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Design-Based Course Sequence in Statics and Strength of Materials*

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We present in this paper an attempt to help students reach the ABET 2000 goals from the context of reforming two engineering courses: statics and strength of materials (mechanics of materials). In the traditional course of statics, students usually learn to obtain only the internal forces for trusses and beams. In the reformed curriculum students are asked to analyze and design a simple structure. Statics, presented in this context, is natural and easier to comprehend. In this approach the concept of stress is introduced early. Strength of materials focuses on the determination of stress and deformation of transversely loaded structures and statically indeterminate structures. In this paper, we outline the topics covered in each of the two reformed courses compared to the traditional curriculum. We discuss the delivery of the design-based courses, and we show the student's and instructor's perspective of the changes.

INTRODUCTION

EDUCATION REFORM in engineering in the past decade has included curriculum revision [1–5] use of computer tools [6–13], and the use of hands-on experience [14–17]. While all three paradigms have their champions, they are not mutually exclusive and often coexist at many institutions. Regardless of the approach, the common goal is to better prepare engineering students for their career. Recently ABET established a set of goals commonly referred to as the ABET 2000 criteria. These criteria turned out to be similar to the wishes of the employers who recruit at the University of Maryland. In this sense, ABET 2000 criteria have been our goals for years. The ECSEL coalition funded by the National Science Foundation [18], of which the University of Maryland is a member, has been working in this area for nearly seven years. We present in this paper an attempt to help students reach these goals from the context of reforming two engineering courses: statics and strength of materials (mechanics of materials).

A typical course in statics covers equilibrium of forces in structures and their components, shear and moment diagrams, and properties of areas. A large part of the course is usually devoted to vector mechanics. Although the techniques learned in this course are necessary for all students who continue their studies in mechanics, it is not apparent to the majority of students how these techniques help them solve engineering problems. As a result, most students retain very little of the materials taught in this class. Ironically, statics is closely related to a wealth of problems that students can easily visualize. Instructors simply don't go far enough so they can relate the class information to the many engineering problems that statics can help them solve.

Analyses in solid mechanics ultimately attempt to answer two questions only: Is the material strong enough? And is the material stiff enough? We answer these questions by first estimating the external forces (deterministic or probabilistic), determining the corresponding internal forces, and after prescribing a stress distribution, determining the stresses within the structure. The current course in statics does not usually attempt to answer these questions. Instead, students are only asked to determine the internal forces of a thin and long structure such as a truss and a beam. This result has little meaning on its own merit. In other words, determining the internal forces in a truss or beam member is merely an intellectual exercise to the students, because they do not relate these intermediate results to the questions of performance. To remedy this problem, we must introduce the concept of stress to help them answer the bottom-line question of whether the truss is strong enough.

Determination of stress components carries the work in statics to a more reasonable stopping point. Therefore, a more logical package should consist of the determination of external forces, internal forces and stresses for each type of structure. This approach is different from the current approach in that students usually learn to obtain only the internal forces. In particular, they learn to obtain the internal forces for trusses and beams. Stress components, in the traditional approach, are covered in the follow-up strength-of-materials course (SOM).

The end result of the proposed realignment of subjects means that statics and mechanics will cover the topics shown in Table 1.

Notice that some items traditionally taught in

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Table 1. Topic alignment for traditional and design-oriented Statics and Strength of Materials courses

Topics	Traditional		Design Oriented	
	Statics	SOM	Statics	SOM
1. Estimation of external forces.			✓	
2. Determination of internal forces in trusses and bars (equilibrium of forces).	✓		✓	
3. Determination of normal stress in trusses and bars.		✓	✓	
4. Statically indeterminate bars and cable structures (compatibility of deformation).		✓	✓	
5. Introduction to vector mechanics.	✓		✓	
6. Determination of internal forces in beams (V and M diagrams).	✓	✓	✓	✓
7. Properties of area.	✓	✓	✓	
8. Determination of stresses in beams.		✓	✓	✓
9. Introduction to tensor mechanics.				✓
10. Deformation of beams.		✓		✓
11. Statically indeterminate beams.		✓		✓
12. Failure criteria.		✓	✓	✓
13. Failure by instability (columns).		✓		✓

strength of materials will be moved to statics. Items 1 and 9 have not been part of these courses, but we feel Item 1 is necessary to make the design more realistic, and we suggest that Item 9 be introduced because stresses are tensor quantities. Early introduction of this concept will help students in subsequent uses of tensors. In this way, the overall contents of the two courses remain relatively unchanged.

DESIGN-BASED INSTRUCTION

Another important outcome of the subject realignment is that students are now given enough information to carry out a design project from start to finish. In fact, at the University of Maryland these courses are design-based. Subjects are introduced from a design point of view. Each lecture begins with the identification of a portion of the design process being studied so that students should always know the context of the material being covered. For example, the lecture on bending stress begins by identifying a typical member that is subjected to bending moment. This topic is related to the design part of the course—in this case the design of a crane. A sub-goal is then defined, and the necessary materials are covered to reach this goal. Discussion with students to define this goal, i.e. the relationship between bending moment and bending stress, helps to put them in an active learning mode.

To reinforce how the material learned in the class helps solve engineering problems, students are given a semester-long, open-ended design project. Periodically, the students are asked to submit reports that require them to use some of the concepts learned in the lectures up to that point. Students work on teams on the project. Besides learning to work in a team environment, more advanced students often tutor their team members, thereby stimulating learning on both sides.

Several engineering tools are introduced to the students to help them with their design projects. Some of the tools we have incorporated in these two courses include:

1. Pro/ENGINEER for 3D modeling.
2. ANSYS for stress analysis.
3. MATLAB for matrix manipulations in vector and tensor mechanics.
4. Maple for symbolic algebraic manipulations.
5. Excel and PowerPoint for trade-off analyses and presentations, respectively.

Naturally, it would be difficult to introduce so many applications to students in a single year along with all the other work they are asked to do. Three factors help alleviate this problem. First, if at least one team member is familiar with the application being used, he or she can help train the other team members. This is particularly helpful because many of these tools are being used in other engineering and mathematics classes. Second, the project is done by a team; not every team member has to learn every tool. When properly managed, team members only need to be proficient in one or two tools. Even if the students do not learn to use some tools proficiently, they are, nevertheless, being exposed to these important engineering tools. Finally, a knowledgeable student staffs the engineering computing laboratory and has been an indispensable asset.

Arguably the most important reason to use a design-oriented approach is the motivation that the design project engenders. Students first see in class how the material being covered fits into the overall design process. They later apply the same knowledge to help them in their design and analysis. In practice, the illustrations and examples used in class only have the effect of providing students with an overall view of the concepts. Only by laboring on their own projects, do they begin to learn the importance and use of the theory being promulgated.

ABET 2000 CRITERIA

The idea of the design project and report preparation initially was formulated to meet the demands of prospective employers. When asked to provide feedback on the students they have hired in the past, they generally agree that the students are well prepared in theory (a somewhat surprising result to us), but these same students work poorly in teams and often lack adequate communication skills. Their shortcomings are not surprising because we traditionally demand individual performance from our students, and with the exceptions of a few courses, written and oral reports are not part of the curriculum. The addition of design projects, therefore, ostensibly remedies these shortcomings.

As it turns out, the addition of the design project has other important benefits. They are closely correlated to the ABET 2000 criteria which we list here. According to those criteria, a graduating engineering student is expected to have:

(a) an ability to apply knowledge of mathematics, science, and engineering;
(b) an ability to design and conduct experiments, as well as to analyze and interpret data;
(c) an ability to design a system, component, or process to meet desired needs;
(d) an ability to function on multi-disciplinary teams;
(e) an ability to identify, formulate, and solve engineering problems;
(f) an understanding of professional and ethical responsibility;
(g) an ability to communicate effectively;
(h) the broad education necessary to understand the impact of engineering solutions in a global and societal context;
(i) a recognition of the need for, and an ability to engage in life-long learning;
(j) a knowledge of contemporary issues;
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

We will show that the design project directly assists students achieve criteria (a), (b), (c), (d), (e), (g), and (k). Criteria (f), (h), (i), and (j) probably cannot be dealt with in a single course; rather, they should be found in the culmination of knowledge from four years of instruction at the university.

INITIAL EXPERIENCE

In comparing the traditional approach to the 'learning by design' approach, we point out that, of foremost importance, the same content must be covered in the new approach. This goal is not easily accomplished in a just-in-time learning environment where the students are asked to discover what they need to learn in order to be able to tell if the structure is strong enough and stiff enough. Another problem is timing. If the students' questions require too much background material, the just-in-time approach becomes about the same as the traditional method of teaching. Therefore, in some instances, the in-class discussions require guidance to ensure that the appropriate materials are taught in a reasonable sequence. Our implementation thus far has not necessitated an inordinate amount of guidance. The bottom line is that the material taught and the sequence in which this material is taught closely followed the syllabus of the traditional lectures.

To date we have taught the statics component of the course sequence twice and the strength of materials component only once. In our first attempt, statics was based on the design of a construction crane. At the very first class meeting the thirty five students were divided into seven groups of five. They were told that we were going to design a construction crane (and build a model if time permitted) similar to the one being used on campus to erect a building for the Engineering Research Center. The students were asked to develop a list of topics that they would need to learn in order to design the crane. The seven lists were evaluated and the course syllabus was composed of the subjects they had identified. Of course, some additions were necessary, and some topics from their lists had to be omitted, but overall the students themselves did a fairly good job of identifying what to study over the semester.

Throughout the semester the students worked hard to learn the materials necessary for the proposed design. Each week hands-on demonstrations of materials requested by students were included into the study periods (1 one-hour segment and 1 two-hour segment each week). These demonstrations included three-dimensional models to demonstrate vectors and vector addition, spring scales to measure force components, moveable incline planes to measure coefficient of friction, etc. By the end of the semester, the groups had worked well together to complete homework assignments as well as the design projects. Time did not permit models to be built, but a senior project class in Mechanical Engineering had also selected designing and building a crane as their project and the students from the statics class followed closely the progress made by those seniors.

The seniors used Pro/ENGINEER to design their crane and many of the students from statics met frequently with the seniors and became proficient in Pro/ENGINEER themselves. The seniors also brought their crane to the statics class and discussed how they had arrived at their final design. At the end of the semester the statics students were invited to view the operation of the crane designed and built (including machining of parts) by the seniors. The mentor role of the seniors helped the students in statics a great deal. Although the students in statics did not build a model, their observation during the progress of the senior project gave them a deeper understanding of the design process and an appreciation for the materials learned in statics.

The second time the static component was taught, the topic was to design a bridge to span a campus creek. Loading for the bridge included a golf cart and pedestrians. The final course syllabus prepared with student input, after editing, was identical to the one used the previous semester. The course went very much like the first time, but homework was done by individuals rather than by groups.

Throughout both semesters materials were delivered in a 'just-in-time' fashion. Most often, the materials were requested by the students, but in some cases the material was provided at the insistence of the instructor. Far fewer 'traditional' lectures were delivered than in the normal statics course and the students were expected to pick up more of the material in discussion within their groups and by viewing the physical demonstrations provided as part of the course. We had both a teaching assistant (a graduate student) and a teaching fellow (undergraduate student) involved in the teaching of the course. They and the instructor interacted closely with each of the groups. This meant less emphasis on derivation of equations and even less time spent going over problems in the classroom. Instead, more time was devoted to explanations of the entire analysis process and the influence of parameters in the computation of forces and stresses (such as moment of inertia and centroid, modulus of elasticity, etc.).

Some of the students from the learning-by-design section of statics took the learning-by-design section of SOM the following semester. The majority of students did not come from this special section of statics. In SOM, the crane design project was continued. ECSEL trained teaching assistants helped students learn the modeling package—Pro/ENGINEER. The finite-element package used was ANSYS. Although a primer for ANSYS was prepared, students had some difficulty using it. Students submitted weekly individual reports on the project. This was required ostensibly to improve their communication skills. They compared their finite-element results to the assumptions made in the development of the simplified theories. These comparisons included the stress distributions and maximum stresses of the crane analyzed as a truss compared to the crane analyzed as a frame. We had hoped to show that finite-element results can also be inaccurate compared to experimental data, but time did not permit the construction and testing of the crane.

Many lectures were given to support the design project. Whenever possible, a part of the design project was used to show how the lecture and textbook contents could help them in their design project. Nevertheless, many students did not seem to see the connections between the design project and lectures, or they did not care that there were connections. When students were reluctant to participate or could not formulate what they needed to learn in order to complete their designs, the instructor furnished the necessary materials.

CONCLUSIONS

Our impression is that the 'learning by design' paradigm benefits those students who are interested in learning the material, but they are not motivated by the traditional teaching approach. A number of students expressed the desire to see as many problems solved in class as possible. The bottom line for these students seems to be the ability to solve end-of-the-chapter exercises. This is perhaps a culture that we have promulgated in the current engineering curriculum. Despite the fact that only 30% of the course grade is assigned to the hourly examinations, students continue to view the test results as the most important indicator of how much they are learning.

The design exercises and report preparation are time consuming to the students. They do not seem to mind devoting a large amount of time to learn tools such as Pro/ENGINEER and ANSYS. However, some students do not readily show this effort in their lab reports. For these students, the large amount of effort spent on learning and using these modern design tools does not translate into a better grade. This seems to be a source of frustration and unhappiness to them, although in reality they have learned some valuable lessons in the process of designing the crane and preparing the report. On a set of questions designed to evaluate how the students feel about their progress in problem-solving ability on open-ended design questions (Questions a, b, c, and e of the ABET 2000 criteria) as a result of the static/strength of materials course, the average score was 2.6. A score of 1 represents no progress, and 4 represents a great deal of progress.

The end-of-the-semester survey shows that on a scale of 1 to 4, 1 representing no progress and 4 represents a great deal of progress, students rate themselves a score of 3.3 on Question g of the ABET 2000 criteria (the ability to function in a multi-disciplinary team). There was no case in which the students' grade was brought down by the design exercise. The average grade on the examinations was 80. The average grade on the design project was 89. Nevertheless, a level of dissatisfaction seems to permeate the attitudes of the students who feel their work merits a higher grade. A few students were highly motivated by the design and spent an extraordinary amount of time and effort on it.

A set of questions was designed to determine the ability of the students to function in a multidisciplinary team (Question d of the ABET 2000 criteria). These questions ranged from a) the ability to resolve conflict in a group, b) ability to listen, c) work collaboratively, d) organize information, e) ask probing questions, and f) evaluate different alternative. The average score for this set of questions is 2.9, in which 1 means no progress and 4 means a great deal of progress.

Item k of the ABET 2000 criteria is implemented through the use of Pro/ENGINEER, ANSYS, Matlab, and a host of engineering tools. The average score for this question was 3.8 in which 5 denotes a strong agreement and 1 denotes strong disagreement. Students across the board improved their report preparation skills (Item g of the ABET 2000 criteria). Interestingly, they rated themselves 3.3 on a scale of 5. Again 5 denotes strong agreement and 1 denotes strong disagreement. This is the area in which we felt they improved the most. Some students felt that they communicated well to begin with; often this was a significant misconception on their part.

In our experience, there is little correlation between the ABET 2000 criteria and doing well in hourly examinations. The final examination grade for the section that used the traditional approach is 81, while the section using the 'learning by design' approach averaged 78 on the identical final examination. Clearly, the ABET 2000 criteria are not directly correlated to the traditional examination grade.

The end-of-the-semester survey shows that students are learning many of the skills that ABET and employers feel are important, i.e. items corresponding to Questions a, b, c, d, e, g, and k of the ABET 2000 criteria. However, the final examination grade is not significantly affected by the learning paradigms. While some may argue that this result shows that the 'learning by design' approach is no better than the traditional approach, it can be said that the 'learning by design' approach improves students' skill in many areas deemed important by educators and employers without affecting their ability to solve traditional end-of-the-chapter problems. The most important benefit of the new paradigm may be the fact that the knowledge learned from this hands-on approach will most likely be retained for a longer period of time. A long-term study should be conducted to determine (1) if the new approach indeed improves knowledge retention, and (2) how students from the traditional approach perform compare with students from the new approach in follow-up courses in mechanics. Regardless of this result, we believe that the 'learning-by-design' approach to statics and SOM helps prepare students for the job market of the new century. Many of the criteria promulgated by both ABET and prospective employers are partially met by the new learning paradigm.

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