Leveraging DoD Relationships and Interests to Improve Undergraduate Education and Enhance the Structural Engineering Profession

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1. Abstract

Department of Defense (DOD) organizations such as the Naval Facilities Engineering Command (NAVFAC), the Air Force Civil Engineering Center, and the US Army Corps of Engineers provide design and analysis of structures to resist blast effects from accidental explosions and terrorist or foreign threats. Current code provisions for designing structures under accidental blast conditions and dynamic loading are given in Unified Facilities Criteria (UFC) 3-340-02 (Change 2, 1 September 2014). The field of structural blast safety is uniquely and acutely more relevant to DOD agencies due to the nature of both malicious and accidental risks. Obviously, terrorist incidents address one component, but the requirement to safely store munitions on DOD installations sparked the formation of the DOD Explosives Safety Board in 1928 after the major accidental explosion at the Naval Ammunition Depot, Lake Denmark, New Jersey. The requirements persist, as all services face the challenges posed by explosives safety.

Beginning in the fall of 2019, researchers at the NAVFAC EXWC in Port Hueneme, CA and faculty at USMA began partnering in search of mutually beneficial research and education opportunities. This paper presents a unique research project and capstone experience at the undergraduate level that will benefit DoD research, active-duty service members, and undergraduate civil engineering students from June 2020 to May 2021. Three civil engineering students embarked on a project-based study to support NAVFAC EXWC in their role as subject matter experts in protective construction for explosives safety for multiple military construction (MILCON) projects on Navy installations.

Student work has extended learning on reinforced concrete (RC), delved into new blast engineering design knowledge, incorporated the generation Mathcad-based engineering tools, and investigated performance-based alternatives to support rotation limits for one-way structural members identified in the UFC 3-340-02. The project has provided a wealth of opportunities to prepare students for graduate level experiences and learn new content, while the analysis and results from this capstone project will provide DOD engineers with new tools for design. This paper reports on the results of this effort leveraging DOD expertise and research with undergraduate experiential learning. The authors will demonstrate that through Project Based Learning (PBL) the synergies associated with the DOD interests substantively improved the student capstone experience, resulting in enhanced undergraduate achievement of broader Accreditation Board of Engineering and Technology (ABET) and American Society of Civil Engineers Body of Knowledge (ASCE BOK) student outcomes, while simultaneously providing useful tools and better trained engineers to the profession.

2. Introduction

DOD organizations such as NAVFAC, the Air Force Civil Engineering Center, and the US Army Corps of Engineers provide design and analysis of structures to resist blast effects from accidental explosions and terrorist or foreign threats. Current code provisions for designing structures under accidental blast conditions and dynamic loading are given in UFC 3-340-02
(Change 2, 1 September 2014). The field of structural blast safety is uniquely and acutely more relevant to DOD agencies due to the nature of both malicious and accidental risks. Obviously, terrorist incidents address one component, but the requirement to safely store munitions on DOD installations sparked the formation of the DOD Explosives Safety Board in 1928 after the major accidental explosion at the Naval Ammunition Depot, Lake Denmark, New Jersey. The requirements persist, as all services face the challenges posed by explosives safety. As a result, many of the ammunition storage facilities are constructed using RC, which over the years has proven difficult and tedious to model under dynamic loading conditions. If an accidental explosion were to occur, the goal is to be able to correctly predict the effects of the blast on the RC structural members used in construction. Though many of the concepts in this area lay in the realm of graduate level knowledge and applications, undergraduate Civil Engineering students at the end of their curriculum are poised to enter and make contributions to the field. This paper will demonstrate the synergistic undergraduate learning outcomes and DOD partner agency benefits resulting from an undergrad Civil Engineering (CE) research team at USMA, mentored by faculty and practicing DOD engineers from NAVFAC EXWC, pursuing a culminating research project that offered practical performance-based alternatives to prescribed code limitations for member blast damages.

3. Background

Undergraduate CE education is accredited by the ABET’s Engineering Accreditation Commission, applying general engineering requirements in conjunction with a set of CE specific requirements informed by input from the ASCE. At the end of a course of study, students are required to complete a culminating design experience that builds upon learned capabilities and achieves more advanced objectives. In this case at USMA, the three CE students that took part in this research project have learned concrete design, structural analysis, and mechanics of materials. They have completed a course in Concrete Design have knowledge of slab, beam, and column design, as well as an understanding of the material properties and behavior of RC. Upon graduation, in addition to meeting program developed educational objectives, students are expected to meet several ABET directed student outcomes, and at the start of the effort, they were poised to pursue key portions of the following ABET Student Outcomes [1]:

**Student Outcomes** – Civil Engineering

At graduation, Civil Engineering Majors will have attained:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics;
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors;
3. an ability to communicate effectively with a range of audiences;
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts;
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives;
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions;
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The ABET Student outcomes above are further enhanced with CE specific goals in math and science, as well as engineering design, that stem from outcomes formulated in the ASCE BOK [2]. The BOK goals align with and reinforce a desire for students to achieve ABET Student Outcomes – applying Bloom’s Taxonomy to map achievement in engineering mechanics, critical thinking & problem solving, risk & uncertainty, design, depth in a civil engineering area, communication, and teamwork and leadership – both at the undergraduate level and beyond. At the undergraduate level, the goal is to achieve the ABET outcomes and work towards achievement in the areas of the ASCE BOK [1, 2]. What will be shown to be an incredibly rich experience was built to achieve the above ends, leveraging both a project and a partnership with the NAVFAC EXWC team.

In the project, student work focused on learning requisite RC design knowledge, blast engineering design knowledge, the preparation of Mathcad based engineering tools, and research related to support rotation limits that bound categories of element damage and performance levels identified in the UFC 3-340-02 and ASCE 59-11 [3, 4]. Much of the design and analysis outlined in UFC 3-340-02 relies on simplifying assumptions that overlook specific behavior in the steel and concrete [3]. This project will relate the moment curvature relationship of RC cross sections to a resistance function that can be modeled in a non-linear numerical analysis method. By describing the internal material effects of RC members under dynamic loading with a moment curvature relationship, conclusions will also be drawn regarding certain design criteria in the UFC 3-340-02, such as the maximum of 2 degrees of support rotation [3].

Outside research has shown that the 2-degree support rotation, which is used to bound levels of element damage, does not fully describe the behavior or plastic hinges forming at the supports, with some cross sections greatly exceeding this criterion and others failing before 2 degrees is reached [5]. The final product for this research will be a set of Mathcad Prime 6.0 sheets that conduct analysis of RC cross sections under various dynamic loading conditions and their capacities, as well as a discussion of the benefits of this type of analysis over current code and design. To accomplish these goals, the moment curvature relationship for a cross-section will retrieve the performance criteria of stress and strain in the RC members at each iteration of the analysis. These Mathcad sheets will give DOD engineers the tools necessary to analyze the effects of blasts on a given structure. They will be modular in nature for efficient use in follow on projects while allowing a range of analysis techniques.

4. Methods of Achieving Optimal Learning and Professional Outcomes

4. A. Project Based Learning

Project-based learning is defined as a student-centered opportunity to apply a multi-disciplinary solution to an ill-defined problem that is centered on a real-world issue [6, 7]. This type of learning built around the fact that students should not be passive learners, and instead
acquire the ability to become lifelong learners who can synthesize and apply knowledge when necessary [6]. Project based learning also provides the opportunity for students to utilize vertical and horizontal learning measures; vertical being the accumulation of subject matter and horizontal being teamwork and other project management techniques [7]. It reinforces classic concepts learned in the classroom and exercises concepts for greater comprehension [8]. This is important because as engineering students enter the real world, the tests they take will not be on paper, but instead will be related to real world projects [8]. As engineers enter the work force, they must be able to utilize project management, communication skills, teamwork, rapid learning techniques, and sourcing information techniques to do well [6, 8].

The PBL utilized in this capstone allows for classroom theory to be implemented into a real-world solution that serves the needs of stakeholders interested in solutions and new methods of engineering. Project-based learning also assisted in learning new techniques not taught within the core curriculum, encouraging students to do research on their own to learn and apply the resulting knowledge in a complex problem. The ABET defines a complex engineering problem as a problem that includes the following characteristics: involving wide ranging or conflicting technical issues, having no obvious solution, addressing problems not encompassed by current standards and codes, involving diverse groups of stakeholders, including many component parts or sub-problems, involving multiple disciplines, or having significant consequences in a range of contexts [1]. Along the way, techniques were researched as the need arose and assisted in making the model more fluid to meet the needs of stakeholders who would be using it. The modern workplace and engineering profession demand that members of the community move past traditional memorization and superficial levels of learning to use new concepts and analysis to add knowledge to the community [5]. This PBL capstone demonstrates this by taking existing Single Degree of Freedom (SDOF) analyses and improving the capabilities of the code.

As mentioned in the background, students at USMA were introduced to the current methods for analyzing RC member behavior under blast loading, and a real scenario in which it was vital to accurately depict this behavior to protect life and the infrastructure of the military. To define this problem, students incorporated current knowledge of mechanics of materials, concrete design, and structural analysis to develop an initial understanding, and then supplemented this knowledge with research into graduate level topics such as resistance functions, blast loading software, and other non-linear analysis techniques.

The PBL method has allowed the students at USMA to take this ill-defined problem, integrate previous knowledge, and acquired knowledge to make decisions on how to best find a solution. Research has shown that PBL allows for higher critical thinking skills that allow for exploration of multiple paths towards a viable solution [6]. Students in this protective design capstone engaged in critical thinking to apply knowledge of fundamental engineering principles to decide what assumptions to include in modeling, and how complex to make a model for the intended purpose. An example of one of these assumptions is to use a total average curvature when finding the performance criteria in the end of the members at the location of the plastic joint formation. This assumption was included because the total rotation can be divided by an assumed plastic hinge length given by the equation

\[ lp = \frac{d}{2} \]
This assumption was used because it simplifies the math and allows a script to be written using Mathcad 6.0, while still being verified by research on the topic of plastic hinge behavior in RC beams [9]. Multiple modeling techniques were analyzed such as finite element analysis and SDOF modeling. A SDOF analysis was chosen because it is less labor intensive and complex when compared to a finite element analysis program and can still provide the performance criteria that is currently missing from many other analyses. This style of SDOF analysis that utilizes simple Mathcad sheets to solve non-linear beam displacement efficiently addresses the problem that was defined when the modeling was first examined.

4. B. Advanced Technical Concepts

Working with DOD engineers to solve complex problems in the new world forces undergraduate students to apply fundamental knowledge to new and unique technical concepts. The focus of this protective design study was to evaluate current design criteria and create an efficient tool that DOD engineers can implement to potentially save lives. The current provisions in the UFC 3-340-02 and the ASCE SEI 59-11 call for specific support rotation criteria for RC members subject to blast loading in tension [3, 4]. To understand the criteria used by these DOD engineers, research was conducted into the SDOF modeling of RC members. It was determined that SDOF analysis uses several assumptions that can be improved in an efficient manner and that material strain performance of the RC member was not quantitatively described in the protective design criteria [5].

To address the assumptions discovered in the research phase of the project, fundamental knowledge was revisited and applied in unique ways. Initially, the moment curvature relationship of a member was applied to RC members and coded into Mathcad. The coding of the moment curvature worksheet illuminated the assumptions and theory behind a moment curvature relationship in reinforced concrete such as assumed stress-strain curves for concrete and simplifications of these curves that are used in design code. Coding skills developed with PTC Mathcad propelled the group’s capability for the application and use of many higher-level programs beyond the levels attained by other students in the CE major. Topics such as concrete stress distribution and material behavior were also defined to a more detailed level than taught in core concrete engineering classes and gave insight on the reasoning and effectiveness for techniques taught and used in code such as the ACI 318-19.

New topics that were learned during the PBL were the effects and nature of the blast environment, the use of blast analysis software, and the modeling of beams using a series element approach. In conjunction with this learning and knowing that blast loading is more complex when it is confined, the project emphasized the need to learn and understand outputs of blast software. Blast software such as BlastX from Engineering Research and Design Center and CONBLAST from NAVFAC and EXWC were among the software learned to assist in pressure-time history outputs. The final technique learned was the series beam technique with assistance from reviewing lectures by Professor Filip Fillipou form University of California - Berkeley [10]. This incorporated to account for nonlinear behaviors occurring in the accumulation of deflections along the analyzed beam. The incorporation of these topics assisted in developing a more realistic model and extended the capabilities and knowledge of the students.
Learning and applying topics that reach past the scope of an undergraduate CE degree forces students to conduct independent research and understand topics through technical writing. This skill is essential for the modern military leader and professional when conducting missions in new environments and using field manuals to solve problems.

4. C. Partnership with DOD Agencies

NAVFAC and EXWC have provided a unique opportunity for students at the undergraduate level to participate in projects and engineering fields not typically covered in undergraduate curriculum. Through a design and research project, students at USMA have been introduced into the field of blast loading and protective design. These fields build upon fundamental knowledge taught in basic engineering courses and applies it to the real world while also serving the needs of the DOD. All work that has been completed in terms of research and Mathcad sheets are submitted to a partner at NAVFAC for use in their projects and for feedback to tailor products to the engineer's needs. The interaction between the engineers at NAVFAC and the students at USMA also helps build a bench of qualified and potentially interested individuals for the future of the field of protective design. Throughout the course of this project, students met with a NAVFAC representative once a week.

The partnership with these DOD agencies is also an opportunity for both undergraduate students, faculty, and the DOD researchers to make connections and build contacts in fields of engineering that have benefits for civilian society and the needs of the United States. In the case of this protective design project, partners at the DOD have been used as references to apply for graduate school. While this may seem to be only a benefit to the students, in fact a graduate student capable of research in the field has been groomed and mentored in the selection of and admission to an advanced education. While DOD researchers often have large networks within the field to begin with, where a student branches out, new connections are formed and the DOD builds an even larger network of potential research engineers they can connect with. From the perspective of the faculty, partnering with the DOD agency aids in offering a student experience that is tremendously richer, more reliably rooted in real problems, and offers expertise that benefits both the students AND the faculty members involved. In addition to added capability for the military, these partnerships with the DOD give another avenue for engineers in the military when considering potential career paths or transitioning to the civilian sector.

5. Outcomes Achieved as a Result of This Project and Partnership

5. A. Achievement of ABET and ASCE BOK Outcomes

This project arguably achieved all technical and professional student outcomes of ABET highlighted earlier, but specifically achieved outcomes 1, 5, and 7 in depth. This project allowed students to identify problems with current blast modeling and apply foundational knowledge on material behavior and mathematics to gain further insight into RC beam response to dynamic loading. Fundamental knowledge was also explored more deeply by researching and understanding underlying assumptions such as small angle approximations, and the relationships between variables such as strain and cross section properties. As was remarked by a student
At the conclusion of this project, students will have achieved Levels 4 and 5 of the ASCE BOK outcome categories of foundational, technical, and professional outcomes [1]. This means that students were able to achieve aspects of graduate level work in multiple outcomes. In foundational outcomes, students were introduced to dynamic modeling using an equation of motion, and Newmark’s Central Difference Method for modeling, as well as plastic hinge length formation and behavior. Additionally, extraction of performance criteria of the RC members was used to draw larger connections between cross section properties and code provisions to determine the adequacy of design code being used in real-world projects. This application of Mathematics and Natural Sciences resulted in Level 5 synthesizing to solve a civil engineering problem [1]. Research on these topics as well as application of blast knowledge, cubic spline interpolation, and performance criteria achieved Level 5 of Breadth in Civil Engineering Areas and Design of the Technical Outcome Category [1]. Students also developed a modular method for the project to allow for simultaneous work on different goals of a project that could be combined to reach the desired end state. Each team member was assigned specific tasks and goals to guide the team towards success in competitions and project completion. These actions allowed students to achieve Level 5 in Communication and Teamwork. In acquiring and understanding new topic to apply in the project, students achieved Level 5 of Lifelong Learning. Finally, by establishing rapport and working with NAVFAC EXWC, students integrated professional attitudes relevant to the project, achieving Level 5 in Professional Attitudes [1].

5. B. Broader Impact of PBL Experience in the Army Profession

The nature of critical thinking and analyzing various ways to achieve a viable solution to solve a problem can be attained through engineering education and applied across the Army profession. The Army Design Methodology (ADM) is depicted in Figure 1. The ADM is a framework for solving complex problems on the battlefield in the same way complex engineering problems, as defined by ABET, are approached.
Conducting an engineering PBL project, the ADM is reinforced for the modern army leader. In terms of the protective design capstone, students analyzed the current state of the modeling and decided what needed to be improved to ensure the safety of the workers and facility being analyzed. This involved determining that performance criteria should be pulled from a SDOF analysis that could verify certain assumptions in the UFC 3-340-02, including the two-degree support rotation limit. Constraints were in place in terms of stand-off distances and usage of the facility, as well as capabilities of engineers. The problem was then framed to decide which, and in what order, the obstacles need to be addressed to achieve the desired end state. An initial approach was developed to meet the goals for each semester. Critically important for this capstone was the ability to continually assess and reframe the problem. After the initial project framing stage, the capstone was moving in the direction of utilizing a moment-curvature relationship in place of a standard resistance function in the SDOF analysis. Through research and a better understanding of the needs of the military, it was determined that first, it is more important to be able to pull out performance criteria from the end rotations of the RC member in order to compare the support rotation criteria outlined in UFC 3-340-02 with material properties of concrete and steel. This meant keeping the initial resistance function in the SDOF solver and using the moment curvature relationship that was developed to input an average total curvature at the hinge and return concrete and steel stress and strain values. This has previously not been calculated by SDOF analysis and will give DOD engineers increased information when making decisions about the design of a protective structure.

The ADM also applies to ill-defined engineering problems that require successive problem definition founded on research acquired knowledge [11]. In a classroom setting, engineering students that are preparing to lead in the Army have adequate time and resources to conduct research, cementing the process as a style of learning. The framework of the Army Design Methodology that has been cemented as a style of learning will be readily available to the Army leader to make the best decision methodically while achieving desired outcomes.
5. C. Benefits from the Perspective of NAVFAC EXWC

By working undergraduate students at USMA, NAVFAC EXWC had the opportunity to acquire unique, tailored Mathcad design products, develop relationships with university faculty for potential further research, develop relationships between the agency and future graduate students, and prepare future graduate students to pursue research in fields of relevance to the agency. In weekly meetings and design reviews, NAVFAC EXWC assisted the development of the Mathcad tool by ensuring it is user-friendly, offering advice on how to debug the tool, and aiding in understanding and application of new relevant knowledge that is applied. As the primary stakeholder of the project, it was important NAVFAC EXWC were in these meetings and design reviews so they can further shape and develop the problem that was solved. These weekly meetings also established rapport between the agency and university faculty that can be leveraged by the agency for future research projects with other faculty and students at USMA. This establishment of lateral relationships within the DOD are important to assist in spreading expertise in various organizations, agencies, and branches.

NAVFAC EXWC has also established relationships with undergraduate students that can be relied on when they attend graduate school. By assisting in a challenging, intellectually stimulating project, NAVFAC has encouraged these students to potentially pursue topics of interest to the agency when they attend graduate school. This can be leveraged for future research and relationship building with other universities depending on where the students wish to attend. This could allow access to more resources and personnel interested in assisting the agency with research and development. It can also allow NAVFAC EXWC to focus their efforts on other issues and priorities while research for solutions to complex problems is conducted elsewhere.

6. Conclusion

Undergraduate students involved in this study have been able to form meaningful connections to DOD engineering organizations and apply fundamental knowledge to advanced techniques and concepts to solve complex engineering problems. This has been done through independent research and cementing a framework for solving problems in an ill-defined scenario. Students have seen examples of work done by DOD engineers and have been introduced to the scale and type of work that is accomplished by these organizations. To apply meaningful work to these projects and aid in the design process, undergraduate students have needed to justify and analyze common assumptions and provide a new and efficient means of solving the complex problem of dynamic analysis due to blast loading through a modular Mathcad sheet. The students had significant levels of achievement in both the desired ABET student outcomes and in the areas of importance in the ASCE BOK. This style of PBL learning has moved students past the common undergraduate learning environment and has equipped those involved with tools to become a successful modern Army leader.
References


