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Work in Progress: Common errors in learning strength of materials concepts as a foundation to an interactive web-based problem-solving assessment interface

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Abstract

This is a work in progress. Despite the prevalence of evidence-based instructional approaches in the teaching, learning and assessment of engineering knowledge, recent research suggests a troubling mismatch between what is taught, what is learned, and what is assessed. Investigations with validated physics and mechanics concept inventories have identified that students' conceptual understanding is in stark contrast to their achievement in courses. Qualitative studies used to investigate this phenomenon have shown that students at varied academic levels i.e. sophomore, junior, etc. often demonstrate expected proficiency in problem-solving, but that conceptual understanding is somewhat lacking. That is, students who progress in their studies become better at calculating solutions to well-structured problems, but some remain deficient in the conceptual principles required to reason through complex or novel problems. The NSF project from which this paper is drawn (DUE – 1841980) seeks to design an interactive problem-solving tool aimed at improving students' conceptual understanding of fundamental mechanic concepts through deliberate, repeated practice. The WIP will set the stage for the development, implementation, testing, and deployment of a technology-rich problem-solving interface for Mechanics of Deformable Bodies in Engineering Science course. Using students' responses to final exam questions across multiple years, this paper will begin to identify problematic concepts and common errors students have about the course concepts.

Background

Engineering knowledge and expertise is often defined as the ability to solve complex and ill-structured problems. In order to prepare engineering students for this reality, engineering courses are often designed with embedded problem-solving activities regardless of discipline or academic level. For disciplines such as mechanical, biomedical, civil, aerospace and ocean engineering, knowledge of mechanics concepts is fundamental. However, years of research have demonstrated that students continue to experience difficulties understanding these concepts at the conceptual level [1-3]. Conceptual change researchers have attributed the ensuing difficulties associated with learning basic mechanics to the following factors: 1) insufficient mathematical knowledge, 2) overall abstractness of the content, 3) students' preconceptions of the content and 4) the degree of logical precision required in problem solving [4-7]. To combat these factors, researchers have recommended the use of multiple representations of the concepts as well as opportunities for repeated practice [8]. Additionally, the use of technology-enabled tools has been reported to significantly reduce the cognitive gap associated with learning fundamental concepts such as mechanics.

The larger project from which this WIP is drawn is rooted in the belief that problem-solving is foundational to engineering education, but that growing class sizes and demands on teaching time, as well as students' prior knowledge and experiences, have deemphasized aspects of problem solving that align with research on learning and evidence-based pedagogical practices. Educational researchers argue that technology-rich learning environments can be used to overcome these challenges and thus foster conceptual understanding. To systematically investigate how a technology-rich problem-solving interface can enhance the teaching, learning, and assessment of complex engineering knowledge, researchers must initially develop

prerequisite understandings of both the processes by which students are actively constructing knowledge in a specific domain, and the critical factors that either facilitate or undermine such active construction. In other words, what are the common conceptual schemas for reasoning through complex problems in the specific domain? Furthermore, what are the common errors students transfer in as prior knowledge when solving problems in the specific domain?
To answer these questions, we studied students' final exams of a Deformable Bodies Course. The final exams spanned two and a half years, or five semesters, and covered a breadth of common topics such as concepts of stress and strain, combined loading, deflection, shear stress etc. In this paper, we present findings from an item analysis of the final exams across multiple years.

Method

To establish a preliminary list of students' conceptual difficulties and misconceptions related to learning solid mechanics of materials, aggregate data from final examinations for an undergraduate-level engineering science and mechanics course on the mechanics of deformable bodies were synthesized. The course introduces the following topics to primarily second-year students: concepts of stress, strain, and deformation; factor of safety; stress-strain relationships and material properties; stress concentrations; area moments of inertia; axially loaded members, torsionally loaded members, and bending of beams; shear and moment diagrams; stresses due to combined loading; thin-walled pressure vessels; transformation of stress including Mohr's circle; and beam deflections and buckling stability. The final examinations assessed students via multiple choice items only, with each item having one correct key answer and nine incorrect distractors. Students marked their responses on machine-readable paper forms, which were then analyzed via automated grading and reporting. Considering that students can consequently earn either full credit or no credit, our synthesis of the aggregate data can only convey to us the assessed topics that were most difficult for students, not explain to us why those assessed topics were most difficult.

The final examinations for which the aggregate data were synthesized were administered over two hours in Table 1. A quick spot check of Table 1 reveals a clear delineation between the number of instructors during spring semesters and fall semesters, explained by the course being offered on-cycle during spring semesters and off-cycle during fall semesters.

Table 1

Information related to Administration of Final Examinations

Semester (Term & Year)	**Instructors (*N*)**	**Items (*N*)**
Fall 2017	2	22
Spring 2018	7	24
Fall 2018	4	23
Spring 2019	7	22
Fall 2019	5	22

Preliminary Findings

First, for a given instructor in any particular semester, individual items were flagged for potential difficulty if greater than or equal to 50% of students responded with an incorrect distractor answer. Second, across all instructors in a given semester, the number of flags were totaled for each item. Third, if an individual item was flagged for at least half of the instructors in a given semester, then the topic assessed by the individual item was compiled in a list. The list of semesters and the difficult topics flagged for each of them are in Table 2. With respect to the 2018 and 2019 semesters, a flag was considered to be strong if an individual item was flagged for at least 75% of the instructors; a flag was considered to be moderate if an individual item was flagged for between 60% and 75% of the instructors; a flag was considered to be weak if an individual item was flagged for between 50% and 60% of the instructors. The same upper and lower bounds were applicable to the final examination form, not number of instructors, for Fall 2017.

Table 2
Flagged Topics, with Strength of Flag, by Semester

Semester (Term & Year)	**Flag**	**Topic**
Fall 2017	Strong	Combined Loading Shear Stress
	Moderate	Pressure Vessels Torsional Stress
	Weak	Bending Stress Buckling Deflection***** Normal Stress
Spring 2018	Strong	Axial Deformation Combined Loading (1) Indeterminate Torsion
	Moderate	Deflection Indeterminate Deflection***** Shear Stress***** Stress Transformation Torsional Deformation
	Weak	Combined Loading (2) Equilibrium Section Modulus
Fall 2018	Strong	Combined Loading Indeterminate Torsion
	Moderate	Bending Stress Buckling***** Deflection
	Weak	Axial Deformation Indeterminate Deflection (1) Indeterminate Deflection (2) Shear Stress
Spring 2019	Weak	Thermal Stress
Fall 2019	Moderate	Combined Loading*****
	Weak	Stress Transformation***** Torsional Stress

***For a given semester, a different item assessing the same topic was not flagged.**

More generally, the list of difficult topics and the frequency with which they were flagged are shown in Table 3. Of note, items assessing the topic of Combined Loading were flagged every semester. Furthermore, items assessing the topics of Deflection, Indeterminate Deflection, and Shear Stress were flagged more than half of the time. From this table, we can determine these concepts to be repeatedly problematic.

Table 3
Flagged Topics by Frequency

Frequency	**Topic**
5	Combined Loading
3	Deflection Indeterminate Deflection Shear Stress
2	Axial Deformation Bending Stress Buckling Indeterminate Torsion Stress Transformation Torsional Stress
1	Equilibrium Normal Stress Pressure Vessels Section Modulus Thermal Stress Torsional Deformation

Content, course structure and assessment approaches

Our tables indicate the course is taught by multiple instructors; however, several efforts were made to normalize instruction. One way this is achieved is through the appointment of a course coordinator. One of the authors currently serves as the course coordinator and their role is to ensure instructors teach from the same material, homework problems are the same and exam items are common for all sections. Additionally, at the end of each semester, instructors are provided with the data from the exams to demonstrate how their students performed on each question. We do recognize that we cannot account for differences in teaching approaches and attempts to actively engage students in the classroom as this varies from instructor to instructor. This is a limitation of this study.

The most frequent topics from Table 3 align with the anecdotal experiences of our authors who have taught the course. Specifically, combined loading problems can have many parts which simultaneously require the student to identify and calculate forces in three directions and moments or torques about all three axes, correctly identify and calculate geometry related values (e.g., moment of inertia, distance from a point to parallel axis), establish and carefully attend to a sign convention, and collectively use these to compute a desired quantity. Such a problem in a final exam context has many potential pitfalls where a student might make errors. Deflection and indeterminate deflection problems are taught towards the end of the course and students may be unable to dedicate as much time and effort to learning them compared to earlier concepts. Finally, shear stress as a frequent flagged problem may because students find concepts of shear stress, shear flow, and the calculation of the first moment of area in the region created by the point where shear stress is being calculated and the distance to the neutral axis to be difficult. In contrast, common accessible examples are more available for students to conceptually understand stretching or compression due to a force applied along an axis (axial deformation) or angle of twist from applying a torque to a shaft (torsional deformation).

Throughout any given semester, all topics are assessed with the same level of frequency, meaning each topic is assessed through homework problems, quizzes, mid- and final semester exams and these questions change from year to year. As mentioned previously, the exam items are often developed collaboratively by instructors and the course coordinator and in all cases the distractors were designed as random numbers within a realistic range for the correct answer.

In this paper, we did not focus on the distractors chosen or what misconceptions they might be aligned with. Instead, we sought to use this study to first identify problematic concepts more broadly with the express goal of providing students repeated practice with solving problems associated with these concepts. This, we believe, will help students develop expert-like problem-solving skills and the ability to understand the content in a conceptual way.

Future Steps

By identifying the concepts that students have had the most difficulties with, we are now able to determine what concepts we will need to write items for interactive software. Since our aim is to provide students with repeated practice so that they develop the ability to conceptualize and solve the problems in more engaging ways, it is important to first understand what concepts are problematic and why students continue to experience difficulties. As we continue to develop our tool, we plan to explore what implications the difficulties outlined in the literature have for not only tool development but engineering instructors more broadly.

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