Failure Analysis – A Technology Enhanced Capstone Experience for Materials Engineers

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Abstract:

The evolution of a highly successful curricular experiment is documented. This unique course is an ancestor to many of the "mechanical dissection" approaches to engineering education which are so very popular today. The paper highlights the value of the course as a culminating experience for the materials undergraduate. It treats the soliciting and selection of projects, the development of team approaches, the analysis of failures and the synthesis of failure hypothesis. The student's presentation of results are discussed, both written and oral. Creation of realistic mock "court-room" and "board-room" environments is treated. The use of case-study approaches in conjunction with modern educational technology is discussed. This presentation is meant to help others develop similar courses or help others create "failure analysis" modules to use in existing courses.

I) Introduction *"O Tempora! O Mores!"*

The question of the character of engineering education has been examined many times in the past fifty years. The most compelling feature of these studies is the uncanny similarity of their recommendations, the remarkable constancy of what is perceived to be important in engineering education. Though each study reflects the challenges of its age, and therefore suggests stronger emphasis in one area or another, the desired threads in the engineering fabric appear to be agreed on and immutable. The specific actions suggested in the reports can often be interpreted simply as efforts to provide damping corrections to prior over or under emphases among this fixed set of characteristics.

What, then, characterizes our age and drives our approach to engineering education? The dominant forces are the globalization of the economy, the end of the cold war, the explosion of information technologies reduced funding for higher education and changing demographics. New responses include an understanding that each institution must respond to challenges in character, that is in a way that reflects its own special mission. Furthermore, there is new emphasis on outcomes of the educational process, and the use of assessment as a feedback tool to improve that process. It is then the development of a systems approach to engineering education itself, rooted in a strong awareness of customer and context.

These changes are evident and fully expressed in the approach to engineering accreditation taken by the Accreditation Board for Engineering and Technology (ABET) in their Engineering Criteria 2000. This document requires that engineering programs demonstrate that graduates possess 1) an ability to apply knowledge of mathematics, science and engineering, 2) an ability to design and conduct experiments as well as to analyze and interpret data, 3) an ability to design a system, component or process to meet desired needs, 4) an ability to function in multidisciplinary teams, 5) an ability to identify, formulate and solve engineering problems, 6) an understanding of professional and ethical responsibility, 7) an ability to communicate effectively, 8) the broad education necessary to understand the impact of engineering solutions in a global/societal context, 9) a recognition of the need for and an ability to engage in life long learning, 10) a knowledge of contemporary issues, and 11) an ability to use the techniques, skills and modern engineering tools necessary for engineering practice. The resonance that these characteristics have with the desired attributes of an engineer published by one major consumer of engineering talent is gratifying, these attributes are a good understanding of engineering science fundamentals, a good understanding of design and manufacturing processes, a multi-disciplinary systems perspective, a basic understanding of the context in which engineering is practiced, good communication skills, high ethical standards, an ability to think both critically and creatively, independently and cooperatively, flexibility, curiosity and a desire for life long learning, and a profound understanding of the importance of teamwork. Clearly, the durability of these characteristics is based in their acceptance by academia and industry.

Notably, both ABET and the Industrial has distanced themselves from specifying the curriculum that individual institutions employ to accomplish these outcomes. They are seen as participants that can advise the process. Clearly then, one difference among educational institutions will be the methodology used to achieve these goals. The methodology will reflect the mission of the institution and the needs of its students and faculty and its community. The mission of the College of Engineering is to educate its graduate and undergraduate students for careers of leadership and distinction in engineering and related fields, to educate graduates who are able to be productive members of the workforce immediately, to educate graduates who are able to seek advanced degrees, to educate all students at the university so that they develop an understanding of technical issues which will allow them to participate meaningfully in the technology driven society of the Twenty-first Century, to apply technology to serve the needs of society and to benefit the public through service to industry, government and professional organizations. The College will accomplish its mission by adhering to three broad goals, it will Empower the College Constituents, it will Provide for Programmatic Excellence and it will Establish and Maintain Linkages to key Partners.

We have created an upper division capstone course treating Failure Analysis which promotes the development of these skills and provides a vehicle for their demonstration. The course is based on a systems approach to engineering challenges. The course provides a laboratory setting for active learning in which students can demonstrate a basic understanding of engineering science, and of design and manufacturing, of experimental design and data analysis. Furthermore, students are encouraged to exhibit skill in the communication of ideas, initiative in acquiring information and knowledge, and a familiarity with contemporary tools, all in a team based open-ended format. Besides creating a forum for the development and expression of the budding engineering professionalism in first quarter seniors, the course appeals to the “Monday morning quarterback” in each of us. It takes advantage of the National News and National Enquirer syndromes; it panders to the innate human interest in the “bad news”, the “dark side”. It is popular with students for the same reason Mario Salvadori’s book “Why Buildings Fall Down” outsells his “Why Buildings Stand Up” two to one.

In the historical perspective, the cause of advancing engineering excellence applies the algorithm of learning from ones mistakes and incorporating that new understanding into the body of engineering knowledge. On several levels the failure analysis course implemented as a capstone by Cal Poly’s Materials Engineering department, which dates back to the late fifties, reflects this paradigm. The course has evolved to reflect the changes in technology over that period.

Course Content

As a capstone course, failure analysis is intended to promote a synthesis of subjects already covered. In this course the students learn to apply the disciplines from many courses, to synthesize the many partial answers given by statics, dynamics, mechanical metallurgy, metallography, NDE, physical metallurgy, strength of materials and other courses or experiences to solve a problem. They discover that failures are often not simple, and as such may not have a single unique cause, but a chain of events leading to the failure. To learn that engineering is often open ended, an on going process of improvement.

Thus one of the main goals of this course is to give the student a basic method to approach a failure analysis. To use the knowledge from previous engineering classes combined with their own experiences and common sense to answer the questions of what, how, and why a failure happened. And then, drawing on this knowledge and their own creativity to recommend ways to prevent future occurrences. Another objective of the course is to broaden the student’s thinking, to consider many approaches to a problem and the possibility of more than one unique solution. A third goal is for the students to learn to develop a plan and then to implement this plan documenting the objectives and results. Which leads to the final goal of the course, for the students to communicate their work in a professional manor, both written and orally.

Course Implementation

The course consists of a one hour lecture and two three hour labs a week. Currently the course uses Metallurgical *Failure Analysis* by Brooks and Choudhury as the primary text. *ASM Handbook Volume 11 Failure Analysis and*

Prevention and Wulpi's *Understanding How Components Fail* are used as principal references. It is from these references that the basic approach to analyzing a failure is synthesized.

One of the first subjects covered in lecture is the importance of obtaining a part history including the standards it was manufactured / used under. This leads to a discussion of various types of standards and how to research them, and a team project to find standards on given samples. Further lectures review fractography and identification of fracture surfaces. Methods of analyzing failures and materials using various instruments such as SEM, EDS, XRD, FTIR, and others are discussed. This leads to team homework projects on given samples. Students are asked to identify their "mystery artifact", determine how it was made and how it failed, and to determine the necessary procedures to prove their theory. In addition, guest speakers, from industry, talk about their experiences and present case studies.

In the lab there are no set experiments. Each student does a complete failure analysis on a part or device that has failed in service. Utilizing an outline of basic approaches synthesized from Vol. 11 and Wulpi the student plans and implements an analysis culminating in an oral presentation to the class and faculty members and a written report.

With everyone doing a unique project, there are no predetermined steps to complete the project. The students must learn self-reliance, the instructor acts more as a guide or manager pointing them to the resources that will answer their questions rather than supplying the answers. The students learn to stop, think, research, and then implement a plan.

The amount of work required in such a project is deceiving, students are tempted to procrastinate. To counter this and to get the students moving, there is a peer review starting the end of the 2nd week. In a brief, (5 minute), informal presentation the student must summarize design, operation, and planned approach to analysis. They must explain their project in terms of the material, manufacturing processes, loading and service conditions at time of failure. Class members critique one another in an open form peer engineer review. The following week a memo is submitted by the student outlining his project and his plan for the investigation. The memo includes what has been done to date, what is in progress, what is planed and a timetable for the investigation.

In the course of his investigation the student is expected to utilize all possible sources for information. Obvious sources are journals and case histories in the library, as well as faculty from other departments. However, library searches are not enough, the student is expected to use additional sources including personal contact with people in industry, internet searches, contact with the manufacturer and service technicians and so on.

The final one and one-half weeks are devoted to presentations. Each student must give a presentation to the class and faculty members. All faculty members from the department are invited to attend the presentations. Students are required to use a computer based presentation package such as PowerPoint to make their presentations. The student has the choice of using overhead transparencies or a data projector for visual aids. The presentation setting is a boardroom conference where as a consultant the students are presenting their findings to engineering staff and management. During the question and answer period the students go first, followed by the faculty. The students then has three days to complete their report, allowing time for revisions prompted by revelations bestowed by the audience during the presentation.

Industry rarely has enough equipment to support the uncoordinated efforts of employees working on parrallel projects – the university certainly does not. It is a physical impossibility for 24 students to effectively use department resources without excellent communication. Equipment scheduling varies from first come first served with the macro cameras to sign up sheets for the SEM. Test using other equipment such as X-ray inspection must be requested and scheduled in advance. This encourages parallel action and planning by the students.

Failure projects are ferreted from many sources, their collection is an endless job. Projects treat all classes of matertials and often materials in combination. One-quarter to one-third of the students provide their own projects for home, work or co-op experiences. These are often particularly instructive because the students have an interest in the project *a priori* and are often solving a problem for their family or their employer. Another source is alumni in industry, who express their appreciation and support of the course by providing interesting failures encountered in the workplace and serving as industrial referees during reporting stages. Another source is local industry; we have received many projects from a heavy construction firm, auto garages, and general aviation shops. These are particularly good because they provide the students an industry contact to work with to develop needed background information. Often a copy of the final report is given to the source company.

Assessment: *"Show me the quan."*
Assessment methodology has changed as the purpose of assessment has evolved. The course uses different assessment tools to accomplish internal formative and summative assessments. Faculty are asked to map the goals of the course onto the goals and objectives of the College and to correlate activities to desired outcomes for students. These are later compared to the student's assessment of the opportunities provided in the course and of the effectiveness of the instructors teaching style. Faculty assessment of student performance is then connected to these measures.

- **Course and Module Profiles**. Faculty members have completed a course profile. This describes the extent to which the different course activities emphasize the various course objectives, the desired student abilities and the specific learning goals.
- **Student Surveys** were used to gage student satisfaction at the close of the course. These surveys were reconciled with the course profiles provided by faculty to see if the faculty objectives were met and with the performance assessments to see if there was correlation between satisfaction and student levels of attainment.
- **Tests and Homework**. Relatively straightforward tests and homework are given, primarily as a tool for formative assessment and to help keep students on track.
- **Laboratory Portfolios**. Students are required to keep a notebook/working journal. This notebook documents the progression of the failure analysis. The notebook is meant to be of "subpeonable" quality and is graded as such.
- **Scenario-Based Assignments.** These tools are based on scenarios generated by faculty and industry advisors that describe typical or critical situations faced by staff in industry. The assignment is a short scenario that sets up the context of an engineering failure--students are asked to describe the process they would engage in to analyze and correct the problem.
- **Failure Analysis Project Report -** Reports will be used to evaluate skill development over the course of a major failure analysis project. The report includes a proposal, an ongoing student log of problems and solutions, and a technical report replete with executive summary. Students are required to give a final oral report that employs visual aids and must include posters. Students present this report to an audience of other students, faculty from several departments and industrial representatives. The process follows a design/failure review format, students answer questions from the audience at the completion of their presentation. Next quarter we will begin an experimental format in a legal setting. Failures will be provided to students in a legal context, treating liabilities, patent infringements, etc… Lawyers on staff will take "depositions" and students will present testimony to a "jury" and be cross-examined on their statements.
- **Taped Observations.** Videotape captures students' oral presentation abilities. In conjunction with the taping, students will complete self and peer evaluations. In combination, these tools will create a multi-dimensional picture of teamwork skills and provide a method for cross-validation of the tools. Students often use these videos as vehicles of demonstration in interviews with prospective employers.
- **Self/Peer Assessments.** These tools create a multi-dimensional picture of teamwork skills. They are used alone and in combination with other assessment tools to report self-proficiency and assign performance ratings to peers. Self/peer reports are useful both for assessment and for facilitating learning by making students more aware of, and responsible for their own development.

Conclusion
This course resonates with a number of the major tenets of Colleges pedagogy, ***Faculty Attention to Undergraduates*** - it provides students with ample opportunity to interact with faculty formally and informally in the classroom and lab. ***Industrial Participation in the Curriculum*** – industry provides the fodder for the student projects and sponsors portions of the course. Industry representatives provide guest lectures and participate in evaluation. The course thus provides excellent ***Linkage***. ***Laboratory Emphasis in the Curriculum*** – students design and carry out their analysis in the laboratory setting. ***Emphasis on Summer Jobs and Coop Experiences*** –

many of the failures studied are brought by students who have participated in professional experience. ***Interdisciplinary Emphasis*** – students draw upon their entire educational experience, and the experience of their teammates, to complete this course. ***Capstone Experience*** - The course provides an undergraduate capstone experience for each student. The experience provides an excellent segue from the discipline dominated world of academia to the function dominated world of industry. ***Communication*** – the course stresses communication skills, verbal, visual and written. It provides opportunities to hone these skills with fellow students, faculty and industry representatives in a variety of settings.

An Educational Failure Analysis

Many universities are discovering what is not working in education, but as pointed out in ***In Search of Excellence*** "....building a new capability is not the simple converse of describing and understanding what's not working, just as designing a good bridge takes more than understanding why some bridges fail." Clearly Cal Poly has discovered a formula that works, built upon its faculty's understanding of the gestalt of engineering education. The intensity of the faculty commitment to undergraduate education is the mark of our excellent institution. It is a manifest of the genuine care faculty and staff have for both students (our product and immediate customer) and industry (our consumer).

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