AC 2011-2105: EVALUATING PREREQUISITE KNOWLEDGE USING A CONCEPT INVENTORY FOR AN ENGINEERING FAILURE COURSE

David B. Lanning, Embry-Riddle Aeronautical University, Prescott

Dr. David B. Lanning is an Associate Professor in the Aerospace and Mechanical Engineering Department of Embry-Riddle Aeronautical University at Prescott, Arizona.

Wahyu Lestari, Embry-Riddle Aeronautical University, Prescott

Dr. Lestari is an Associate Professor at the Aerospace and Mechanical Engineering Department at Embry-Riddle Aeronautical University in Prescott, Arizona.

Shirley Anne Waterhouse, Embry-Riddle Aeronautical University

Dr. Shirley Waterhouse is the Senior Director of the Office of Academic Excellence and Innovation at Embry-Riddle Aeronautical University in Daytona Beach, Florida. She is also the author of six books, and the most recent is The Power of eLearning: The Essential Guide for Teaching in the Digital Age, Allyn and Bacon Publishers, 2005.

© American Society for Engineering Education, 2011
Abstract

A unique laboratory-based course in engineering failure, entitled *Aerospace Engineering Failure*, has been developed to prepare undergraduate students to design structures and materials for challenging engineering environments. The course content includes advanced fatigue and fracture, thermo-mechanical failure, fastener failure, wear, select types of corrosion, impact damage, statistical evaluation of failures, non-destructive evaluation (NDE), and an introduction to structural health monitoring. Weekly hands-on laboratory sessions accompany the majority of these topics. Prerequisite knowledge includes topics of stress state, static failure theories and related failure surfaces, and basic fatigue and fracture mechanics. A concept inventory exam has been drafted, in multiple-choice format, to evaluate the students’ depth of understanding of the prerequisite concepts. The short exam is given to the students at the beginning of the semester, and again at the end of the semester, the latter to assess whether or not these concepts have been reinforced in this new course. Students enrolled in the aerospace structures course that is the prerequisite to *Aerospace Engineering Failure* were also given the concept inventory exam. This paper includes a description of the new course in engineering failure, and presents question samples as well as student results from the concept inventory exam.

Introduction

Prerequisite knowledge is often critical for a student to be successful in his or her chosen degree program. For instance, a strong background from a course in statics is crucial to performing well in subsequent courses in solid mechanics and dynamics (and many other follow-on courses, for that matter). A lack of prerequisite knowledge not only affects the student, but also an entire class if the instructor has to expend valuable time repeating concepts that should have been learned elsewhere.

One of the authors has been attempting to bolster students’ prerequisite knowledge through the use of a prerequisite skills exam in his solid mechanics courses. This exam is used to help students review and achieve a level of competence in certain skills, primarily first taught in a course on statics. However, addressing the skills of students is only one component of needed knowledge. Another part of that knowledge, which isn’t quite addressed in this skills-based exam, is whether or not the student fully understands the reasoning and concepts of a particular subject matter.

The Prescott, Arizona campus of Embry-Riddle Aeronautical University specializes in undergraduate education, with a current enrollment of close to 1700 students. The College of Engineering houses the largest department at the campus, the Aerospace and Mechanical Engineering Department. All engineering programs at the Prescott campus are strictly
undergraduate degree programs. The department strives to provide close student-faculty instruction and mentorship, significant design experiences, and a hands-on learning environment. However, the organizing structure of the degree programs is not particularly unusual, and many of the elements in the curriculum are similar to those in many other four-year degree programs in aerospace and mechanical engineering.

With a specialty in undergraduate education as at Embry-Riddle, there comes a natural commitment to improving student outcomes. A general view exists that students, at least the ones that manage to be successful into their junior and senior year and are more-or-less on track to graduate, develop a certain level of competence at problem solving, but often do not understand the general concepts behind certain problems well enough to extend those concepts to new situations. This is especially a difficulty with marginal and struggling students. Evaluating the level to which students understand certain concepts is often complicated. One tool for such evaluation that has found some use in recent years is the concept inventory exam.

**Concept inventory exams**

A concept inventory exam is a tool to aid learning, and can be viewed as a tool to assist and evaluate not only the student, but also the instructor. A number of such exams have been devised, including several in the current authors’ areas of interest. Some of the earlier work leading to such tools was the Force Concept Inventory, developed to assess physics students’ understanding of Newtonian mechanics. This work has been driven by the interest in developing new tools for assessment of student learning. This style of exam often utilizes a multiple-choice format, where a number of seemingly easy questions probe student understanding of basic concepts. If an exam is carefully written, a statistically significant number of students complete the exam, and the instructor pays attention to trends, the instructor can uncover weaknesses. These weaknesses might be due to insufficient coverage of a topic in a course, but also might show a number of students holding incorrect preconceived notions of which the instructor was unaware. The instructor is then better able to address such notions.

Such exams may not be as easy to write as one might suspect, if the goal is to uncover incorrect underlying notions that student bring with them to the classroom. Much iteration of the language of the questions and answers can be warranted. One of the current authors became particularly interested in this style of exam after he recently gave his class one of the aforementioned concept inventory exams on solid mechanics written by other researchers. A new course in engineering failure was to be developed by the authors of the current paper, and this seemed like an appropriate venue for such an exam.

**Course in engineering failure**

A new three-credit hour upper-level technical elective, created through a National Science Foundation CCLI (Course, Curriculum, and Laboratory Improvement) grant, entitled *Aerospace Engineering Failure*. This is a one semester, three-credit hour upper-level technical elective in the Aerospace and Mechanical Engineering Department at Embry-Riddle in Prescott, Arizona. The course is team-taught and the emphasis is on structural and materials failure mechanisms, highlighting the aerospace industry. This unique 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.

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 by two of the authors of this paper, and the third author was the formal project evaluator. This course was again offered during the Autumn 2010 semester, and it was this latter semester in which the concept inventory exam was written and administered.

The prerequisite course for *Aerospace Engineering Failure* 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 was desirable that the degree-program 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 are kept to a minimum.

The prerequisite course of Structures I is critical to making acceptable progress in this elective course. Particular topics that have been identified as important prerequisite knowledge, primarily covered in Structures I (and solid mechanics to a lesser extent) are:

- States of stress and use of Mohr’s circle,
- Different modes of loading,
- Criteria for ductile and brittle failure,
- Knowledge of stress-life fatigue testing and constant-life diagrams, and
- Notions of fatigue crack growth.

With these topics identified, the authors wrote a first version of a sixteen-question concept inventory exam during the 2010 summer.

**Engineering failure concept inventory exam**

The concept inventory exam, in its current form, has sixteen questions on several primary topics. It was given to the students in *Aerospace Engineering Failure* during the first week of the course, and again during the last week of the course. Some of the topics were addressed directly during the semester, but a larger number of the questions were addressed in a little more indirect fashion within the course content, so that simple recall would not be the primary means of answering the questions. There were sixteen students enrolled in the new course during the Autumn 2010 semester.

The exam was also given to students in the prerequisite course *Aerospace Structures I*, during the last week of the Autumn 2010 semester. There were two sections of this course, and it is worthwhile to note that the topics that were included in this concept inventory exam were
covered in *Aerospace Structures I* at the beginning of the semester, so that the students that did 
well on this exam should be students who did a better job of retaining the material. Fifty-one 
(51) students completed the exam in this course (although a few more did, but did not write their 
names on the papers, so these exam results were not included). In all courses, the concept 
inventory exam was not administered as a part of the course grade. Students were merely 
encouraged to do well.

The questions were developed in three categories. The first group of questions (six questions) 
was focused on mechanisms of failure due to various static loadings, the second group (three 
questions) was on the ultimate stresses that cause failure, and the last group (seven questions) 
was on fatigue and fracture concepts. The questions were developed with consideration given to 
identifying misconceptions on failure mechanisms and corresponding causes of the failure.

Results of the exam from the three student groups are presented in Table 1. The results indicate 
that the student understanding of these failure concepts just upon entering *Aerospace 
Engineering Failure* is about the same as for these students at the end of the *Aircraft Structures I*, 
which makes sense since the latter is the prerequisite course for the former. There is a little 
improvement in the scores at the end of the semester compared to their scores at the beginning of 
the semester, but this improvement is small and rather disappointing.

<table>
<thead>
<tr>
<th>Course</th>
<th>Number of students</th>
<th>Score (out of 16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aero Engr. Failure (beginning of semester)</td>
<td>15</td>
<td>7.3</td>
</tr>
<tr>
<td>Aero Engr. Failure (end of semester)</td>
<td>14</td>
<td>8.8</td>
</tr>
<tr>
<td>Aero Structures I (end of semester)</td>
<td>51</td>
<td>7.3</td>
</tr>
</tbody>
</table>

The authors intend to use the results to modify course lectures to clarify these misconceptions 
and improve understanding of failure mechanisms. There are some common misconceptions 
regarding the failure mechanism due to simple loads. Table 2 shows the detailed percentage of incorrect answers for each problem. The questions regarding failure mechanism have the highest 
incorrect answers among the three categories. On average, about 66 % of the students answered 
the questions incorrectly, while in the other categories the incorrect answers were between 45% 
and 49%. This result indicates that these students suffer from an apparent lack of physical 
understanding of these failure mechanisms. There is a disconnect between the ability to perform 
theoretical analysis and correlating the results with the behavior of the structures. This may be 
partly due to insufficient classroom discussion on physical behavior and the implication of 
various loads. The authors believe that encouraging our students to spend more time thinking 
about what physically happen in materials under various load conditions is equally important to a 
well-rounded understanding about the subject, and this exam leads to such conclusions on 
student understanding.

It is noticeable that the first, second, and fifth questions have a very high percentage of incorrect 
answers. The first two questions are closely related, on rods made of two different materials, i.e. 
brittle and ductile materials, which are subjected to pure torsion and tension, respectively. A 
majority of the students (93%) failed to correlate the applied load and the stresses that lead to
failure. For example, Problem 1 (Figure 1) is on a cylindrical rod made of a brittle material subjected to torsion, which is translated into shear stresses at any location in the rod. Knowing this, most students answered that the rod should fail in maximum shear stress, answer (c). In reality, since the rod is made of brittle material, it will fail in a tension mode, answer (a). The authors believe that since the applied load generates shear stresses, the students think that the rod will fail due to shear stress without considering the type of material. Similar observations are made for Problem 2, which is similar in concept to Problem 1 but with different material and load conditions.

Table 2: Detail results of the incorrect answer for each question.

<table>
<thead>
<tr>
<th>Course</th>
<th>Aero Engr. Failure</th>
<th>Aero Strc. I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question</td>
<td>Beginning sem.</td>
<td>End semester</td>
</tr>
<tr>
<td>1</td>
<td>93%</td>
<td>71%</td>
</tr>
<tr>
<td>2</td>
<td>80%</td>
<td>43%</td>
</tr>
<tr>
<td>3</td>
<td>47%</td>
<td>57%</td>
</tr>
<tr>
<td>4</td>
<td>47%</td>
<td>21%</td>
</tr>
<tr>
<td>5</td>
<td>87%</td>
<td>93%</td>
</tr>
<tr>
<td>6</td>
<td>47%</td>
<td>21%</td>
</tr>
<tr>
<td>7</td>
<td>40%</td>
<td>29%</td>
</tr>
<tr>
<td>8</td>
<td>27%</td>
<td>43%</td>
</tr>
<tr>
<td>9</td>
<td>87%</td>
<td>71%</td>
</tr>
<tr>
<td>10</td>
<td>13%</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>67%</td>
<td>50%</td>
</tr>
<tr>
<td>12</td>
<td>93%</td>
<td>50%</td>
</tr>
<tr>
<td>13</td>
<td>40%</td>
<td>43%</td>
</tr>
<tr>
<td>14</td>
<td>73%</td>
<td>71%</td>
</tr>
<tr>
<td>15</td>
<td>0%</td>
<td>36%</td>
</tr>
<tr>
<td>16</td>
<td>27%</td>
<td>21%</td>
</tr>
</tbody>
</table>

This misconception is corroborated by the results of Problem 3 (Figure 2). This particular problem describes a similar case, a rod of a brittle material subjected to torsion. However, the question is regarding the physical deformation and failure plane of the rod. About half of the students selected answer (a), which would be correct when there is no necking, but is an incorrect failure plane (perpendicular to the longitudinal axis of the rod). There are perhaps two possible ways of explaining this answer. First, the knowledge that brittle materials fail in tension leads to a failure plane perpendicular to the load direction since the load is parallel to the length of the rod. Another possible thought may come from an assumption that the rod will fail due to shear stress, leading to the choice of the perpendicular plane as the failure plane, since this is the shear plane. The correct answer is (b), where the rod does not experience necking and the tension plane is at an angle of 45° with respect to the length of the rod.
Another misconception of a failure mechanism is shown in Problem 5 (Figure 3), where a rod of a ductile material is subjected to torsion. More than 80% of the students selected answers (c) or (d) which describe possible necking before failure. This may be motivated by the fact that the rod is made of a ductile material, which has significant deformation and yielding properties before failure. However, this necking can only occur under a tensile load and not under shear loading. Additionally, about 60% of the students selected answers that show the failure plane at an angle. Again, this could be motivated by the idea that the shear failure occurs at an angled plane with respect to the applied load, which is the case for uniaxial tensile loading. The thought that the shear plane is at an angle is incorrect in this case, since the applied load is torsion instead of tension. The correct answer is (a) where the deformation will not cause necking and the failure plane is perpendicular to the line of action of the load.
5. A cylindrical rod made of ductile material is loaded to failure in torsion as shown. Select the sketch that best shows the failure plane and deformation (possible necking) of the rod.

![Figure 3: Sample of question from Inventory Concept Quiz: Problem 5.](image)

A stress-fatigue life diagram is shown below for testing in which all loading is tensile. The solid line (F) represents the experimental results for tests, all of which were performed at the same value of mean stress, $\sigma_{\text{mean}} = (\sigma_{\text{max}} + \sigma_{\text{min}})/2$.

![Figure 4: Sample of question from Inventory Concept Quiz: Problem 12.](image)

12. If the mean stress is increased, the resulting stress-life curve is expected to

   a. Shift right (from F to G)
   b. Shift left (from F to E)
   c. Remain the same

![Figure 4: Sample of question from Inventory Concept Quiz: Problem 12.](image)

One last problem, which had a very high percentage of incorrect answers from the students, is shown in Problem 12 (Figure 4). This problem requires students to first understand sets of data on a stress-life fatigue plot. The question requires that they understand that fatigue results
depend not only on the maximum stress in a fatigue cycle, but also on the minimum stress. In this regard, the fatigue problem is a two-parameter problem, and one must account for both in obtaining a solution. The correct answer ends up not being the obvious answer, and this was perhaps the most challenging problem within the group of problems on fatigue and fracture. The answer is (a).

Overall, by the end of the semester, Aerospace Engineering Failure students have a better understanding of the concept presented in this exam. However, the improvement shown from the results in Table 2 is not nearly what was hoped for by the authors. On average, the correct answers improved by 10%. There are some puzzling results, which instead of showing improvement in understanding seem to indicate the authors caused confusion. This was not appreciated, of course. A significant drop in understanding is shown in the results of Problem 15. The failure mechanisms are still phenomena that are not understood clearly by our students and needs to be explained and discussed more detail in the course.

Future work and summary

In summary, the authors believe that much was learned in writing and implementing this first version of a concept inventory exam. Revisions on both lecture and laboratory materials will be planned based upon reflection of these student scores. The underlying principles of the misconceptions established from the test results are not unique to this course. The knowledge and learning process gain by developing such exams, which can be implemented in other courses, especially prerequisite courses and other courses closely related to structures, materials and failure mechanics.

Aerospace Engineering Failure is planned to be offered every two or three semesters, and the concept inventory exam will become a permanent part of this course. However, the prerequisite course, Aerospace Structures I, is a required course for aerospace engineering degree students and provided to a fairly large number of students each semester (between 40 and 75 or so), and the concept inventory exam might be used here each semester, to better modify and otherwise fine-tune it as an assessment tool.

Availability of concept inventory exam

The authors are happy to provide any educator with the latest version of this concept inventory exam. Be aware that this is a work in progress. Please send inquiries to the David Lanning (lannind@erau.edu) or Wahyu Lestari (lestariw@erau.edu).

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0837009. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.
The authors also wish to thank student assistants Matt Bender and Brad Pols for their dedicated efforts.

Bibliography


