Applications of Acoustic Technologies: A Multidisciplinary Forensic Engineering Freshman Project

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ABSTRACT

This paper provides an overview of a multidisciplinary project focused on application of acoustic technologies in the discipline of forensic engineering. This freshman project was developed by faculty in civil, mechanical, and electrical engineering to highlight collaboration between disciplines and provide students a highly interactive hands-on experience. The course objectives were to: identify the broad range of applications of acoustics in electrical, mechanical, and civil engineering to solve complex technical problems, apply acoustic and ultrasonic technologies to collect and analyze data for material classification and flaw detection, nondestructively evaluate material characteristics of products and structures, construct and destructively evaluate reinforced concrete beams, and to clearly and succinctly present technical data in written, visual, and oral formats. The format of the lectures, hands-on laboratory exercises, and homework assignments are provided. Course and teacher survey data highlight the many aspects of the project that were successful and data comparisons between other courses are made. Recommendations for how this topic could be included in other discipline-specific courses and potential modifications due to Covid-19 are presented.

INTRODUCTION

In 2009, the College of Engineering at Villanova University reinvented its freshman experience by introducing a two-semester course sequence that is required for all freshman students. An integral part of this new course was an interdisciplinary project-based experience, EGR 1200. Six projects were offered, and students selected two; one in the second half of the fall semester, and a second in the first half of the spring semester. The goal of this initiative was to create interdisciplinary, hands-on, interactive, real world problems that would expose students to multiple engineering disciplines. Another goal was to generate student interest and excitement in their chosen educational path. Following the two project sequence students made a non-binding decision on which discipline to pursue.

To facilitate an inclusive classroom environment EGR 1200 has an average section size of no more than 30 students. This course has two 75-minute meetings per week. Emphasis is on interdisciplinary real-world applications and hands-on experiences. The content is taught in an integrated manner, so that students are able to apply concepts to solve larger, complex, and more interesting problems much earlier in their academic careers. An overview of this curriculum and its continued improvement is provided by Caverly, et al. (2015). A minimum of two faculty members from different engineering disciplines co-teach the project portion of the course. Two projects had faculty from three disciplines. Both of these projects included civil, mechanical, and electrical engineering. Dinehart et al. (2010) provides an overview of the role of structural engineering in these two projects, while Ural et al. (2011) presents how combining finite element modeling, engineering analysis, and experimental investigation in a project can be executed effectively. This paper focuses on the multidisciplinary project involving the application of acoustic technologies in the discipline of forensic engineering from the perspective of civil/structural, mechanical, and electrical engineering.

LITERATURE REVIEW

Over the past 20 years there have been numerous efforts aimed at improving freshmen engineering curricula, with some focusing on discipline specific experimental work (Perna, A. and D. Hanesian, 1996). Other institutions have implemented multidisciplinary experimental experiences that incorporate all major disciplines (Hesketh et al., 1997). These topics continue to fill conference sessions at American Society of Engineering Education conferences and National Science Foundation workshops as programs work towards continuous improvement.

Progress has been made recently on combining design challenges across disciplines to improve students' perceptions about their ability to solve multidisciplinary problems. Telenko et al. (2006) introduce how designettes, design charette challenges, are rapid and creative learning tools that enable educators to integrate design learning across disciplines. Multiple examples are provided that show how subjects can be integrated and applied to open-ended problems and grand challenges. None of the examples presented included the study of engineering failures.

The study of engineering failure and flaw detection via nondestructive examination (NDE) can offer students increasingly valuable insights into technical, ethical, and professional issues. Lessons learned from failure have substantially affected engineering practice and in the last twenty years case studies have been used in classrooms to educate the next generation of engineers. Delatte (2000) outlined three approaches for bringing forensics and failure case studies into the civil engineering curriculum: stand-alone forensic engineering or failure case study courses, capstone design projects, and integration of case studies. Lewis et al. (2004) focus on case studies of real accidents, broadly focused on consumer products and presented case studies which included legal background, technical reports, and highlights of the lessons learned. Various failure modes and materials were included, and the forensic toolbox chapter highlighted important material tests engineers utilize.

Many tools and techniques exist for nondestructive testing and evaluation of structures. These include visual examination, the use of dye penetrants, magnetic particle inspection, radiographic examination, and the use of acoustic or ultrasonic techniques. The objective of each of these techniques is to identify the precursor flaws that could eventually cause catastrophic failure of the structure. Of all these techniques, a strong case can be made that acoustic methods offer the most reliable, accurate, and universal method for NDE of structures for flaws. Acoustic technologies are well advanced and are founded on the science of sound wave propagation through solid media. It is the authors' opinion that exposing students to acoustic NDE technologies and tangible applications will provide an ideal backdrop for an enriched multidisciplinary freshman project.

PROJECT PREPARATION AND COURSE FORMAT

This project was developed by six faculty members from three departments and was executed in the initial offering by the authors. The civil engineering faculty member provided structural engineering background and focused on material behavior and destructive characterization techniques. The mechanical engineering faculty member provided context for mathematical background on wave behavior, vibrations, data collection and analysis, and NDE flaw detection. The electrical faculty member provided the students with the fundamentals of signal generation, measurement, Fourier analysis, and filtering. Furthermore, the electrical engineering faculty provided expertise in the ultrasound imaging technique for flaw detection and signal classification of structural elements.

The authors worked closely to provide a cohesive experience to the freshmen students. Months of preparation went into developing the project and exercises detailed herein. Figure 1 presents the slide template that was developed for uniformity of appearance between the three faculty members' lectures. Table 1 provides a description of the course schedule with the topics covered.

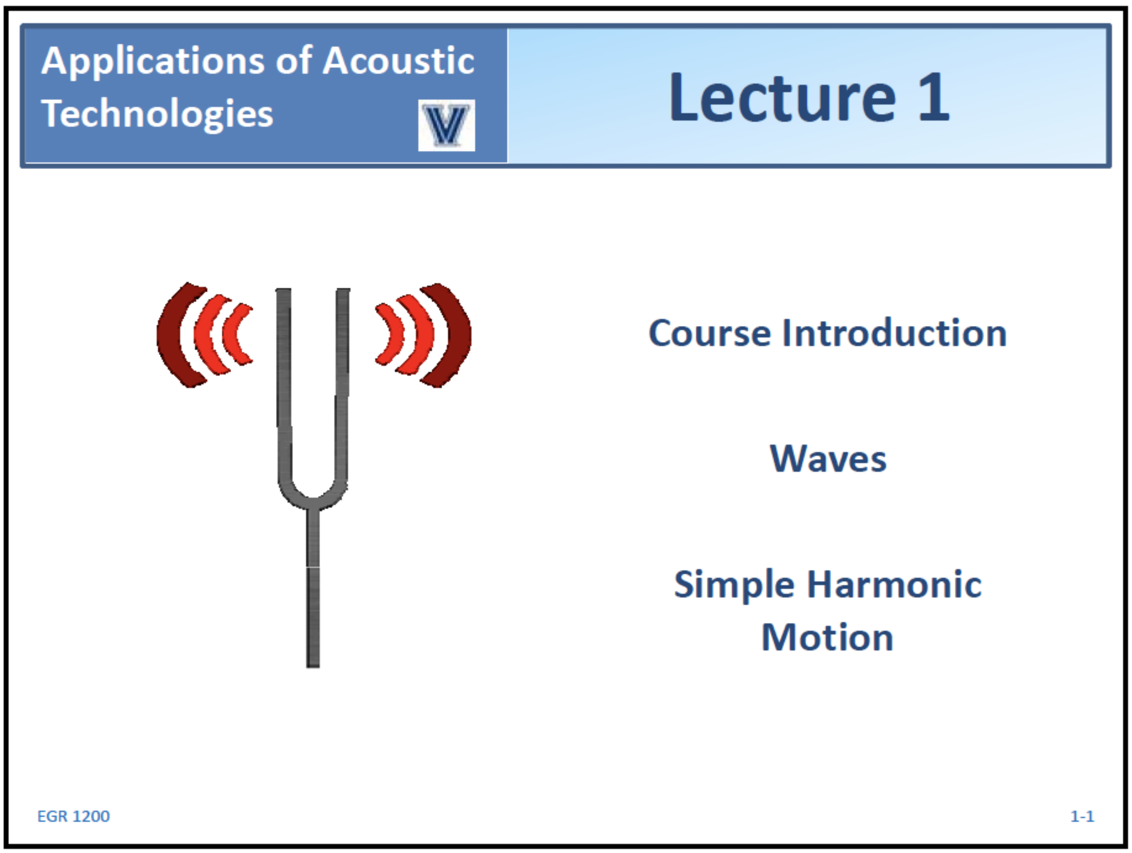


Figure 1. Slide template.

The following sections present additional details for the specific class meetings: Learning outcomes, forensic engineering topic utilized, laboratory experience, and deliverables.

DESCRIPTION OF CLASS MEETINGS

Each class meeting of the course starts with a slide on the learning outcomes for the project. The five learning outcomes are:

Table 1. Schedule for Semester.

Period #	Focus and Topics Covered
1	*General Overview: Introduction to Vibration and Frequency* Topics: Waveform, frequency, amplitude, resonant frequency
2	*Nondestructive Examination Applications and Concrete Structures* Topics: Fault detection principles, technologies, concrete mix, concrete beam design basics
3	*Data Measurement Fundamentals* Topics: Acoustic/ultrasound data generation, recording, device overview
4	*Acoustic Applications in Mechanical Engineering* Topics: Vibrations, single degree-of-freedom systems, elastic modulus (E), relationship between ultrasonic wave propagation and E, nondestructive testing
5	*Data Measurement and Processing I* Topics: Using spring-mass-systems, accelerometers, National Instruments (NI) data acquisition cards, and LabVIEW to record and measure the natural frequency of oscillation.
6	*Defect Detection* Topics: Using the pulse echo technique, an ultrasonic pulse-receiver, and an oscilloscope to measure the elastic modulus of metals and the location and extent of defects in metallic parts.
7/8*	*Construction of Two Concrete Beams in the Structures Lab* Topics: Lab safety, formwork construction, reinforcement type, mixing concrete, slump test, cylinder preparation, and beam pour
8/7*	*Data Measurement II and Processing I* Topics: Equipment use, impedance matching, units, determination of elastic moduli
9/10*	*Concrete Cylinder and Beam Bending Tests* Topics: Cylinder testing, crack mapping, load-displacement, failure characterization
10/9*	*Data Measurements III and Processing II* Topics: Use of acoustic technologies to identify structural damage
11	*Project Data Analysis* Topics: Students were provided a work period to analyze the data collected in the previous meeting
12	*Technical Communication I* Topics: PowerPoint and poster presentations
13	*Technical Communication II* Topics: Technical report writing
14	*Course Summary and Assessment*
15	*Poster Presentations* (for all freshman projects)

* To facilitate manageable lab groups periods 7/8 and 9/10 were run concurrently with half the group participating and two faculty members running the different laboratory activities.

1. Identify the broad range of applications of acoustics in electrical, mechanical, and civil engineering to solve complex technical problems
2. Apply acoustic and ultrasonic technologies to collect data, classify materials, and detect flaws or damage
3. Nondestructively evaluate material characteristics of products and structures
4. Construct and destructively evaluate reinforced concrete beams
5. Clearly and succinctly present technical data in written, visual, and oral formats

This slide is followed by the learning outcomes for the specific class meeting (lecture/lab) and a brief discussion of how they are related to the course learning outcomes.

The initial class meeting was a lecture-based format that included an introduction of the faculty team and their backgrounds. The schedule for the semester was reviewed and the resources provided on the course website were highlighted. Figure 2 was used to explain the multidisciplinary nature of acoustics and how each of the engineering disciplines discussed can play a role in object identification, fault detection, property measurement, and structural health monitoring.

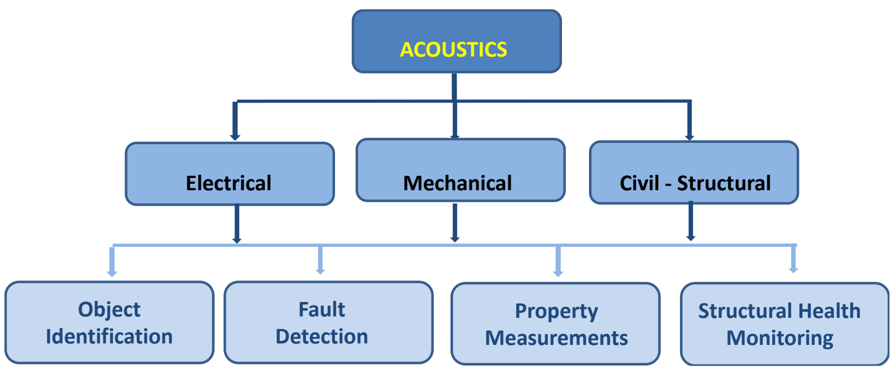


Figure 2: Multidisciplinary aspects of acoustic technologies

The technical learning outcomes for this meeting were to define waves, longitudinal and transverse waves, relate frequency, wavelength, and wave velocity and to identify, formulate, and solve problems involving simple harmonic motions. Numerous video files were used to demonstrate wave behavior and an example problem of a simple harmonic problem was presented. This class prepared students for the more advanced problems to be addressed in meetings four and five.

The second meeting focused on NDE applications and provided an introduction to concrete material and design. The civil engineering faculty presented the following learning outcomes: Identify applications of acoustic and vibration technologies in civil/structural engineering; identify the constituents and proportions of concrete; explain why concrete is reinforced; explain the difference between steel and fiber reinforced polymers; calculate the load at which a concrete beam of a specified cross-section will crack; and calculate the displacement of concrete beam subjected to a point load at mid-span at initial cracking. The presentation included information on the following: Concrete constituents, stress strain plots of steel and fiber reinforced polymer concrete beams, limit states, flexural behavior and a moment curvature plot of reinforced concrete beams, and an example problem of calculating the cracking moment. This class prepared the students for predicting the cracking load for the beams (homework assignment) they would construct in meeting seven and test to failure in meeting nine.

Meeting three was a lecture given by the electrical engineer and covered the fundamentals of signal generation, measurement, and processing. The concept of amplitude and frequency of a sinusoidal signal was introduced, and students were instructed on how to generate that signal using a MATLAB simulation. Sinusoidal signals were also generated using an arbitrary waveform generator, and a digital signal oscilloscope was used to measure and record the waveform. Students transferred the results to a computer for processing. The students were taught to use a Fourier transform to analyze the signal spectrum and perform filtering to mitigate undesired signal components. The objective of this module was for the students to understand signals and their representation in the frequency domain; measure and analyze signals using MATLAB software and an oscilloscope.

The learning outcomes for meeting four were: Identify some applications of acoustics in mechanical engineering; solve simple single degree-of-freedom vibration problems; define elastic modulus; and relate ultrasonic wave propagation to elastic modulus. This lesson introduced students to the fundamental science behind the use of acoustics for NDE. It defined concepts such as natural frequency, elastic modulus, and the relation between wave speed and elastic modulus. The homework assignment reinforced these concepts with problem solving exercises in simple harmonic motion and the calculation of wave speeds in different metals.

In meetings five and six, students engaged in hands-on exercises that reinforced the concepts of the previous meeting. In meeting five, students were given several mass-spring combinations and were asked to experimentally determine the natural frequency of oscillation of each of the combinations. In meeting six, students were first assigned the task of determining the elastic modulus of three different metals (steel, aluminum, copper) using the speed of sound. A second task involved using the ultrasonic pulse echo method to locate and size defects buried inside a metal block. As a homework assignment, students were asked to report their results in a formal written report. This period prepared students for meeting eight/seven where they would identify the three materials via acoustic technologies.

Students assembled in the Structural Engineering Teaching and Research Laboratory for meeting seven. Students were given a mix design, technical drawings for two reinforced (one steel and one glass reinforced fiber polymer, GFRP) concrete beams, and the supplies to construct the beams. The students formed the beams, mixed the concrete, conducted a slump test, and poured the beams and concrete cylinders. Figure 3 shows the students working with the concrete. This was noted as a favorite activity of the students.

Figure 3. Slump testing and pouring of concrete beams and cylinders.

The following meeting consisted of three parts. First, the faculty member demonstrated the concept of discrete Fourier transform and its implementation in MATLAB. Subsequently, the concept of treating vibration signals as damping signals characterized by spectrum frequencies and damping factors was presented. Examples of sinusoidal and damping sinusoidal signals are presented with their sound, time-domain waveform, and spectrum. Different sounds with distinct frequency spectra were generated by hitting metal pipes with different materials, namely, copper, aluminum, and steel, the same materials investigated in meeting four. These sounds were recorded using a computer microphone and processed with MATLAB for spectrum analysis. The dominant frequency components were used for their classifications as shown in Figure 4.

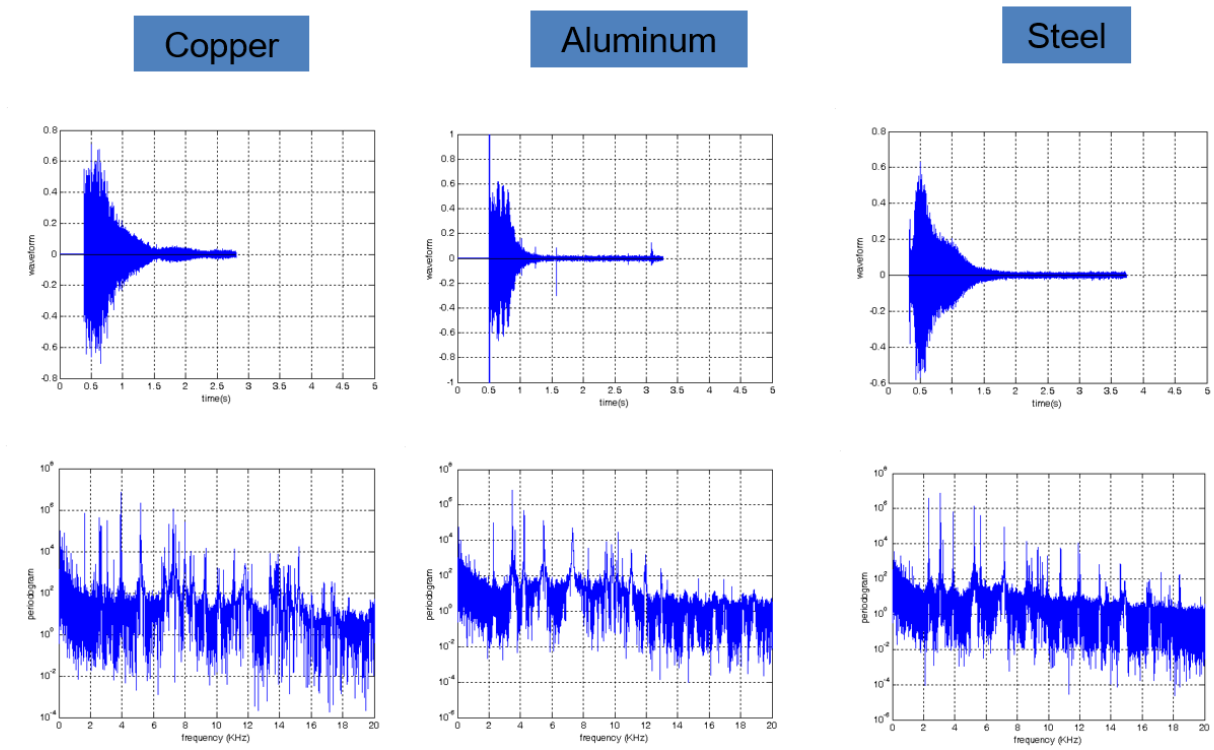


Figure 4: Sound files and corresponding spectra for metal pipes with different materials.

For meeting nine the students returned to the Structural Engineering Teaching and Research Laboratory to destructively test their concrete cylinders and beams. Students conducted the cylinder tests to determine the seven-day strength of their concrete. Students placed a two-inch grid in red chalk on their beams as shown in Figure 5. Students were provided crack gages and black markers and mapped cracks throughout the tests. A hand pump and a hydraulic cylinder were used to load the beam, and linear variable differential transformers and dial gages were used to measure the displacement.

A load and displacement plot was displayed on the data acquisition system. Students were encouraged to take notes of the state of the beam and photos at their predicted cracking loads. For their homework assignment they were required to plot the load versus deflection (dial gage data) for their two beams, as shown in Figure 6, and discuss the observed differences in stiffness and cracking behavior (width and patterns) between the GFRP and steel reinforced beams. It is clear to the students that the steel reinforced beam is appreciably stiffer than the GFRP reinforced beam, and that the cracks are wider and easier to identify.

Figure 5. Crack mapping of reinforced concrete beams.

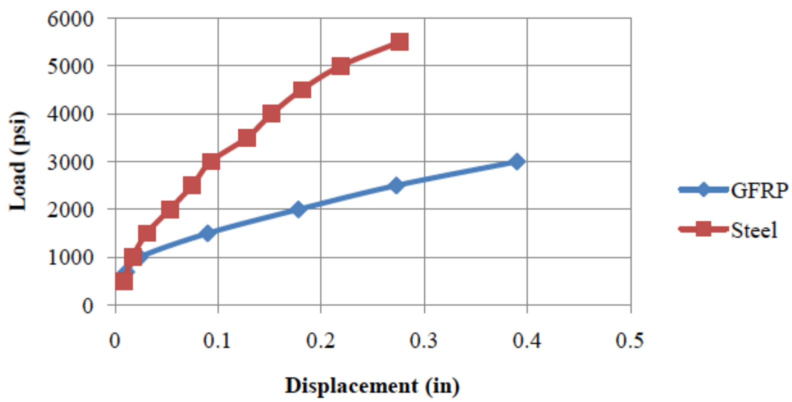
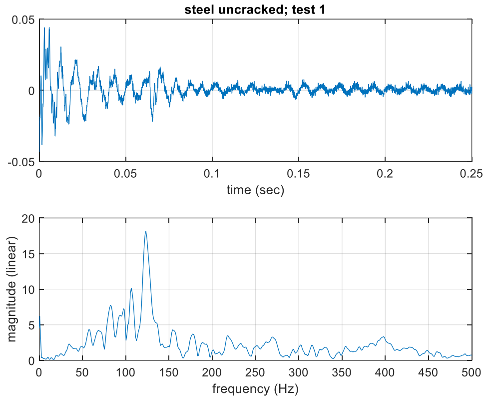


Figure 6. GFRP and steel reinforced concrete beam load deflection plots.

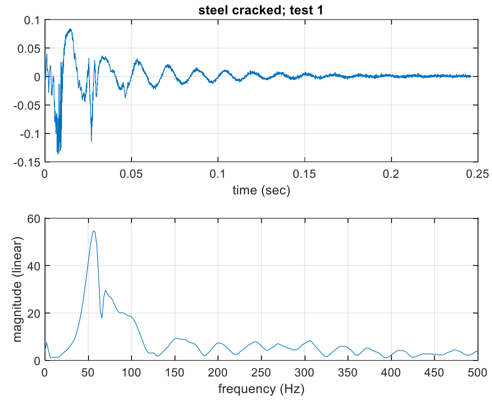
It should be noted that, prior to the start of this project, four concrete beams identical to those constructed by the students were fabricated. Two beams were reinforced with traditional steel and two were reinforced with GFRP bars. One of each beam type was loaded until it had an initial crack; at which time it was immediately unloaded. Following unloading the cracks were not visible. The replicate beams were not loaded. These beams were used for NDE data collection during meeting 11.

In meeting ten, students were introduced to how signal processing techniques can be applied to improve acoustic and speech signals. The main focus was on the equalization technique that enables acoustic reverberation cancellation. Delayed echoes were iteratively cancelled, and their effects were demonstrated using a reverberated speech signal, and the processed sound results exploiting MATLAB were audibly verified at each equalization stage. The students were shown examples of acoustic signal separation and echo cancellation techniques.

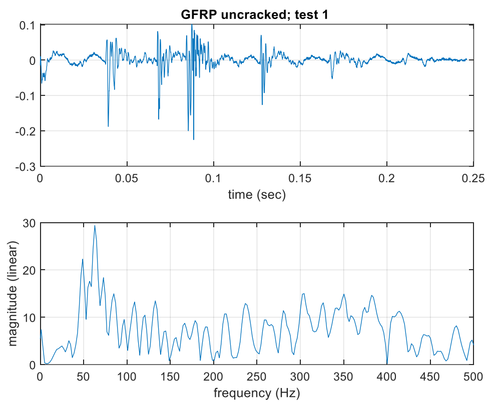
In meeting 11, each team was assigned a time slot to collect vibration data respectively for healthy steel, cracked steel, healthy GFRP, and cracked GFRP reinforced concrete beams using a digital oscilloscope. The students excited the beam with a vibration, and the vibration data for each of the four concrete beams were measured using an accelerometer and recorded on an oscilloscope. The oscilloscope file was transferred to a computer for further processing to identify the difference between different beam materials so that the students could attempt to identify the damaged (cracked) beams. The graphical results are shown in Figure 7. In general, cracking will reduce the beam stiffness, thereby lowering the resonant frequencies. As such, students have a hands-on experience using acoustic technologies to identify structural damage of the concrete beams. The students were required to prepare a report based on data collected to identify the types and conditions of the beams by comparing their results.



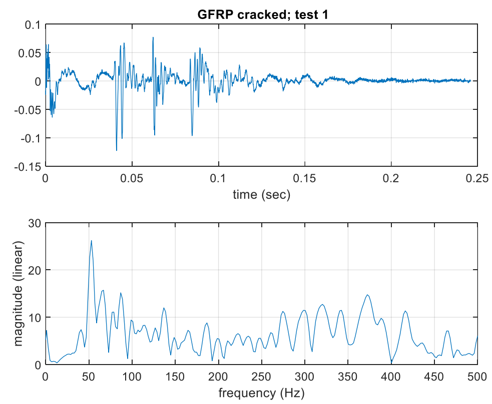
a) Healthy steel



b) Cracked steel



c) Healthy GFRP



d) Cracked GFRP

Figure 7: Comparing the waveforms and spectra of steel and GRFP beams.

Meetings 12 and 13 were dedicated to technical communication. During meeting 12 the following learning outcomes were introduced: Identify different forms of technical communication; identify key elements of “good” and “bad” technical presentations made with PowerPoint; Identify the key elements of thorough technical presentations made via a poster. To meet these objectives a PowerPoint lecture was presented that included over the top “bad” and ineffective slides and examples of “good” of effective slides. To convey effective poster presentations, there were a dozen technical posters from recent undergraduate and graduate projects. Students were given 15 minutes to review the posters and take notes on the pros and cons of each poster reviewed. The class discussion focused on the common “good” and “bad” themes.

Meeting 13 focused on writing an effective technical report. The importance of effective formatting and the sequence of sections. Each of the following sections were discussed: Cover Sheet, List of Figures, List of Tables, Abstract, Introduction, Theory, Experimental Methodology, Results, Discussion of Results, Conclusions, Appendices, References, Notations, and Example Calculations. The importance of presenting data effectively in tabular and graphical forms was highlighted in both meetings. Students were provided with an example report and provided with strict formatting guidelines, similar to a conference or journal paper.

Meeting 14 was used for administering the university required Course And Teaching Surveys, CATS, for all instructors. Students are required to answer 23 questions about the course and teaching. Responses to the statements are given on a scale of 1 to 5 as follows: (5) Strongly Agree; (4) Agree; (3) Neutral; (2) Disagree; (1) Strongly Disagree. The results of this assessment are made available to the faculty after the completion of the semester and are reported in the following section. Students were given half of the period to practice their poster presentations.

Meeting 15 was a conference-style poster presentation by two of the six engineering freshman projects. Four of the six projects involved a competition and chose not to participate in the poster presentation event. Of note, based on this initial success of the conference-style event, it became mandatory that all freshmen groups participate. Project posters were displayed through the four levels of the Center for Engineering Education and Research building and guests freely roam the halls to view the posters and talk with the freshmen. All faculty, staff, undergraduate students, and graduate students were invited to the two-hour event. Selected faculty and graduate students not involved in the class were invited to formally judge the posters. Figure 8 presents two of the posters for the acoustic project.

Figure 8: Example Freshman Acoustic Project Posters

STUDENT ASSESSMENT AND FEEDBACK

The CATS data for all of the projects in EGR 1200 were generally positive. Table 2 presents the average score and standard deviation for the 6 projects with respect to the following: Hard work was required, the material was intellectually stimulating, I learned a great deal, and overall value of the course. The CATS were collected for each course section and for each course instructor. In total there were 21 specific assessments used to create Table 2. Section sizes average 25 students.

Table 2. Student Evaluation

Course And Teacher Survey Question	Mean of All Projects	Stand. Dev.	Mean of Acoustic Project*
Hard work is required to get good grades in this course	4.27	0.33	**4.45**
I found the course intellectually stimulating	4.25	0.32	**4.55**
I learned a great deal in this course	4.18	0.35	**4.50**
Overall value (Try to set aside your feelings about the instructor)	4.13	0.35	**4.40**

* The civil engineering professor's average CATS data for the two sections are used herein.

Many tangible positive outcomes resulted from this multidisciplinary forensic focused freshman initiative. The assessment data clearly shows that the forensic-based acoustic project was nearly one standard deviation above the other projects in terms of difficulty, intellectual stimulation, learning, and overall value. Additionally, students indicated that the goals of the course were clear, 4.6/5.0, and class time was used effectively, 4.5/5.0. These scores were above the 75th percentile for the courses taught in the College of Engineering.

Written comments on the CATS were limited. The most common response was that students liked the interactive/hands-on experiences. Many students noted that the lab activities were their favorite part of the course. There were multiple comments about the amount of work compared to other projects and courses. The data verifies this student perception as the CATS asks specifically how many hours a week outside of class did students spend doing work for this course, with the following scale: (5) 9 or more hours; (4) 7-8 hours; (3) 5-6 hours; (2) 3-4 hours; (1) Less than 3 hours. The average for the course was 2.7, while the mean for all courses taught in the College of Engineering was 2.0 and the 75th percentile was 2.3.

While the students noted the significant workload, many referenced that they felt that they learned a lot more than students in other projects. Some students mentioned the beneficial focus on professional technical communication. Peer evaluation of teams via surveys showed that most teams performed well; however, there were a couple isolated cases of individual nonperformance.

BROADER CONSIDERATIONS

Since its inception this freshman course sequence has continued to be modified and improved upon. Caverly et al. (2015) provide a detailed account of the lessons-learned in working with first-year engineering students during the first six years that the first-year experience has been taught. A discussion of an assessment tool based on pre- and post-testing to gauge student performance in selected areas of the course and the results of this assessment tool and how it is being used in course improvement is included. The average freshman engineer retention for the 13 years prior to starting this new project-based curriculum was an impressive 84.8%. In the eleven years since its inception, retention has improved to 92.3%. This data was not collected on a per project basis; consequently, conclusions for the project described herein cannot be made.

In developing any freshman program balancing the workload of faculty and students must be considered. Significant effort was required to achieve a high-level education product that balanced three disciplines. Ultimately, the use of three faculty members in two sections of one freshman project was deemed unsustainable by the college administration. Future freshman projects were team taught by only two instructors and consequently focus on only two engineering disciplines. From the student experience it is also necessary to balance workload and ensure grading consistency across projects. A cost cutting casualty was the poster boards. In subsequent years students were forced to print 8 ½" x 11" sheets and tape them together. This decision was not popular with the authors or the students.

COVID-19 has had a dramatic impact on teaching format and learning, especially on laboratory-intensive experiences. Hands-on learning is still required in our discipline. Videos cannot replace the experience of constructing formwork, mapping cracks, and applying acoustic technologies in person. To offer a safe and socially distant environment, it is recommended that the lecture components of this project be recorded and offered in an inverted format. Students would be offered personal protective equipment and the lecture time freed up can then be used to have additional time in the lab with smaller groups.

SUMMARY AND CONCLUSION

Many tangible positive outcomes resulted from this multidisciplinary forensic focused freshman initiative. The use of acoustic technologies in material identification and flaw detection creates a realistic backdrop for multidisciplinary engineering. The project described herein served to intellectually stimulate freshman, improve learning, and impart useful lifelong technical communication skills. Data showed that freshman retention has improved as a result of the project-based freshman curricula.

ACKNOWLEDGEMENTS

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