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Developing CAE Skills Through Web-Based Course Modules Across the Undergraduate Mechanical Engineering Curriculum

This paper describes a series of web-based course modules that have been developed to incorporate computer-aided engineering tools across the mechanical engineering curriculum. The modules are used at Carnegie Mellon University in required and elective undergraduate courses at the freshmen through senior levels, and they have been written through a collaboration among faculty members and students. The modules lead students through software use in the context of particular engineering problems, and so little or no classroom time is spent describing the "picks and clicks" needed to create numerical models. Instead, instruction and pedagogy emphasize interpretation and the extraction of important results from the flood of data available in a numerical model. The exercises are self-paced, and they encroach little on classroom time or traditional engineering science content. One such module has been used in a summer outreach program to expose elementary school students to computer-aided design, analysis, and manufacturing.

Introduction

Information technologies and computer-aided engineering tools are ubiquitous in mechanical engineering, with applications that include solid modeling, finite element analysis, motion simulation, machine tool path planning, and feedback control. In many industries, project management software is used for collaboration between conceptual designers, design and manufacturing engineers, marketing experts, and others—indeed, the backbone of distributed product development. Today, few would dispute the importance of CAE in mechanical engineering industrial practice. However, the educational community has adopted various models for balancing traditional engineering science content with these tools, and for integrating them with engineering curricula. The availability of CAE tools has not changed the fundamentals of mechanical engineering, but the revolutionary changes in how fundamentals are applied in industry point to the need for re-inventing mechanical engineering curricula.

A skill in demand for graduating engineering students is the ability to combine computational tools, intuition, and fundamentals effectively. Those factors are arguably more critical now than previously because today's engineers are often expected to make significant design decisions before any product testing can be done. This reality of industrial practice, where engineers fuse computer modeling and physical intuition with design and analysis, challenges the modernization of curricula with respect to familiarizing students with CAE software.

One difficult issue is the balance between traditional instruction of "engineering science" content and the

exposure to computer-aided engineering software packages and their often complex interfaces. We have found that self-paced and web-led CAE tutorials are a useful means for balancing traditional content and software training (in particular, Pro/ENGINEER Wildfire, ANSYS, Solidworks, Adams, and Matlab). In this paper, we discuss web-based modules for a variety of mechanical engineering courses. The intent of the effort is for students' use of the software packages to be transparently overlaid onto a traditional lecture-based curriculum – a so-called background curriculum. Significant planning by the entire faculty has gone into how and where computational engineering skills should be included in undergraduate instruction, and those plans have been incorporated into the department's process for continuous improvement of the undergraduate curriculum. The philosophy taken is one of full integration into both core and elective courses, beginning in the freshman year, so that students see information technologies as natural extensions of the fundamentals that they learn in the classroom. In the following sections, we discuss using the course modules in a required introductory course at the freshmen level and in required and elective courses offered to sophomores, juniors, and seniors.

The goal of this initiative is not to train students in navigating CAE software interfaces. Instead, it is to develop the ability to effectively combine computational tools, hands-on intuition, and engineering fundamentals. Because the web-based tutorials lead students through software use, no classroom time is spent describing the "picks and clicks" needed to create numerical models. Instead, classroom instruction and projects emphasize the interpretation results



and the extraction of important results from the flood of data available in a numerical model. Students should be able to “think in front of a computer” with a healthy skepticism of numerical results.

CAE Course Modules at the Freshmen Level

In 1991, Carnegie Mellon instituted major changes in its curriculum for first-year students in the college of engineering. In particular, first-year students began enrolling in discipline-specific introductory engineering courses. Rather than expose first-year students to engineering through seminars or a course which would survey all of the traditional fields, the alternative approach was taken in which each engineering department began offering a core introductory course. Engineering students complete two such courses during their first year, and after having been thus exposed in some depth to two fields, students declare a major. In 1996, a semester-long team experience in computer-aided design, analysis and manufacturing was incorporated into the introductory mechanical engineering course using web-based tutorials. Our experience in teaching the course “Fundamentals of Mechanical Engineering” [1] is that early exposure to computer-aided engineering can have a major impact on the perception that first-year students have of the mechanical engineering profession. Comments from students via course evaluations document that many students at this level are otherwise unaware that mechanical engineers use computers on a daily basis for design, simulation, and manufacturing operations.

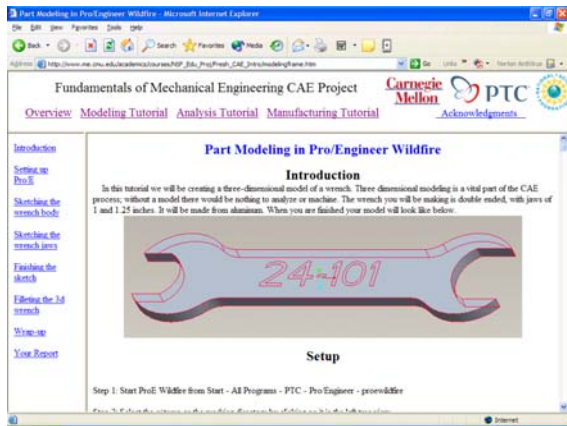


Figure 1: Screen shot of the introduction to the three-part tutorial sequence for modeling, stress analysis, and manufacturing of a wrench.

A web-based CAE course module in the freshmen year is an ideal means for exposing students to design, finite element analysis, and machine tool programming, and to leverage students’ natural interest in computer applications to motivate their study of engineering. Approximately 110 students enroll in the mechanical engineering course each semester, which carries a workload comparable to traditional first-year courses in mathematics and the sciences. As shown in Figures 1 and 2, the module has three parts:

- **Modeling:** Preparing the solid model and engineering drawing for an open-ended wrench.

- **Analysis:** Conducting a finite element stress analysis of the wrench including the steps of applying loads and boundary conditions.
- **Manufacturing:** Selecting tools for rough and fine pass cuts, and path planning, to machine the wrench from aluminum on a computer-controlled mill. The students are also given the option of producing their design in a rapid prototyping system.

In the end, each student walks away from the exercise with a wrench that he or she designed, analyzed, and fabricated without using paper, and through a process of seamlessly integrated computer software and hardware. In the analysis portion of the project, numerically-obtained stresses in the handle of the wrench are compared to those predicted on the basis of elementary beam bending equations. From the start, students are introduced to the concept of checking numerical results using “back of the envelope” calculations. The exercise is completed by some 220 freshmen students each academic year, about half of whom will eventually select mechanical engineering as a major. Feedback demonstrates that students’ changes in their perception of mechanical engineering as brought on by the this module have had a significant and favorable impact on their decision to choose mechanical engineering as a major.



Figure 2: Sequence of modeling, analysis, and manufacturing steps involved in completing the CAE wrench tutorials.

CAE Modules Across the Curriculum

Following the introductory exposure in the freshmen year, students continue to use self-paced CAE modules in the sophomore through senior years in both required and elective courses [2]. Links to all of the tutorials described in this paper can be found through www.me.cmu.edu, or at: www.me.cmu.edu/academics/courses/NSF_Edu_Proj/NSF_Overview.html. The modules include links for course descriptions, CAE assignments, and a list of skills developed in each module. All information on the web site is available for use by instructors in mechanical engineering programs at other universities.

As shown in Table 1, web-based CAE course modules have been developed for courses in different areas of mechanical engineering. In each case, the tutorials have



been written through a collaboration of students (typically undergraduate students) and faculty members.

Finite Element Modules for Sophomore- Senior Stress Analysis Courses

One series of tutorials developed for use by students after the freshman year involves use of the ANSYS finite element software for stress analysis [8]. These tutorials are used in a required course in the sophomore year which combines strength of materials with an introduction to more sophisticated stress analysis, and in an elective course taken primarily by juniors and seniors. The elective course builds on the required course, covering topics that include the equations of elasticity, finite element methods and fracture mechanics.

The stress analysis modules comprise five exercises: A Plate Under Uniform Loading, A Beam Under 4-Point Bending, A Plate with a Hole, Analysis of a Bicycle Pedal Crank and A Double Edge-Cracked Plate. These exercises encompass a range of modeling sophistication. However, each problem is presented via the same set of high-level steps, including: Specifying the Geometry, Applying Boundary Conditions and External Loads, Refining the Mesh and Interpreting the Results. The goal is to give students a feel for the major steps needed to construct and interpret a finite element model, independent of the model's details.

Because the first exercise is simply that of a plate under uniform uniaxial tension, the emphasis is on obtaining a first introduction to the software interface, accurately setting up the problem, and extracting (known) results. Using this easily-understood problem, the concepts of linearity and symmetry conditions are introduced. The beam bending problem is another example where the strength of materials student can analyze a problem easily interpreted by using handwritten calculations. Contour plots generated in this problem are an ideal means for demonstrating St. Venant's principle, which can otherwise be difficult for students to grasp.

link to an ANSYS database file (a full analysis results file) for the student to download. Emphasis is placed on the student's use of the postprocessor and interpreting the results that it provides. In the model of a loaded crank in the horizontal position, the crank is subjected to bending, torsion and shear. The roughly rectangular shape of the crank makes it an excellent platform for introducing the torsion of non-circular cross sections in an elective course.

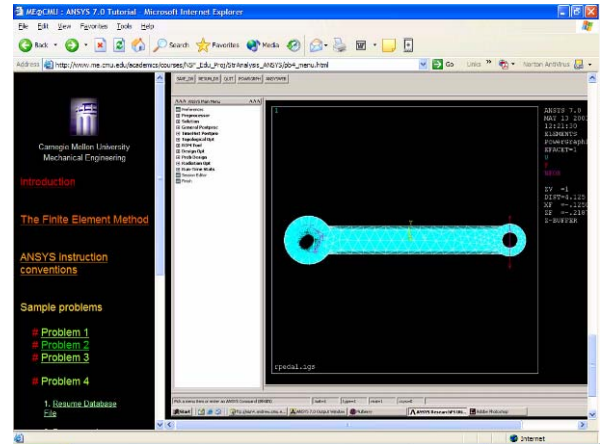


Figure 3: Screen shot of the stress analysis tutorial for a bicycle pedal crank.



Figure 4: Use of the design/analysis/manufacturing project in an outreach program for middle school students.

Year	Course	Web-based Tutorial	Software	Reference
Freshmen	Introduction to Mechanical Engineering	Integrated Exposure to Computer-aided Design, Analysis, and Manufacture	Pro/ENGINEER Wildfire	3
Freshmen	Introduction to Mechanical Engineering	Slider-crank Mechanism Motion Simulation	Adams	4
Sophomore	Statics	Tutorials for Statics	Solidworks	5
Junior	Dynamics	Motion Simulation Tutorials for Dynamics	Adams	6
Junior	Thermal-Fluids Engineering	Tutorials for Viscous Flow and Thermal-Fluids Engineering	ANSYS	7
Soph/Junior	Stress Analysis	Stress Analysis Tutorials	ANSYS	8
Junior	Dynamic Systems and Control	Tutorials for Dynamic Systems and Control and Feedback Control	Matlab	9
Senior	Design	Tutorials for Senior Design and Integrated Product Development	Solidworks	10
All	Graphics	Short Course Tutorials for Engineering Drawings	Pro/ENGINEER Wildfire	11

Table 1: Summary of web-based CAE tutorials in mechanical engineering.

Figure 3 shows a screen shot from the exercise entitled Analysis of a Bicycle Pedal Crank, the component that links the bicycle pedal to the crank shaft. This module includes a

Outreach Opportunities

During the summers of 2004 and 2005, the freshmen-level CAE module [3] was also used as the basis for a summer outreach short course. This activity was conducted in collaboration with the Carnegie Mellon Institute for Talented Elementary Students, a structured outreach program at the university that offers year-round courses in conjunction with various academic units. In each short course, 15-20 seventh- and eighth-grade students completed the wrench design, analysis, and manufacturing project over a three day period (Figure 4). These students, having no prior exposure to CAE, completed the exercises without difficulty, and left the program with an appreciation and enthusiasm for modern mechanical design practice.

Summary

Web-based course modules have been developed to expose mechanical engineering students to various



computer-aided engineering packages, and these have been implemented in courses across the curriculum from the freshmen through senior years at Carnegie Mellon University. Because the exercises are self-paced and can be completed with little or no supervision by instructors or teaching assistants, they generally encroach little on classroom time and detract little from emphasis on traditional engineering science.

We have found that student familiarity with the software packages and their interfaces can be useful on several fronts. First, lecture derivations and instruction are by their nature restricted to idealized geometries, and those concepts and models can be reinforced by providing students with tutorials on more realistic situations encountered in engineering. For instance, students can perform double checks of the computer simulations using the idealized models developed in lectures. Second, the CAE modules provide students with a means to visualize complex motions and geometries. Third, the tutorials provide students who are interested in computer simulation, and those who are interested in project work, with an alternative learning format that can improve their interest and motivation [12]. Our experience is that students who have a difficult time excelling in traditional lecture and test environments can thrive in activities that more closely parallel today's engineering practice.

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Pro/ENGINEER Wildfire, ANSYS, Solidworks, Matlab, and Adams are trademarks of Parametric Technology Corporation, ANSYS Incorporated, Solidworks Corporation, The Mathworks Incorporated, and MSC Software Corporation, respectively.

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