AC 2007-569: DIRECT ASSESSMENT OF MECHANICS OF MATERIALS LEARNING WITH CONCEPT INVENTORY

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Direct Assessment of Mechanics of Materials Learning with Concept Inventory

Introduction

This paper presents a tool for direct formative assessment and the results of continuous improvement activities in teaching mechanics of material topics in a mechanical engineering technology program. The tool is a beta version of a concept inventory assessment[1] and, as such, is a mid-term multiple-choice quiz with conceptual questions rather than procedural questions.

Feedback from the tool is provided to the students in a non-threatening manner so they can assess their understanding of the topics and identify areas for improvement. Instructors can use the results for continuous improvement of topic coverage in the courses. To date, the assessment has been conducted for the same group of students in their junior and senior years as a longitudinal design[2]. It has also been conducted on a subsequent group of students in their junior year as a baseline-data design[2]. The results of the assessments are provided and discussed along with continuous improvement activities in each course.

Background

Recent criteria for ABET accreditation requires an assessment of learning objectives and outcomes[3]. Monitoring the learning process[4, 5] is a key part of continuous improvement of higher education. Many forms of assessment[6, 7] are currently being developed to monitor the leaning process. Concept inventories[8] have become a popular form of assessing students' conceptual knowledge of important topics. Concept inventory assessment tools have been or are being developed for engineering topics such as force[9], dynamics[10], heat transfer[11], fluid mechanics[12], etc. This work presents a concept inventory for direct formative assessment of student learning in mechanics of materials.

Often, assessment activities have been indirect in that they question or survey students on their perception of their ability to meet course objectives which can obviously produce some subjective results. Currently, ABET accreditation requires more direct assessment of learning outcomes to provide more objective results and, in turn, better direction for continuous improvement activities. The accreditation requirement of direct assessment rather than indirect assessment is a valuable one which is certainly expected to continue.

At Penn State Erie, The Behrend College, the focus of the mechanical engineering technology program is applied design. As a result of this focus and industrial advisory board input, the curriculum has a strong and sometimes repetitive emphasis on relatively advanced topics in mechanics of materials such as three-dimensional Hooke's Law and transformation of stress and/or strain. Students are exposed to these advanced topics in more than one course and by different instructors. In an effort to satisfy each instructor's procedural requirements, students often do not comprehend the underlying concepts and even develop misconceptions about the topics. As they lack comprehension of the underlying concepts, they may even perceive a contradiction of the concepts as taught by different instructors.

In an effort to directly assess student learning and to assure consistency of the topics as taught throughout the curriculum, a concept inventory of three-dimensional Hooke's Law, transformation of stress and/or strain, etc. was developed collaboratively by the instructors that teach those topics in various courses. The assessment tool serves at least three distinct purposes. First, since it was developed collaboratively, it provides baseline-data design of assessment as it assures consistency of the topics when taught in various courses and by various instructors. Second, it provides a direct assessment of student understanding of the topics and how the topics relate to each other. Third, it provides an assessment of student learning longitudinally, or retention of knowledge from year to year or from course to course.

The Assessment Tool

The assessment tool or quiz is found in the Appendix along with a brief discussion of the answers and each question's importance. The assessment tool or quiz is administered in a junior level advanced mechanics of materials course and in a senior level finite element stress analysis course. The junior level course is a prerequisite for the senior level course. In the junior advanced strength of materials course, students are presented the assessment tool as an unannounced in-class quiz, which are typically worth 2% to 3% of the total course grade. They are told that the quiz counts so that they take it seriously but, in the end, no grade is entered for the assignment. The instructor tabulates the answers for each question but does not tally a score for any of the students. The results as tabulated by the instructor are used for assessment and continuous improvement.

The quiz is returned to students, they are told that it did not count toward their grade, and it is reviewed and discussed as a group exercise. Students tally their own score as the assignment is reviewed. This approach seems to relieve students from the anxiety of getting a low quiz grade and allows them to assess their progress in a non-threatening way. While reviewing the quiz with the students, the instructor tells the students the response weight for each possible answer. The instructor states that some of the multiple-choice selections are so bad that the response weight is negative, which often draws a humorous response from the students. At the end of the group exercise the instructor surveys the results with a show of hands in order of descending tallied scores. Unfortunately, those results have not been documented.

In the senior finite element stress analysis course, students are presented the assessment tool as an announced out-of-class quiz that is worth 2% to 3% of the total course grade. In the senior finite element stress analysis course, the instructor has made the quiz count toward the course grade. In preparation for the quiz, students were not given much detail about its content; they were just told to review their mechanics of materials concepts. Many senior students voiced their displeasure with the quiz and its effect on their course grade.

There may be some anomalies in the data or some duplication that was not corrected. For example, some students may have been in the junior level course both times the assessment was administered. A very small number of students may have been in the junior level and senior level courses simultaneously, having taken the quiz in each course. In all cases, the entire raw data was used and none was removed or adjusted. There were 46 juniors surveyed the first year. There were 38 seniors and 48 juniors surveyed the second year.

Assessment Results

The following table shows a summary of the assessment results. There are many ways that the data and numbers could be analyzed and presented. The authors have chosen a weighted response based on assigned weights for each response. For reference, the table shows the percentage response for each administration of the quiz.

			Percentage Response			Weighted Response		
Question No.	Response Choice	Response Weight	Jr.'s FA06	Jr.'s FA05	Sr.'s FA06	Jr.'s FA06	Jr.'s FA05	Sr.'s FA06
1	a	-2	17.0	23.9	13.2	**19.2**	**30.4**	**55.2**
	b	2	36.2	54.3	68.4	(-100<x<100)		
	c	0	46.8	21.7	18.4			
2	a	2	87.5	84.8	89.5	**75.0**	**69.6**	**79.0**
	b	-2	4.2	8.7	2.6	(-100<x<100)		
	c	-2	8.3	6.5	7.9			
3	a	0	54.2	57.8	26.3	**33.3**	**37.8**	**63.1**
	b	-2	6.3	2.2	5.3	(-100<x<100)		
	c	2	39.6	40.0	68.4			
4	a	-2	8.3	19.6	10.5	**23.0**	**-21.8**	**46.1**
	b	2	52.1	32.6	71.1	(-100<x<100)		
	c	-2	27.1	39.1	15.8			
	d	1	12.5	8.7	2.6			
5	a	-2	14.6	0.0	7.9	**66.6**	**91.4**	**84.2**
	b	-2	2.1	4.3	0.0	(-100<x<100)		
	c	2	20.8	28.3	31.6			
	d	2	62.5	67.4	60.5			
6	a	2	29.2	13.0	55.3	**0.0**	**-26.1**	**47.4**
	b	0	31.3	34.8	23.7	(-100<x<100)		
	c	-2	29.2	39.1	7.9			
	d	0	10.4	13.0	13.2			
7	a	-2	2.1	6.5	2.6	**20.8**	**-56.5**	**42.1**
	b	-2	33.3	58.7	21.1	(-100<x<100)		
	c	-2	4.2	13.0	5.3			
	d	2	60.4	21.7	71.1			
8	a	-2	10.4	23.9	0.0	**45.8**	**4.4**	**63.2**
	b	-2	6.3	15.2	7.9	(-100<x<100)		
	c	-2	10.4	8.7	10.5			
	d	2	72.9	52.2	81.6			
9	a	2	70.8	47.8	86.8	**70.8**	**47.8**	**86.8**
	b	0	29.2	52.2	13.2	(0<x<100)		
10	a	2	70.8	47.8	76.3	**70.8**	**47.8**	**76.3**
	b	0	29.2	52.2	23.7	(0<x<100)		

Comments on Results

The weighted responses of questions 1 through 8 can take on values between -100 and 100. The weighted responses of questions 9 and 10 can take on values between 0 and 100. Comparisons can be made two ways with the weighted responses. First, juniors from Fall 2006 can be compared to juniors from Fall 2005 for baseline-data design of assessment. This comparison will reflect continuous improvement activities, or interventions, of the instructor. Second, seniors from Fall 2006 can be compared to juniors from Fall 2005 for longitudinal design of assessment. Since this is the same group of students, this comparison will reflect how well students retain key conceptual information.

There are two general trends that occur with most questions. The first is that juniors during the second administration did better than juniors during the first administration. This is a reflection of the instructor's intervention for continuous improvement in areas that needed it. There were, however, exceptions to this trend which were discouraging. The most notable exception to this trend is question #5.

The second trend is that seniors did better than they did when they were juniors and they did better than their junior counterparts. This was by far the most encouraging result of the assessment tool. It indicates that students generally do retain this key conceptual information. It may also indicate that juniors not retaining this information did not become seniors.

Continuous Improvement Activities

Continuous improvement activities are discussed here in two aspects. The first is in use and administration of the beta version of the assessment tool. The second is in specific course activities directed at helping students retain key conceptual information.

For the assessment tool in the junior level course, the quiz was administered with open textbooks so the students could clearly see the formulas and equations referred to in the quiz. Students used this opportunity to read the text in search of the answers. It is doubtful that the text was much help but in the future the quiz will be administered with closed textbooks and the formulas will be provided with the quiz. In the senior level course, the quiz was administered on-line in ANGEL, Penn State's course management system, and students were asked to not collaborate. However, there needs to be more assurance that there is no collaboration amongst the seniors. Also, minor revisions or additions to the beta version questions may be necessary.

For specific course activities, question 4 which deals with the definition of Poisson's Ratio, went from a weighted response of -21.8 to 23.0 for the juniors due to the instructor's increased lecture emphasis and examples on uni-axial vs. general loading. Also, question 6 which deals with the plane stress treatment of material beneath strain gages, went from -26.1 to 0.0 for the juniors due to the instructor's increased lecture emphasis and examples on plane stress vs. plain strain loading. Questions 7 through 10 improved for the juniors due to the instructor's increased lecture emphasis and examples on known vs. unknown states of stress. Future continuous improvement activities could involve control chart plotting of the weighted responses and/or statistical analyses as conducted on concept inventory assessments for other topics[10].

Conclusion

The tool has provided a valuable means of ongoing direct assessment of student learning and has provided direction for continuous improvement activities. During its development process, it has assured consistency of instruction from instructor to instructor (or from course to course) on advanced and difficult topics that are sometimes duplicated. It has also provided a measure of student retention of key conceptual information which goes somewhat beyond current ABET assessment requirements. The assessment process will continue to be refined, both in terms of the actual administration of the tool and in how the tool is used to revise and improve course activities.

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Appendix

The assessment tool or quiz is provided below. Students are asked to select the *best* answer. There is also a brief discussion of the answer and the questions' importance

1. The equations of true stress and true strain and how they relate to engineering stress and engineering strain, shown below, apply for materials stressed:
   a) below their yield stress
   b) above their yield stress
   c) both a and b

$$\varepsilon_T = \ln(\varepsilon + 1)$$
$$\sigma_T = \sigma(\varepsilon + 1)$$
$$\sigma_T = K\varepsilon_T^n$$

The equations of true stress and true strain and how they relate to engineering stress and engineering strain are meant to characterize a material's behavior after yielding in a standard uni-axial tensile test. The equations may or may not provide an accurate characterization of the material behavior before yielding. This is a unique topic for students in a mechanical engineering technology curriculum with a focus on applied design because most of their analysis and design work involves consideration of materials loaded below yielding. Students must understand that this is an important concept but that it applies more to the manufacturing arena and the forming of metals.

2. Generalized Hooke's Law equations, shown below, apply for materials stressed:
   a) below their yield stress
   b) above their yield stress
   c) both a and b

$$\varepsilon_x = +\frac{\sigma_x}{E} - \frac{\nu\sigma_y}{E} - \frac{\nu\sigma_z}{E}$$
$$\varepsilon_y = -\frac{\nu\sigma_x}{E} + \frac{\sigma_y}{E} - \frac{\nu\sigma_z}{E}$$
$$\varepsilon_z = -\frac{\nu\sigma_x}{E} - \frac{\nu\sigma_y}{E} + \frac{\sigma_z}{E}$$

Generalized Hooke's Law equations apply only to materials stressed below their proportional limit which is effectively the yield point. Since the material property modulus of elasticity *E* is used, a direct relationship between stress and strain is assumed which only occurs below yielding. Obviously, the application of Hooke's Law equations to materials stressed above their yield point can create serious errors.

3. The equations of stress transformation, shown below, apply to materials stressed:
   a) below their yield stress
   b) above their yield stress
   c) both a and b

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$
$$\tau_{x'y'} = -\frac{\sigma_x - \sigma_y}{2}\sin 2\theta + \tau_{xy}\cos 2\theta$$
$$\sigma_{y'} = \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2}\cos 2\theta - \tau_{xy}\sin 2\theta$$

The equations of stress (or strain) transformation can be applied to materials stressed above or below their yield point. Transformation operations are carried out on the quantities of stress or strain which are independent of material properties such as modulus of elasticity and yield strength.

4. Poisson's Ratio υ is defined as:
   a) υ = - *lateral strain/axial strain* for stress in the lateral direction only
   b) υ = - *lateral strain/axial strain* for stress in the axial direction only
   c) υ = - *lateral strain/axial strain* for any stress direction(s)
   d) υ = E/2G-1

Poisson's Ratio is defined as – *lateral strain/axial strain* for stress in the axial direction only. Students are taught this in the introductory mechanics of materials course but tend to forget it in an advanced mechanics of materials course. For example, students are prone to taking the ratio of measured strains from general plane stress loading and calling that Poisson's Ratio.

5. If a mechanical component is observed to have excessive deflection when loaded, but the component retains its original size and shape when unloaded, which of the following would be a solution to reducing the deflection when loaded:
   a) heat treat and quench the component
   b) case harden (carburize) the component
   c) change the material modulus of the component
   d) change the size and/or shape of the component

There are two equally correct answers to this question. The key to the question is that the observed deflection is elastic meaning that thermal treatments to increase strength or hardness will not change the elastic behavior of the mechanical component. From the author's experience, this question is known to have been used during the interviewing process of engineering candidates with alarmingly poor responses from the candidates.

6. Two strain gages are adhered very close to each other on the surface of a mechanical component so that they are perpendicular to each other and the surface is exposed to the atmosphere. When the mechanical component is loaded, the material (or stress element) directly beneath the strain gages can be considered:
   a) plane stress
   b) plane strain
   c) both a and b
   d) neither a or b

Students need to know that the element in this case should be treated as *plane stress*. There will be a small normal stress perpendicular to the surface but that is atmospheric pressure which is negligible compared to most stress magnitudes experienced by a mechanical component. The element could be close enough to a stress concentration to negate the plane stress treatment. However, if there is enough physical space to install strain gages, the element beneath the gages is probably far enough away from any stress concentration to satisfy the plane stress treatment.

7. A single strain gage is installed on a steel ($E = 30x10^6$ psi, $\upsilon = 0.3$) part that is loaded with forces and moments in unknown directions. The strain in the direction of the gage is 0.001. What is the stress parallel to the gage?
   a) 9,000 psi
   b) 30,000 psi
   c) 100,000 psi
   d) cannot be determined

Questions 7 through 10 are related. The basis of the answers is such that a single strain gage can be used if and only if the state of stress is known. If the state of stress is known, the orientation of the strain gage does not matter; transformation and Hooke's Law relationships can be utilized to overcome a poorly oriented gage in the case of a known state of stress. However, in most real situations, the state of stress is probably not known, that's why strain gages are used in the first place. A common misconception is that replacing a single strain gage with two strain gages, perpendicular to each other, can be used to determine an unknown state of stress. With two such strain gages, it is true that the normal stresses in the direction of the gages can be determined but shear stress, if present, will be totally missed. The only way to properly determine an unknown state of plane stress is with a strain rosette.

8. A single strain gage is installed on a steel ($E = 30x10^6$ psi, $\upsilon = 0.3$) part that is loaded with forces and moments in unknown directions. The strain in the direction of the gage is 0.001. What is the stress perpendicular to the gage?
   a) 0 psi
   b) 9,000 psi
   c) 30,000 psi
   d) cannot be determined

See discussion of question 7, state of stress is unknown.

9. A single strain gage is installed on a circular steel shaft loaded in torsion only. However, the strain gage is misaligned 10º from the axis of the shaft. The magnitude of the shear stress of the material element beneath the gage can be determined from the reading of the single strain gage.
   a) true
   b) false

See discussion of question 7, state of stress is known.

10. A single strain gage is installed on thin-walled, spherical pressure vessel. The magnitude of the stress(es) of the material element beneath the gage can be determined from the reading of the single strain gage.
    a) true
    b) false

See discussion of question 7, state of stress is known.