TRANSITIONING STUDENTS TO FINITE ELEMENT ANALYSIS AND IMPROVING LEARNING IN BASIC COURSES

Paul S. Steif[1], Edward Gallagher[2]

Abstract - **Much engineering practice today involves computer aided engineering tools. While the associated underlying theory is often beyond the abilities of many undergraduates, we still must prepare students who will be expected to use such tools in the workplace after graduation. At the same time, computer-based tools may also be used to improve learning in even the most basic subjects. For example, a significant aid in learning mechanics of materials is visualizing the basic patterns of deformations. Using readily deformable objects in class, such as foam bars, is one aid to visualization. This paper describes a very simple web-based finite element program, which can serve two purposes. First, it acquaints students with the basic steps in carrying out a finite element analysis. Second, this program makes a wide range of deformation patterns available for visual inspection, and thereby can facilitate an increased understanding of some of the variables of importance in mechanics of materials.**

Index Terms – deformation, finite element analysis, mechanics of materials, visualization

INTRODUCTION

Engineering educators must continually adapt to changes in the practice of engineering. One prime change is the increasing prominence in CAE tools that engineers use to simulate simple and complex engineering systems. In contrast to the past, it is clear that these tools are and will be used by bachelors-level engineers and, increasingly, even technicians, who have no grounding in the underlying theories upon which these packages are based. How should curricula reflect this changing reality?

Of course, there have been efforts for many years to introduce finite element analysis into undergraduate engineering programs [1-10]. Recent efforts tend to fall into two categories. One approach has students use commercial FEA packages [7,9-10], often comparing the results with other methods of analysis or with design efforts. A second approach involves assignments that expose students to the underlying numerical method [5,8].

These approaches will appeal to some departments and instructors, but not others. Many engineering departments do not want to focus on teaching the intricacies of the user interface of specific programs, although some schools have effectively off-loaded the learning of parts of the interface to tutorials, which students can work on outside of class. In addition, not all schools can offer many students access to commercial packages. For some departments, focusing on the underlying numerical method is not of interest.

This paper offers a new instructional paradigm for addressing the clear importance of computer aided engineering in the workplace, which remains true to the traditional strengths of engineering education at universities. Specifically, we argue the criticality of students learning the physical significance of the principal input and output variables of the CAE method of interest. Second, we believe that students should learn the main conceptual steps associated with applying CAE method, and how those steps relate to the physical system being simulated. We demonstrate this approach for the case of Finite Element Analysis (FEA) of stresses in elastic bodies. In short, we accomplish these goals through a greatly simplified, yet highly accessible finite element program, which can be run, among other means, over the web.

There is a second, and perhaps equally compelling, motivation for developing this simplified FEA program: it can even improve learning of fundamentals in elementary engineering science courses, particularly in mechanics of materials. Within the physics education community, it widely appreciated that even students who apparently can solve traditional physics problems with paper and pencil have serious flaws in their understanding of physics concepts. These naïve views of physics are revealed only upon close observation, for example, in interviews of students [11-13]. These interviews typically call upon students to interpret observable phenomena through the concepts of physics; the interviews betray an extremely

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weak connection between the symbols students manipulate in equations and the reality that those symbols represent.

The prominence of making those connections has been articulated by Laurillard [14], who contends that learning at the university level includes working effectively with representations of phenomena in the world. As she puts it, learning includes "relating the sign to the signified." In engineering, this means relating the variable to what it represents. Indeed, this is precisely what Trowbridge and McDermott [11] were probing in their interviews of students regarding velocity. In mechanics of materials motion, relative motion and deformation are important concepts. To demonstrate a grasp of these concepts, students must be able to interpret these concepts in particular instances when they are relevant, and to connect them to representing variables (displacement, stretch, and strain). To grasp these concepts, one must observe instances of deformation first hand.

As an example of offering first-hand experience with physical examples of the concepts under study, recent work [15-16] in Statics and Mechanics of Materials has taken advantage of students' senses of touch and sight. Activities include students observing and manipulating systems that deform. Being able to view the deformation produced by forces appears to play a powerful role in helping students perceive the very presence of forces. The ability of students to visualize deformation modes (bending and torsion) seems to be facilitated by experiences manipulating flexible (e.g., foam) members with highly visible lines drawn on them.

We seek the opportunity to acquaint students with a greater variety of deformations than can be readily accomplished with actual deforming members. It is our contention that a finite element program that displays the deformed shape of a loaded body can be similarly exploited to provide nearly physical counterparts to a variety of deformation states that are addressed in elementary strength of materials courses. This paper describes, therefore, the basic features of simple web-based program that we are developing, as well as how this program is used to improve understanding of the basic variables and conceptual steps of finite element analysis.

ELEMENTARY FEA PROGRAM

For the reasons given above, we have developed a web-based finite element program, which is accessible, conceptually and technologically, to students at the very beginning of a mechanics of materials course. This accessibility derives from the absolutely minimal, but carefully chosen, capabilities of the program. Specifically, the current version of this program has the following elements:

- features and highlights the primary steps of a commercial finite element program (specify domain, material, element type, mesh, and boundary conditions, as well as solve and obtain results)
- has limited capabilities (only 2-D rectangular domains, uniform mesh, linear elasticity, force or displacement at each node) and is simple to learn and use
- augments visualization of deformation state by movement of a slider, and displays displacements, external forces, stresses and strains at any point.

The program, which includes only a single screen, is shown in Figure 1. The program has been written in Java and can be run over the web. (Triangular elements are always paired as part of a rectangle, and triangles are not shown to simplify the display.)

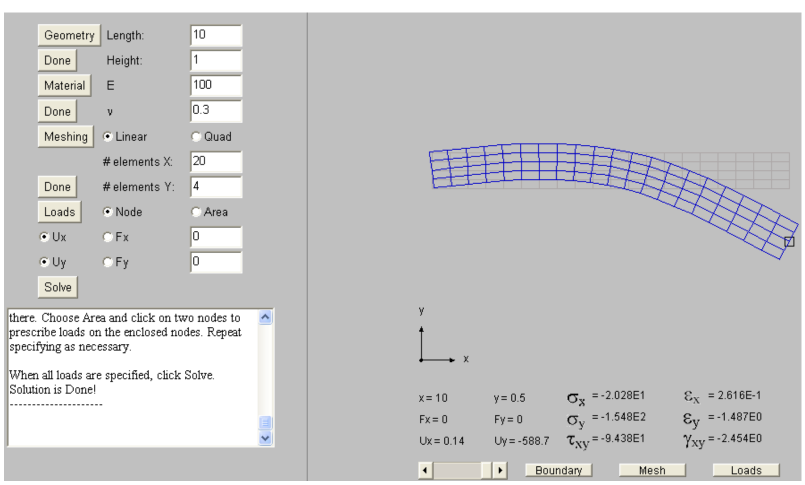

FIGURE 1
SINGLE SCREEN GRAPHICAL USER INTERFACE FOR FEA PROGRAM

USE OF PROGRAM IN COURSE

The program is envisioned to have two primary uses: (i) for instructors with access to a computer and projection equipment in lecture hall to demonstrate ideas through pre-defined example problems, and (ii) for students to do homework assignments that complement typical problems solved in mechanics of materials.

Pre-defined problems for demonstration in class

In each of the examples below, we would draw the idealized problem on the board, and then solve the problem with the FEA program.

The example in Figure 2 illustrates the fundamental, but difficult to comprehend, idea of internal force:

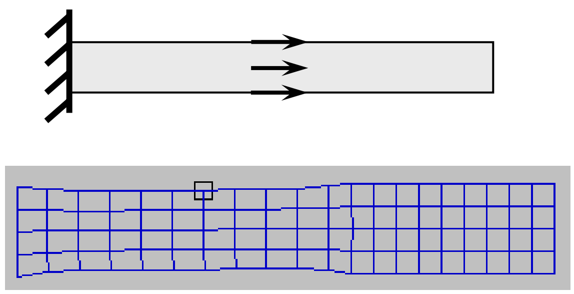

FIGURE 2
PROBLEM ILLUSTRATING CONCEPT OF INTERNAL FORCE.

The example in Figure 3 illustrates St. Venant's principle, that the precise distribution of applied force affects the result near the applied loads, but not far away:

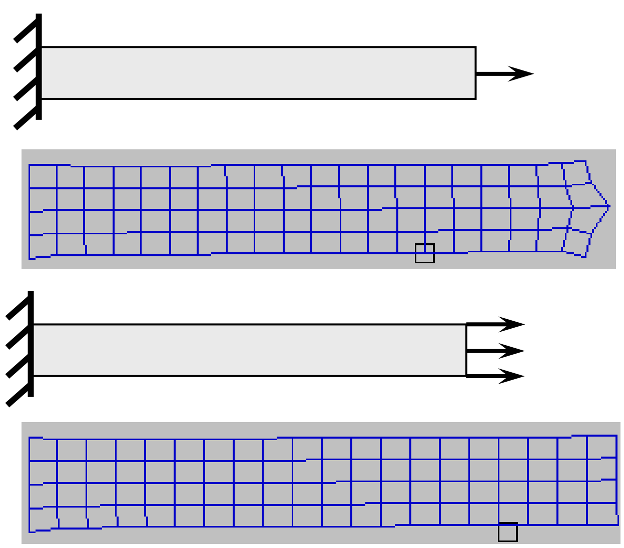

FIGURE 3
PROBLEMS ILLUSTRATING ST. VENANT'S PRINCIPLE.

The example in Figure 4 illustrates the effect of applying an axial force off the center-line of a bar:

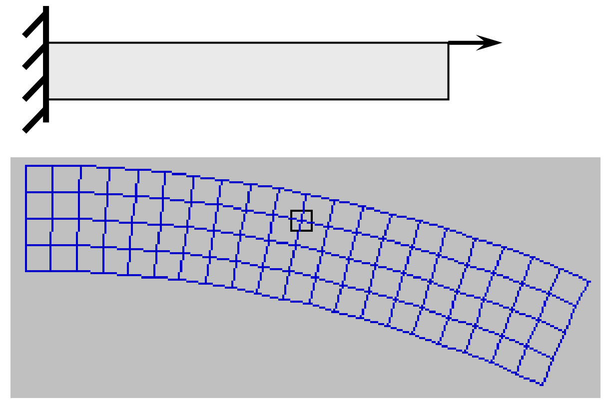

FIGURE 4
PROBLEM ILLUSTRATING THE BENDING EFFECT OF AN AXIAL FORCE WHICH IS APPLIED OFF THE CENTER-LINE OF THE BAR.

HOMEWORK ASSIGNMENTS

A wide variety of homework problems can be devised which require students to use the FEA program on their own. Typically, these problems are tightly coupled with other more traditional problems in the same week's homework assignment. This approach draws on the idea that people learn a topic more effectively when they see the same ideas in different contexts.

As one example (Figure 5), a homework assignment which addresses bending deformation and stress included the following textbook problem:

A thin strip of steel of length L = 20 in. and thickness t = 0.2 is bent by couples M_0. The deflection δ at the midpoint of the strip measured from a line joining its end points is found to be 0.25 in. Determine the longitudinal strain at the top surface of the strip, the bending moment M_0, the curvature, the final length of the top and and bottom, and the stress at a distance of 0.04" above the bottom surface.

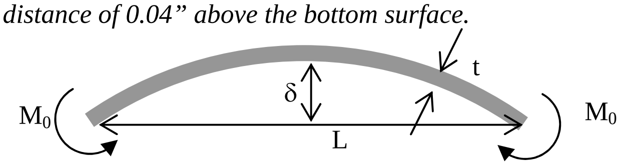

FIGURE 5
TYPICAL HOMEWORK PROBLEM ADDRESSING BENDING OF A STRIP.

In this same assignment, students solved the following complementary FEA problem (Figure 6):

The region to be analyzed should be 30 long by 6 high (by default it always has thickness in the plane of 1). Let the Young's modulus E be $30x10^6$ and the Poisson ratio be ν = 0.3. Interpret all units as being in combinations of lb and inches. Use a mesh which is 30 divisions in the x direction and 12 divisions in the y direction. There are loads prescribed only on the four corners. At A, both x- and y-

displacements are zero; at B, the x-displacement is zero, and the y-force is zero. Forces in the x-direction are applied at C and D in the directions shown with magnitudes 20,000 at each point. There are no y-forces at C and D.

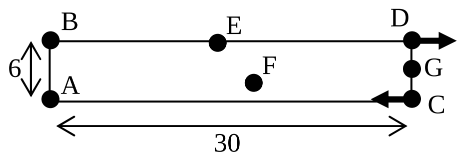

FIGURE 6
FEA ASSIGNMENT THAT COMPLEMENTS THE TRADITIONAL HOMEWORK PROBLEM IN FIGURE 5.

From the FEA extract:

- *the stresses σ_x at points E and F (locations given).*
- *the deflections u_x and u_y at point G.*

This problem is one which you can analyze using bending theory. Use bending theory to predict the same quantities which you extracted from the FEA and compare them.

The complementary problem above using the FEA code features a two-dimensional region with a loading that causes it to deform like a beam. The results can be compared with traditional methods of predicting stress and deformation in beams that the student has just learned (finding the stress from the bending moment and cross-section and finding the curvature from M, the cross-section and the elastic modulus).

Certain lessons can be learned from examining the FEA solution to any problem, including this one. If the student looks at different points in the domain and observes the motion (left or right, up or down), these motions are seen to correlate with the variables u_x and u_y, which gives meaning to these symbols. Likewise, the strains ε_x and ε_y can be seen to reflect whether individual elements get longer or shorter in each of the coordinate directions. Both the motions, and sometimes the changes in length, are made more evident by "animating" the deformation of the body (with the slider).

A number of ideas can be clarified which are peculiar to these two problems. The application of a couple at the end tends to be something students use without thinking about its meaning. Students need to be reminded that this load is always applied with forces, which is more apparent in the FEA. Likewise, the cantilevered support at the left end could be brought about in many statically equivalent ways. Here, just two points are held, leading to a force at each. The resultant of these forces can easily be seen to correspond to a force and moment. Should more points at the left end be restrained and all the reaction forces extracted, then the combination of forces is still found to be equivalent to the required force and a moment. Using the scroll bar that animates the deflection, students can see the curvature of beam and the downward deflection of the end; they can even see that elements at the top elongate and those at the bottom contract. The meaning of the cantilevered support as far as deflections can be seen with the center-line remaining nearly horizontal at the left end.

This same problem (and many others) can be used to highlight St. Venant's principle. The student tracks the values of the stress σ_x, as the cursor is moved over various points on the top of the bar. The stress is uniform, as is predicted; but when approaching the ends the stress increases due to the proximity to the concentrated force. One can also, very quickly, remove the forces at the right end, and apply an equivalent couple, using the top and bottom faces. The student sees that the deflections are very close to the previous case, and that the stresses are similar, at least away from the loaded end. Differences in stress exist where the loads are applied.

The following FEA problem (Figure 7) can be used to illustrate the meaning of strain components and their relation to displacements on the one hand and to stresses and loads on the other. Horizontal displacements are prescribed uniformly across three cross-section – at say the leftmost, center and rightmost cross-sections. The displacements can be adjusted to give tension or compression in each of the two segments of the member. As before, the student gets to see the motion (animated with the slider), and its correlation with the variables u_x and u_y. Likewise, the axial strains, differing in the two segments but constant within each, are correlated with ε_x; transverse strains are seen to differ as well, correlated with ε_y. The displacement u_x is seen to increase proportionally with distance from the fixed left end, consistent with the constant strain in the left segment. The strains are consistent with the stresses through the modulus and the Poisson ratio. Finally, the stresses can be related to the external forces acting at the cross-sections (summing the nodal forces F_x), reinforcing the very difficult idea that internal forces, which are related to stresses, are distinct from the external forces.

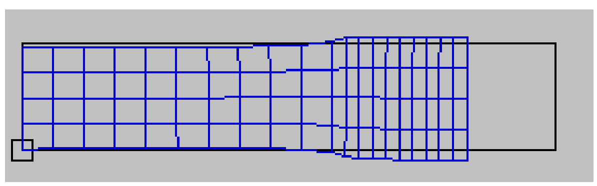

FIGURE 7
FEA ASSIGNMENT EXERCISING VARIOUS ASPECTS OF THE DEFORMATION OF A BAR IN AXIAL LOADING .

EXPERIENCE OF STUDENTS USING PROGRAM

Students used the program for 7 homework problems during the Spring 2003 semester. (There might typically be 5 to 8 problems in a typical week's homework.) The problems were similar to those illustrated above in the section on Homework Assignments. Students were surveyed near the middle of the semester regarding various aspects of the course, including use of the simple FEA program. At that time, students had used the program for 4 problems. The following questions were included in the survey. After each question are the responses from which students could select, and the numbers of students who selected each option.

If you have done at least a few FEA assignments, did you find them valuable?
No value_1 Slightly valuable_13 Somewhat valuable_32 Very valuable _7

If you have done at least a few FEA assignments, did they improve your understanding of the non-FEA material?
No help_5 A little_24
Moderately_19 Significantly_6

This response during the first year had been sufficiently positive that further development was considered to be worthwhile. The program may be accessed at http://www.me.cmu.edu/academics/courses/nsf_edu_proj/mini_fea/.

CONCLUSIONS

Undergraduate engineering programs need to accommodate the significant role that computer aided engineering, such as finite element analysis, plays in engineering practice today, and the reality that engineers will use these technologies without the benefit of understanding the basic theories underlying them. Here we argue that at a minimum students need to understand the significance of the key input and result variables used in such programs. In fact, we also propose that a basic finite element program, which is simply accessed and displays both the deformation and values of key variables, can indeed, help students to understand the significance of these variables. Such a program has been developed and its use in the classroom and for homework assignments has been demonstrated. Reactions of students to using initial versions of this program have been positive.

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