A Laboratory-Based Course in Aerospace Engineering Failure

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Abstract

This paper reports on a unique laboratory-based course in aerospace engineering failure created for undergraduate engineering students. The three-credit hour course is intended as an upper-level technical elective for students in the Aerospace and Mechanical Engineering Department at Embry-Riddle Aeronautical University at the Prescott, Arizona campus. The lecture is held twice a week and the two hour and forty minute laboratory is conducted once each week. The emphasis is on structural and materials failure mechanisms, tailored with an emphasis on the aerospace industry. The course is composed of a set of learning modules, and includes advanced fatigue and fracture, thermo-mechanical failure, fastener failure, wear, corrosion, impact of composite materials, statistical analysis of failures, non-destructive evaluation (NDE), and structural health monitoring. Typically, these topics are not presented in most undergraduate engineering degree programs. The course has significant "hands-on" learning, and students use equipment such as the scanning electron microscope, hydraulic load frames, and damage detection equipment which are not offered for undergraduate use in most engineering programs. A significant amount of new learning materials has been created and are being made available to the public online, and a select portion of the laboratory component will be assembled into a module to be presented to high school students at the yearly Aerospace Engineering Summer Camp held at Embry-Riddle.

Introduction

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 are close to five hundred students in these two degree programs, most of which are in AE. There are no engineering graduate students at the Prescott campus. 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 summer of 2010.

The Prescott campus of ERAU might be thought of as a "teaching institution," where emphasis in the undergraduate engineering programs is placed on faculty-student interaction, design experiences, and hands-on laboratory learning. Design projects are sprinkled throughout the curriculum starting from the freshman year[1], culminating in a significant and intensive two-semester design, manufacturing, and testing sequence during the senior year[2]. Many of these design experiences require students to spend considerable time in the machine and fabrication shop constructing test articles and additional time in the laboratory completing testing. Aerospace engineering students specialize in either aircraft design or spacecraft design. The recently formed ME degree program is also tailored to have an aerospace flavor, and the senior design specializations are air-breathing propulsion and robotics.

A 20,000 square foot manufacturing and laboratory facility was completed and opened in May 2006[3], and is dedicated solely to the AE and ME degree programs. This facility more than doubles the existing manufacturing and laboratory space for these degree programs, and is both a campus showpiece and a critical tool for implementing the kind of hands-on instruction important to ERAU. In this facility, students have access to equipment not normally available to undergraduate engineering students at most universities; the use of this equipment is regularly incorporated into the engineering curriculum at ERAU. Features 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, several load frames as well as a large reaction frame for structural testing, and a materials science and microscopy suite. Students are expected to become reasonably competent at operating certain laboratory equipment, such as wind tunnels, load frames, and scanning electron microscopes (SEM), to which they would receive minimal exposure at many other universities, and this makes Embry-Riddle unique in this regard.

Within this context, the authors wrote a successful proposal to the National Science Foundation (NSF) to fund the creation of a laboratory-based course on materials and structural failure. The emphasis is on failure modes and related issues that especially pertain to the aerospace industry, primarily because of the overall emphasis on the aerospace industry generated at Embry-Riddle Aeronautical University. The course syllabus is influenced by the technical skills and knowledge of two of the primary authors, Lanning and Lestari.

Course in engineering failure

The name of the new course is *Aerospace Engineering Failure*. The three-credit hour course is an upper-level technical elective for undergraduate students in the Aerospace and Mechanical Engineering Department in the College of Engineering at the Prescott campus of ERAU. The lecture is held twice a week (two credit hours) and the laboratory is conducted once each week for two hours and forty minutes (one credit hour). The prerequisite course for the proposed *Aerospace Engineering Failure* course is the junior level Aircraft Structures I, from which students are expected to have a knowledge of basic fatigue and fracture concepts, stress and strain failure criteria, and finite elements. While it would be desirable, the Engineering Materials Science with Laboratory that is required of both AE and ME students is not a prerequisite. A fair number of students put off this engineering materials course until their very last semester or two, unfortunately. Therefore, to allow for adequate enrollment in this new elective course, 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 accompanying most laboratory topics, the presentation of a subset of laboratory results on the course webpage (to be made available to the general public at aerospacefailure.erau.edu), and the submission of an electronic portfolio of all laboratory work at the end of the semester.

The lecture is in large part meant to ready students for the laboratory sessions. The importance of laboratory work is critical to a proper 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 dimensions, specimen surface preparation and cleaning, strain gage placement, test planning, and interpretation of results. Fracture surface evaluation for various modes of failure, 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 as written by the engineering faculty at the Prescott campus of ERAU. 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 fall 2009 semester. The course will again be taught during the fall 2010 semester. It is intended that improvements and revisions to the course learning materials occur during the spring and summer of 2010, and that the course will be taught with some regularity thereafter.

Course content

A summary of each course module is provided here, by topic, in the intended sequence of presentation. Each module has a duration from one to two weeks. It is intended that the laboratory sessions quickly follow the appropriate lectures for continuity. There is no course text, since the authors know of no appropriate text that would satisfy most 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.

Introduction

An introduction includes an historical perspective of engineering failure, with an emphasis on the aerospace industry, including a survey of prominent failures and comparisons between fail-safe, safe-life, and damage tolerant design strategies. For the laboratory session, an introduction to failure surfaces is performed. A range of failure surfaces are rapidly produced through various loading modes, producing a range of failure surfaces. Macroscopic and microscopic preparation and characterization techniques, including the use of the scanning electron microscope (SEM), is practiced. Students develop a database of fracture surfaces, which is maintained throughout the semester.

Stress-life and strain-life fatigue analysis

Students will have had an approximate two-week introduction to fatigue and fracture mechanics during the prerequisite course, Aircraft Structures I. The aim of the first three weeks of *Aerospace Engineering Failure* is to provide advanced studies in fatigue and fracture mechanics. Stress-life methods are quickly reviewed here. Strain-life methods are usually not covered in the prerequisite course. Monotonic and cyclic stress-strain behavior are therefore discussed, including cyclic hardening and softening, mean stress effects, and the Coffin-Manson relationship[4,5]. The laboratory experiment is intended to consist of cycling cylindrical fatigue specimens (three or four during the course of the week) to failure with maximum stresses above yield, including the generation of hysteresis loops and fatigue parameters from several of the so-called power-laws used for common strain-life analysis. This laboratory session did not occur during fall 2009 semester due to some difficulties in manufacturing appropriate specimens, but will be strongly considered for inclusion when the course is again taught in the fall 2010 semester.

Notch fatigue

Notch analysis in fatigue is a one-hour lecture topic. Stress-life methods, fatigue notch factor, notch sensitivity, and notch size effect are covered. The use of finite element analysis (FEA) to solve certain problems is expected. The laboratory requires the students to stress-life test several notched flat fatigue specimens. The instructors previously tested baseline unnotched specimens of the same material prior to the start of the semester. The students use both data sets to perform a fatigue notch analysis. Students use the SEM to view fatigue striations and the overload region.

Crack growth

A quick review is provided of fracture mechanics concepts learned in the prerequisite course, such as stress intensity factor, fracture toughness, and the Paris equation. The use of common solutions for the stress intensity factor (center-cracked panel, semi-elliptical crack in a plate, etc.) is applied to monotonic and cyclic crack growth problems. The plastic zone size and effect on crack growth are also discussed. The second and third lectures include crack propagation from notches, crack closure concepts, the effect of overloads and underloads, and crack growth under variable amplitude loading. The laboratory requires students to perform crack growth tests with compact tension specimens. The required AE/ME course in Engineering Materials Science, which students may or may not have taken at the time they take *Aerospace Engineering Failure* , currently has a one-week laboratory on the use of direct current potential drop (DCPD) to perform basic crack growth analysis using the Paris equation for several compact-tension (CT) specimens cycled at constant-amplitude loading conditions. The laboratory session in this new course does not assume prior knowledge of crack growth testing. Baseline constant-amplitude crack growth data are be available from testing performed by the instructors prior to the beginning of the semester. The focus will be on crack growth rates influenced by periodic overloads, variable amplitude loading, or some other topic that goes beyond work done in the engineering materials course.

Thermo-mechanical failure

One week is spent on thermo-mechanical failure. The topic is introduced with material properties at elevated temperatures and thermal shock. Creep behavior, creep models, and general viscoelastic behavior is then presented. The laboratory session consists of elevated temperature testing, such as tension testing, relaxation (constant displacement) testing, or creep (constant load) testing. As usual, fracture surfaces are retained for microscopic examination.

Fastener failure

One week is spent on practical aspects of fastener failure. Fastener types, such as various rivets, bolts, and welds are discussed, along with typical failure modes (fastener shear, bearing, shear-out, bolt bending, pull-through, etc.), edge distance influence, improperly installed fasteners, and weld efficiency. Two laboratory sessions are required for manufacturing and testing fasteners. Students manufacture a number of specimens for subsequent testing (Figure 1). Strips of metal or composite material are fastened with various rivets and bolts for axial tension or fatigue testing. Additional variations, implemented on a student-by-student basis, include edge violations, over- and under-driving of rivets, the use of various rivet patterns, flat head versus counter-sunk rivets, and over- and under-tightening of bolts. Mechanical testing of the manufactured specimens is conducted during the second week of the fastener laboratory. Students document the mode of failure for each specimen, compare specimen strengths to predictions based upon both theory discussed in lecture and fastener strength data, and perform microscopy on a subset of the fracture surfaces.

Figure 1. Students constructing fastener test specimens.

Wear

One week is spent on a survey of wear damage. Included topics are various types of wear, fretting, rolling contact, erosion, and the effect of these on mechanical properties. No accompanying laboratory was conducted during the fall semester of 2009, but a future option is to devise a method for inducing a quantifiable amount of abrasive wear on standard dogbone specimens, test in either tension or fatigue, and compare to results from undamaged specimen testing.

Corrosion

One week is spent on failures due to corrosion. A quick summary of the various forms of corrosion (Fontana's eight forms of corrosion[6]) is provided. A subset of these forms of corrosion are discussed in depth: galvanic corrosion, stress corrosion cracking, and hydrogen embrittlement. An experiment on stress corrosion cracking of aluminum alloys following the guidelines from ASTM G47[7] is performed. A student was hired to build a device for alternately soaking and drying the pre-strained specimens (a motorized Ferris-wheel, Figure 2), and ended up building a beautiful fully-functioning test apparatus. Corroded specimens are subsequently failed in tension and fatigue, and predominately compared to uncorroded specimens through examination of the fracture surfaces.

Impact and composites damage

Figure 2. Device for alternating soaking and drying of corrosion test specimens.

One week is spent on impact damage and damage to composite materials, including high strain rate loading, impact energy, foreign object damage (FOD), and the various failure modes seen in a variety of impacted composite materials (matrix cracking, fiber pull-out, delamination, and debonding). The Charpy impact test is mentioned only briefly, since this is a standard topic and laboratory exercise in the required Engineering Materials Science course. Students build several panels from pre-impregnated glass and carbon composite sheets, cure the panels under vacuum bagging in an oven, and then used a simple impactor device to create damage. These damaged plates are then used in a health monitoring experiment (discussed subsequently). The student assistant who built the corrosion device mentioned above has drawn up plans for a drop tower for measured impacting of specimens, to be built prior to the beginning of the fall 2010 semester.

Statistics for failure

Several lectures are spent on the use of statistics for failure analyses. Topics include the use of statistical distributions to model failure data and elementary reliability theory. Example problems with small and large data sets are presented. A one-week laboratory experiment generating a significant amount of failure data is conducted. The fall 2009 semester experiment was the three-point bend testing of glass microscope slides, which could be accomplished numerous times rapidly, generating a data set that can be successfully modeled by various distribution functions and reliability theories.

Nondestructive evaluation

Students are given a one-week introduction to non-destructive evaluation (NDE) techniques, in which several available technologies to identify failure in aircraft structures are discussed. Conventional and advanced NDE technology includes visual inspection, liquid penetrant, magnetic particle inspection, eddy current, ultrasonic, acoustic emission, shearography, and laser ultrasonic methods. The laboratory consists of demonstrations of selected NDE techniques, i.e. liquid penetrant, magnetic particle inspection, eddy current, and ultrasonic, conducted on several metallic test samples with introduced flaws.

Structural health monitoring and aging aircraft

The lectures on NDE serve as a segue for discussions on aging aircraft and structural health monitoring (SHM) issues. The course material is comprised of basic theory and general concepts of SHM methods and an introduction of maintenance concepts for both aging and current aircraft. The students are introduced to a broad range of SHM techniques, e.g. vibration based, wave propagation based, acoustic based, and impedance based, as well as several sensor and actuator technologies. The course materials necessarily must remain simplified for undergraduate engineering students, who in particular may not have been yet exposed to many of the background prerequisite concepts. A one week laboratory on the demonstration of vibration-based SHM technique is conducted using the impacted composite specimens from the earlier laboratory on composite materials failure.

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 campus, the sister campus to the ERAU Prescott residential campus. She has been leading the evaluation through monitoring the preparation of learning materials as well as the preparation of assessment tools, conducting faculty interviews, and leading a student focus group at the end of course implementation. The overall project goal is to monitor the development, and thereafter the adequacy and effectiveness, of new teaching and learning materials developed for *Aerospace Engineering Failure*. The evaluation also pays attention to the use of the laboratory environment to teach and reinforce failure concepts in structural and materials engineering. 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

Details of the timeline for the proposed activities are provided in Table 2. Dates correspond to spring, summer, and autumn semesters at ERAU. A concept inventory exam will be created and used during the fall 2010 semester as part of the overall evaluation.

Evaluations are very positive to date, and suggest that the enrolled students were quite satisfied with the new course, especially with the ability to perform new and unique laboratory work. The instructors for the course (Lanning and Lestari) indicated that they believe preparations were generally successful, and they reported end-of-semester general satisfaction with the way the course has been proceeding. The instructors noted that there is room for improvement with some of the learning materials, to be expected with any new course, and this will occur during the second year of the project in anticipation of teaching the elective course a second time during the fall 2010 semester. The results of the final evaluation, the on-site focus group with enrolled students, will be made available to the instructors after final grades have been submitted for the semester and the Evaluator has written the final evaluation report for the first year (February 2010).

Table 1: Evaluation timeline

Dates	Activity	Participants
Summer 2009	Monitoring and evaluation of preparation of new learning materials and learning assessments	PI, Co-PI, Evaluator, and one student assistant
Week of Sept. 22, 2009	Student survey - evaluation of learning materials, course monitoring	Evaluator and enrolled students
	Instructor survey - evaluation of learning materials, course monitoring	Evaluator , PI and Co-PI
Week of Oct. 21, 2009	Student survey - evaluation of learning materials, course monitoring	Evaluator and enrolled students
	Instructor survey - evaluation of learning materials, course monitoring	Evaluator , PI and Co-PI
December 2, 2009	On-site focus group discussion with enrolled students	Evaluator and enrolled students
February 2010	Final report from Evaluator	Evaluator , PI and Co-PI
Spring to Summer 2010	Creation of concept inventory exam	PI and Co-PI
Fall 2010	Administer concept inventory exam	PI and Co-PI

Future work and summary

Select portions of the laboratory component are being assembled into a module on engineering failure for the yearly Aerospace Engineering Summer Camp held at Embry-Riddle, which exposes high school students to advanced laboratory equipment and creates excitement and interest in science, technology, engineering, and mathematics (STEM) disciplines. This will be first conducted in June 2010.

The challenges associated with this new course are much the same as the challenges of any new course, although the focus on strong student participation in the laboratory environment necessarily leads to an increased workload in preparation for the new and unique laboratory experiments and exercises. The enrollment of this course ended up at eight students during the fall 2009 semester, which was below the expectations of the instructors. However, the students enrolled were almost all quite strong students, and the smaller enrollment allowed for close guidance throughout the course. Also, this allowed for more flexibility during the laboratory sessions when various tasks took longer than expected.

Aerospace Engineering Failure will be taught again during the fall semester of 2010, and it is hoped that it will thereafter be taught at regular intervals and eventually incorporated into the ERAU Prescott campus academic catalog as a permanent addition to the technical electives offered in the AE and ME degree programs. The course website, which at this time primarily consists of selected student results from the laboratory, will eventually contain a full range of learning materials developed during this project.

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