AC 2010-2211: A UNIQUE UNDERGRADUATE LABORATORY-BASED COURSE IN ENGINEERING FAILURE

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A Unique Undergraduate Laboratory-Based Course In Engineering Failure

Abstract

A unique laboratory-based course in engineering failure has been created for undergraduate aerospace and mechanical engineering students. This is a one semester, three-credit hour upper-level technical elective in the Aerospace and Mechanical Engineering Department at Embry-Riddle Aeronautical University in Prescott, Arizona. The course is team-taught and the emphasis is on structural and materials failure mechanisms, highlighting the aerospace industry. The course is composed of learning modules including advanced fatigue and fracture, thermo-mechanical failure, fastener failure, wear, corrosion, impact, composite materials failure, statistical analysis of failures, non-destructive evaluation (NDE), and structural health monitoring. Typically, these topics are not presented in undergraduate engineering degree programs, especially in a laboratory-based format. A significant amount of new learning materials has been created and is being made publically available through course webpages. In addition, student learning assessments and project evaluation tools are being constructed, including a short concept inventory exam. Select portions of the laboratory component are being assembled into a module on engineering failure for the yearly Aerospace Engineering Summer Camp held at the Prescott campus of Embry-Riddle, exposing high school students to advanced laboratory equipment and a range of engineering concepts. Select details of the course content, new learning materials, and a summary of the assessment tools and mid-project evaluations are provided in this paper.

Introduction

Recent and emergent developments in technology, together with changes in the social and professional context of engineering, generate continuing challenges for engineering practitioners and consequently for engineering education as well. Engineering education must be realigned to provide adequate knowledge for the students and prepare them to enter the engineering profession[1]. Considering the often weak linkage between engineering education and practice, effort needs to be placed in creating courses that better support anticipated future workplace requirements. In light of this issue, and considering students' learning styles, hands-on interactive engineering courses should be developed that introduce undergraduate students to real-world problems that otherwise would be addressed in a lecture-based course with only cursory discussion. Moreover, such courses can initiate improved engineering problem-solving and encourage the examination of related science, technology, engineering, and mathematics (STEM) disciplines.

With this mindset, the authors wrote a proposal to the National Science Foundation (NSF) Course, Curriculum, and Laboratory Improvement (CCLI) program to create a new and unique laboratory-based course in engineering failure mechanisms. The course syllabus is influenced by the skills of two of the authors of this paper, Lanning and Lestari, and the course structure is adopted to fit the learning environment of the university at which this work is being conducted.

The Embry-Riddle Aeronautical University environment

The Aerospace and Mechanical Engineering undergraduate degree programs at Embry-Riddle Aeronautical University (ERAU) in Prescott, Arizona, are four-year undergraduate engineering degree programs; there is no graduate engineering degree program. The Aerospace Engineering (AE) degree program is ABET accredited, and the Mechanical Engineering (ME) degree program, which is new on the Prescott campus, will undergo its first ABET accreditation visit during the autumn of 2010. Embry-Riddle might be considered a "teaching institution," where emphasis is placed on faculty-student interaction, design experiences, and hands-on laboratory learning. Design projects are placed throughout the degree program starting from the freshman year[2], culminating in an intensive two-semester design sequence during the senior year[3]. Machine shop and laboratory testing skills are among those valued in these degree programs, especially in conjunction with design-focused coursework. Aerospace engineering students specialize in either aircraft design or spacecraft design, and the recently-formed ME degree program has senior design specializations in air-breathing propulsion and robotics, both tailored to the aerospace industry.

A relatively new 20,000 square foot manufacturing and laboratory facility opened in May 2006[4], dedicated to the AE and ME degree programs. This allows students to access equipment that in large part is unavailable to undergraduate engineering students at many other universities. Features of the facility include a machine shop with adjoining light fabrication spaces (the latter for after-hours work), rapid prototyping capabilities, an astronautics lab with shaker tables and vacuum chambers and an air bearing, multiple load frames as well as a large reaction frame for large-scale structural testing, and a materials science and microscopy suite. Wind tunnel facilities are housed in a nearby facility. Students are expected to become reasonably competent at operating laboratory equipment, such as wind tunnels, load frames, and scanning electron microscopes (SEM), to which they would receive minimal exposure elsewhere, and we believe this makes ERAU attractive to undergraduate students and somewhat unique. Within this context of laboratory-supported and hands-on engineering education, the authors created this unique course.

Course in engineering failure

The title of the new three-credit hour upper-level technical elective is *Aerospace Engineering Failure*. The lecture-laboratory format is modeled after a required Materials Science for Engineers course; the lecture is held twice a week for a duration of one hour (worth two credit hours) and the laboratory is conducted once each week for two hours and forty minutes (worth one credit hour). During the Autumn 2009 semester, the lecture was held on Monday and Wednesday afternoons and the laboratory was conducted on Thursdays. The course was team-taught; the PI (Lanning) conducted approximately the first two-thirds of the lectures and laboratory sessions, and the Co-PI (Lestari) conducted approximately the last one-third of the course.

The prerequisite course for *Aerospace Engineering Failure* course is the first-semester junior level Aircraft Structures I. From this prerequisite course, students are expected to have a knowledge of basic fatigue and fracture concepts, stress and strain failure criteria, and finite element analysis. It is desirable that the required Engineering Materials Science with Laboratory course be a prerequisite for *Aerospace Engineering Failure*. However, a fair number of students put off this engineering materials course until their very last semesters in the degree programs. Therefore, to allow for adequate undergraduate enrollment in this new elective, prerequisites must be kept to a minimum.

Students receive separate grades for the lecture and laboratory portions of *Aerospace Engineering Failure*. The lecture grade consists of scores from homework, scheduled quizzes, one midterm, and a final exam. The laboratory grade is based upon assignments following most laboratory experiments, the submission of an electronic portfolio of all laboratory work at the end of the semester, and the construction of a course webpage for the purpose of publically presenting a subset of laboratory results (to be made available to the general public at aerospacefailure.erau.edu). Table 1 shows the makeup for the lecture grade, and Table 2 shows the makeup for the laboratory grade.

Table 1: Makeup of lecture grade

Graded event	**Percentage of final grade**
Homeworks (7 total)	20%
Scheduled quizzes (6 total)	20%
One midterm	30%
Final exam	30%

Table 2: Makeup of laboratory grade

Graded event	**Points towards final grade**
Written laboratory assignments (7 total)	Between 25 and 50 points each
End-of-semester portfolio	25
Laboratory website assignment	50

While the lecture grade is comprised of percentages, the laboratory grade is comprised of points from individual assignments and end-of-semester events. The latter allowed for flexibility in laboratory assignments as the semester progressed; some laboratory results can vary from what might be expected, especially when running a laboratory-based course for the first time.

Electronic portfolios are collected at the end of the semester. Students are to ensure that all laboratory documents were in digital form, presented in a logical and accessible manner, and documented such that any electronic file in the portfolio, upon being opened by the instructor, will be readily understandable and usable.

The laboratory website project is a work-in-progress. A portion of the fifty (50) points are given for an initial submission. Students, working in groups of two or three, submit results and commentary for a single laboratory experiment; each group is assigned a different experiment (four experiments in all submitted during Autumn 2009). A student assistant, hired for this project, posts the results and commentary on the course website (aerospacefailure.erau.edu). The remaining points are assigned when the instructors ask students, this time working individually, to provide critique and updates to ALL of the results posted. This latter portion of this end-of-semester assignment was allocated more points towards the laboratory grade during Autumn 2009 because the instructors found the initial submissions were rather poor. The critiques are given to the laboratory assistant, who places the updated information on the revised webpages. The final intent is to create and maintain a set of course webpages that is readable by the general public, and especially targeted to K-12 students (emphasis on 5-12) to help attract students to STEM fields.

The lecture portion of this new course is in large part meant to ready students for the laboratory sessions. The laboratory work is critical to a thorough study of engineering failure. Students are expected to understand proper testing procedures, such as found in the comprehensive ASTM International (originally American Society for Testing and Materials) standards, and to use state-of-the-art equipment to perform testing and post-failure analyses. Detailed laboratory methodology is required, such as taking accurate dimensions, specimen surface preparation and cleaning, roughness and hardness testing, test planning, and interpretation of results. Fracture surface evaluation for various modes of failure, especially using the scanning electron microscope (SEM), is emphasized in many of the laboratory sessions.

It should be noted that laboratory experiences are critical to achieving ABET accreditation, especially for the ABET plan written by the engineering faculty at the Prescott campus of Embry-Riddle. However, since this course is not a required course, but an elective course, it can only serve in a supplementary way towards achieving ABET objectives and outcomes.

The course was first taught during the Autumn 2009 semester. The course will again be taught during the Autumn 2010 semester. It is intended that improvements and revisions to the course learning materials occur during the spring and summer of 2010 in the second year of the NSF CCLI project, and that the course will be taught with some regularity thereafter.

Lecture content

A list of each course module is provided here, by topic, in the intended sequence of presentation. Each module has a duration of one to two weeks. There is no course text, since the authors know of no appropriate text that would satisfy the majority of the goals of this unique course. In fact, this was one of the arguments made by the authors in the proposal requesting NSF support, as an indication of the distinctiveness of this course within undergraduate course catalogs. Additional details of the lecture material are given elsewhere[5].

1. Introduction – A survey of prominent failures and design strategies (fail-safe, safe-life, damage tolerant design, etc.)
2. Stress-life and strain-life fatigue analysis –Stress-life testing, Goodman diagrams, strain controlled testing, and fatigue life predictions
3. Notch fatigue – Stress concentrations, fatigue notch factor, notch sensitivity, and notch size effect, finite element analysis with elastic-plastic straining

4. Crack growth – Stress intensity factor, Paris equation, plastic zone size, overloads and underloads, variable amplitude testing, and crack closure
5. Thermo-mechanical failure – Creep, relaxation, viscoelastic models, and thermal shock
6. Fastener failure – Fastener types, typical failure modes (fastener shear, bearing, shearout, bolt bending, pull-through, etc.), edge distance influence, improperly installed fasteners, and weld efficiency
7. Wear – Fretting, rolling contact, erosion, and the resulting effects on mechanical properties

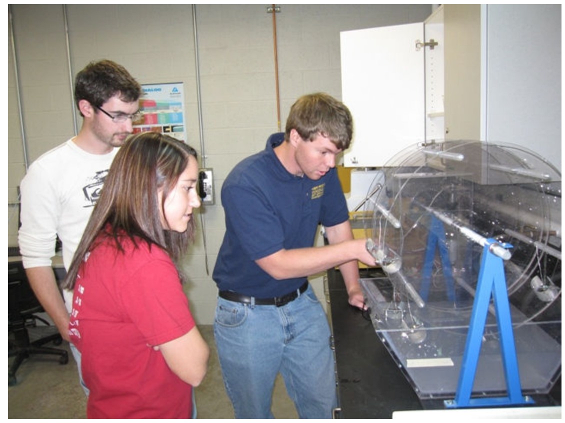

Figure 1. Laboratory device for soaking and drying corrosion test specimens.

8. Corrosion – A summary of Fontana's eight forms of corrosion[6] and subsequently a subset of these forms including galvanic corrosion, stress corrosion cracking (see Figure 1), and hydrogen embrittlement
9. Impact and composites damage – High strain rate loading, impact energy, foreign object damage (FOD), and the various failure modes seen in impacted composites (matrix cracking, fiber pull-out, delamination, and debonding)
10. Statistics for failure – The use of statistical distributions to model failure data and an introduction to elementary reliability theory
11. Nondestructive evaluation – Introduction to non-destructive evaluation (NDE) techniques, including visual inspection, liquid penetrant, magnetic particle inspection, eddy current, ultrasonic, acoustic emission, shearography, and laser ultrasonic methods
12. Structural health monitoring (SHM) and aging aircraft – Introduction to basic theory and concepts of SHM methods and a survey of SHM techniques, (vibration based, wave propagation based, acoustic based, and impedance based, as well as several sensor and actuator technologies)

Laboratory content

Since in-laboratory learning is perhaps the primary objective of this new course, the lecture content is in large part designed to support this goal. While most of the learning modules listed above have accompanying laboratories, a few do not. The laboratory experiments may change in the future as the course develops and matures. Obviously, it is intended that the laboratory sessions quickly follow the appropriate lectures for continuity. Table 3 provides a summary of the laboratory experiments conducted during the Autumn 2009 semester. Some additional details are provided elsewhere[5].

Table 3: Laboratory experiments conducted during the Autumn 2009 semester

Laboratory	**Duration**
Fracture surface features of various materials and loading conditions	Two weeks
Stress-life testing of notched specimens	Two weeks
Fracture toughness testing	One week
Thermo-mechanical relaxation testing	One week
Fastener testing	Two weeks
Stress corrosion testing of aluminum, ASTM G47[7] (see Figure 1)	One week*
Bend testing and statistics of multiple glass slides	One week
A-scan and dye penetrant testing for cracks in structures	One week
Eddy current testing for damage in structures	One week
SHM demonstration on impact-damaged composite plates	Two weeks

*Does not include the four to five weeks that samples spent under corrosive conditions

In one or two cases, laboratories overlap so that two laboratory experiments may have been occurring simultaneously, and a few of the laboratories had elements of more than one of the lecture learning modules.

Evaluation

The evaluator for the project is Dr. Shirley Waterhouse, University Director of the Centers for Teaching and Learning Excellence, Office of the Provost, Embry-Riddle Aeronautical University. The Office of the Provost is based on the Daytona Beach, Florida campus, the sister campus to the Prescott, Arizona residential campus. She has been leading the evaluation by preparing assessment tools, monitoring the preparation of learning materials, conducting faculty interviews, and gathering student feedback and leading an end-of-semester student focus group. The evaluation has the following objectives:

1. Monitor the development of the course materials prior to course implementation and develop course evaluation tools
2. Document instructor and student satisfaction with course materials and student achievement
3. Document the positive, as well as negative, effects of learning materials on student learning outcomes
4. Examine the effect of the use of laboratory-based failure modules on reinforcing failure concepts

With regards to Objective 1, Dr. Waterhouse developed several project assessment tools and conducted several teleconferences with the instructors prior to the start of the course, and found that the instructors felt that they generally made adequate preparations for the course, and that the new learning materials were being prepared in a sufficient manner.

To accomplish part of Objective 2, Dr. Waterhouse administered several mid-semester written surveys to both the course instructors and students, and found very positive satisfaction with the new learning materials for *Aerospace Engineering Failure*. Students were especially interested in the ability to perform new and unique laboratory work. The instructors for the course indicated that they believed preparations were generally successful, and they reported end-of-semester general satisfaction with the manner in which the course proceeded. Further, a review of the student portfolios at the end of the semester, as well as a continual review of work submitted for the lecture grade, indicated that the students were meeting a majority of the learning objectives as stated in the syllabus.

The end-of-semester focus group session with Dr. Waterhouse and the students was primary to meeting Objective 3 (and some part of Objective 2). The main topics of the evaluation were categorized as follows: (a) learning tools, (b) resources, (c) laboratory assignments, (d) correlations with previous courses and (e) overall impressions.

A. Learning tools

The students really enjoyed the hands-on experience. They strongly felt that the correlations between the lectures and laboratories were helpful. Additionally, they valued the structure of the course since it brought together elements from various courses in the degree program to provide a global picture of structural engineering. The research-topic style of some homeworks was also well appreciated since it allowed the students to study topics of particular interest. They also suggested having two mid-term exams, instead of only one, to help them focus on a narrower range of course material at a time.

On the other hand, some students felt that it would be beneficial to have the Materials Science as a prerequisite or co-requisite if possible. Furthermore, they considered the amount of homework assignments and lab reports was sometimes overwhelming and certain the instructions in the homework laboratory assignments were unclear and need improvement.

B. Resources

The handouts and lecture PowerPoint slides were regarded as great supplements to the notes and were very useful for completing homework and laboratory assignments. Additional written laboratory resources were considered helpful. Students suggested broadening some of the topics and including more examples and/or photographs of real-life situations in the lecture.

C. Laboratory assignments

The students felt that the lab assignments were very meaningful, extremely helpful in understanding the material, and corresponded well with the lectures. The structure and objective of the assignments were considered well chosen, i.e., not too detailed, not too simple, and emphasizing the key information. They also liked the fact that the laboratories were relevant to current technologies used in industries. They enjoyed performing the work and discussing the applicability of the procedures to industry.

D. Correlations with previous courses

The course was regarded as a combination of several courses they took previously, e.g., Materials Science, Solid Mechanics, Aerospace Structures, and Structures and Instrumentation. They felt that the knowledge from previous courses were sewed together very well in this course and expanded into more real-world applications. They liked the fact that this course brought the knowledge together and had more explanation of engineering rules of thumb.

E. Overall impressions

Overall impressions of this course were very positive, and that the course was enjoyable. The students were very appreciative of the team-teaching that blends the expertise of two professors with their respective specialties. They also felt that the course brought more current information, i.e., cutting-edge technology, to the engineering degree programs. At the same time, the fact that the lecture and laboratories were complementing each other and closely related was considered refreshing and helpful.

Objective 4 will be met during the summer and autumn of 2010, when a short concept-inventory exam will be created and then administered. This will be given to both the students enrolled in *Aerospace Engineering Failure*, as well as to students enrolled in the prerequisite course, Aerospace Structures I, as a method for evaluating student learning of key concepts in structural and materials failure.

Future work and summary

A few short parts of the laboratory component will be presented at the yearly Aerospace Engineering Summer Camps held at the ERAU Prescott campus, to be first conducted in June and July 2010. These engineering camps expose high school students to engineering concepts and advanced laboratory equipment to create interest in science, technology, engineering, and mathematics (STEM) disciplines. The week-long camps lead students through a series of short learning modules including CAD, flight controls, wind tunnel testing, and structures and testing. This final module will be supplemented with a small sub-set of the new learning materials and laboratory exercises. There will be some challenge in streamlining procedures so that each member of a group of nearly twenty high-school students during each week-long camp gets a chance to take part in a structural test, supplemented by some hands-on time preparing and examining a failure surface with the SEM, but the rewards accompanying the use of such equipment by high school students are substantial.

The enrollment of *Aerospace Engineering Failure* was eight students during the Autumn 2009 semester, below the expectations of the instructors. However, the students enrolled were almost all quite strong students. This enrollment allowed for flexibility during the laboratory sessions and close mentorship of each student, both of which are especially useful during the first offering of a new course. *Aerospace Engineering Failure* will be taught again during Autumn 2010, and it is hoped that it will thereafter be taught at regular intervals and eventually incorporated into the ERAU course catalog as a permanent addition to the technical electives available in the AE and ME degree programs. The course website, currently consisting of selected student results from the laboratory as a selection of supplemental handouts, will eventually contain a full range of learning materials developed during this project.

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