existing technology in combination with research to create a new, efficient technological application in construction. The limited amount of literature related to research-centric engineering capstone projects, also stated in Zahraee's literature review, highlights the relevance of this topic.

CIVENGR 451 & CIVENGR 451 – Civil Engineering Capstone Design I & II

The culminating design experience in the USAFA civil engineering program had been a project that was nested within a single semester construction management course [10]. The project had a real-world customer and was thus linked to industry, similar to what Howe and Wilbarger [2] described. Although the project met all the requirements for a culminating design experience, the department made the decision to transition to a year-long culminating major engineering design experience. The decision was made as part of the continuous improvement process and took input from students, internal program assessments, and what other programs around the nation are doing. The two-course capstone experience for the USAFA civil engineering program was first executed during the 2023-2024 academic year. CIVENGR 451 (Civil Engineering Capstone Design I) occurs in the fall and CIVENGR 452 (Civil Engineering Capstone Design II) occurs in the spring. Each course is worth 3.0 credit hours, and has the following objectives:

1. Work effectively within a design team in a professional and ethical manner.
2. Apply the civil engineering design process and conduct iterative analysis and design of a solution to a challenging, ill-defined and open-ended problem.
3. Apply knowledge of math, science, and engineering to design a system, component, or process in more than one civil engineering context in accordance with applicable codes and regulations.
4. Incorporate contemporary issues, such as economic, environmental, social, political, ethical, health and safety, manufacturing, and sustainability, as applicable into the solution of an engineering problem.
5. Communicate and justify an engineering design through oral and written form.

Students work within small teams, and each team has a unique project that falls within one of three overarching areas: design, design-build, or reached-focused design. The focus of this paper is how a research-centric project serves as one of the USAFA civil engineering capstone projects. Although the project yielded a journal article [11], this case study will only describe some aspects of the research project to provide context related to the ABET requirements.

Ultra-High-Performance Concrete (UHPC) Research-Centric Project:

A group of four students conducted an independent study on UHPC during the spring semester of their junior year and then continued their work as a senior capstone project during the 2023-2024 academic year. Two primary objectives of their independent study were to become familiar with UPHC and to identify potential research areas that would be suitable for a capstone project. The team identified a lack of previous research related to reinforced UHPC beam specimens that had low fiber volume fractions (less than 2%). The low fiber volume fraction is atypical in proprietary UHPC mixes, but as the steel fibers are often the most expensive constituent in UHPC, exploring structural response when fiber volume fraction is low could be particularly economical. The team also determined that high longitudinal reinforcement ratios, from about 3% to 8%, had not yet been studied in reinforced UHPC specimens. Their literature review resulted in three research questions [11]:

1. How do short span R/UHPC beams with a stirrup spacing of "d" and 1% steel fibers by volume perform compared to beams with a stirrup spacing of "d/2" and only 0.5% fibers, where "d" represents the beam's depth?
2. How does short span R/UHPC beam performance change when the reinforcement ratio is increased?
3. How does fiber orientation differ when R/UHPC beams are cast from the center of the mold compared to when cast from the end?

The capstone team cast seven small scale beams as part of their project. The specimens were 26.5 in. long, 4.0 in. wide, and 7.0 in. tall, and varied in reinforcement ratio, the amount of transverse steel, and the fiber volume fraction. The specimens were cast by placing UHPC in two methods (from the middle or from the end) to address the third research question. The team used fiber volume fractions of 0.5% and 1.0%, which are both lower than the 2% recommended by the supplier of the UHPC. Three of the beams included four Grade 60 No. 6 bars for longitudinal reinforcement ($\rho = 9.5\%$) and four of the beams only had two Grade 60 No. 6 bars ($\rho = 4.1\%$). The transverse reinforcement (stirrups) consisted of Grade 100 No. 3 bars and were spaced at either 5.38 inches or 2.69 inches, which was approximately "d" or "d/2." The team allowed the beams to be cured for 28 days and then tested them to address the research questions. Please see [11] for a full discussion of the testing methods and associated results.

How the UHPC project met capstone requirements:

The UHPC project involved designing a series of beams and investigating the impacts of three experimental variables. For each beam, the team calculated compression, tension, and shear strength and tailored the designs to achieve desired failure modes and failure loads; therefore, the "engineering design" requirement was achieved.

The team used engineering standards such as the Building Code Requirements for Structural Concrete (ACI 318-19) as well as the Federal Highway Administration's "Structural Design with Ultra-High-Performance Concrete" (FHWA-HRT-23-077), which provides specific guidance for UHPC structures. The team also two American Society for Testing and Materials (ASTM) standards related to the casting and testing of the specimens:

ASTM C1437: Standard Test Method for Flow of Hydraulic Cement Mortar
ASTM C1856: Standard Practice for Fabricating and Testing Specimens of UHPC

The capstone project considered constraints identified in previous literature and practice, particularly the high initial cost and carbon footprint for UHPC. The decision to examine low fiber volume fractions was directly related to reducing the cost of the UHPC beams. In addition to the constraints related to codes and costs, they were constrained by constructability of the beams and the schedule associated with needing to complete the research within their senior academic year. The USAFA is an undergraduate only university; therefore, there was not an opportunity to continue the research project as a graduate student.

Students on the UHPC project leveraged the knowledge and skills they acquired in several earlier courses. They built upon knowledge of shear and moment diagrams, which was learned in

CIVENGR 330, *Elementary Structural Analysis*, and reinforced in CIVENGR 372, *Behavior and Analysis of Structures*. Additionally, three of the four students took CIVENGR 474, *Behavior and Design of Concrete Members*, which they leveraged to analyze and design the beams, specifically shear strength, moment strength, and development length. The team leveraged CIVENGR 385, *Project Management and Contract Administration,* while developing and maintaining their project's schedule. Lastly, students used the welding skills they developed during CIVENGR 351, Field Engineering and Readiness Lab, to assemble the rebar cages. They also used the material testing knowledge and skills obtained during CIVENGR 351 to conduct the testing of their beams.

As a point of reference, there were six different research-centric projects within the USAFA civil engineering program that were conducted during the 2023-2024 academic year. Prior to each project being offered as a capstone, faculty advisors had to justify how they anticipated the project would meet the ABET criteria. Additionally, faculty within the USAFA civil engineering program discussed all six projects and assessed each of them against the criteria as part of the course assessment process. If the project was assessed as weak or lacking in any of the three areas, the plan was to either modify the project to strengthen compliance or to simply not offered it again as a capstone project. One of the 2023-2024 projects was assessed to be weak in compliance. Although the project provided a valuable learning and developmental experience for the students, the department opted to discontinue that project, or something like it, as a capstone option during the 2024-2025 academic year.

Closing Comment:

This is just the second year of the year-long capstone experience within the USAFA civil engineering program, and we are optimistic that the program will be able to continue to offer research-centric projects as one of the options. The author is also hopeful this case study will be useful for other programs if they are considering the incorporation of research-centric projects into their culminating design experience.

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