Use of Simplified FEA to Enhance Visualization in Mechanics

Paul S. Steif, Edward Gallagher
Carnegie Mellon University

Introduction and Background

Many recommendations have arisen from national reports[1,2] which noted the increasing need to improve undergraduate education in engineering. A central suggestion is that "Institutions of higher education should provide diverse opportunities for all undergraduates to study science, mathematics, engineering, and technology as practiced by scientists and engineers, and as early in their academic careers as possible"[3]. This is also recognized in the ABET criterion[4] that graduates must have "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice."

Among the modern engineering tools, it is clear that computer-aided-engineering tools, for example, CAD, FEA and CFD are essential to the contemporary practice of engineering. Finite element methods, for example, have been taught for some time, with some of that experience recorded in the literature[5-15]. Most experience being at the upper level undergraduate or graduate level, although some departments even have experimented with having students learn the underlying basis for finite element methods in elementary mechanics courses[11].

A drawback to using them is that commercial CAE packages, while possessing enormous capabilities, can take some time to learn to use. Instructors may also shy away from having students work with FEA because even linear elasticity, the simplest theory underlying finite element analysis as applied to continuous solids, is well beyond what undergraduate students typically learn. Yet, many such students will come to use such CAE tools as practicing engineers without further education in the underlying fundamentals. *Undergraduate education needs to address this reality*. It is also hard for many instructors to justify the introduction of commercial computer-based engineering tools into a course without a strong link to the primary learning of students in that course. Indeed, as now explained, we believe that the use of a simplified finite element program can advance primary learning in the subject in pedagogically sound ways.

Relevant Lessons from Research on Learning

It is widely recognized now that while students learn to solve traditional physics problems (by manipulating the correct memorized equations), their explanations of observable phenomena still reflect naïve concepts of physics. Experience with the Force Concept Inventory (FCI), for example, which asks simple questions interpreting observable phenomena through the concepts of physics, provides proof of this proposition[16]. Instructors in science and engineering should help students develop the ability to relate observable aspects of the everyday world to the subject they are learning.

Another view of this idea is due to Laurillard[17], who contends that learning at the university level means, at least in part, working effectively with representations of phenomena of interest in the world. Moreover, as she puts it, learning includes “relating the sign to the signified.” In engineering, this means relating the variable to what it represents. In mechanics of materials, displacement and deformation of bodies are the most readily observed quantities. Thus, if students can visualize deformation, and connect that deformation to the variables that represent it (displacement, stretch, strain), and to the variables that are related to it (forces and stresses), then a student has many essential concepts of the subject in hand.

Recent work[18,19] has focused on teaching mechanics to take greater advantage of other sensory modalities of the student, including the senses of touch and sight. For example, to make forces real, students balance objects and themselves and relate the forces they feel to the predictions of Statics. Also to make forces real, students observe and manipulate systems that deform, both in Statics and in mechanics of materials. Being able to view the deformation produced by forces appears to play a powerful role in helping students relate the quantities of mechanics to what they actually represent. For learning bending and torsion, for example, the use of a flexible (e.g., foam) member with highly visible lines drawn on it, can be effective in class. There would be benefits in extending this idea to demonstrate a greater variety of planar deformation states, say with a thin flexible sheet, although this proves to be difficult in practice. Here, we contend that a two-dimensional finite element program that displays the deformed shape of a loaded body may be used to a similar purpose.

It is also known that rapid feedback on student efforts during learning is of great benefit[20]. When one can specify points at which a body is fixed and points at which forces are applied and see the resulting deformation of the body, surely this constitutes feedback. Indeed, this is termed intrinsic feedback[13], or a direct consequence of a student’s actions; by contrast, extrinsic feedback is the grade a student receives on a homework assignment, for example. Moreover, if a FEA program that displays the deformation of a loaded body allows one quickly to consider a variety of load cases, then the conditions are set for students to obtain rapid feedback.

Elementary FEA Program

For the reasons given above, we believe it would be beneficial to make finite element analysis (FEA) accessible, conceptually and technologically, to students at the very beginning of a mechanics of materials course. While a commercial FEA program could be used for the purposes explained below, we think it is far more feasible to have a program which more attuned to the task. That is, a program that is extremely easy to use, and is accessible to all students. We describe here an effort to do this by developing a simple, intuitive FEA program, the simplicity made possible by virtue of the absolutely minimal, but carefully chosen, capabilities of the program. A preliminary version of this program has the following features:

- features and highlights the primary steps of a commercial finite element program (specify domain, material, element type, mesh, and boundary conditions, and 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
- displays deformed state immediately, and permits the usual quantities (displacements, forces, stresses and strains) to be evaluated 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.)

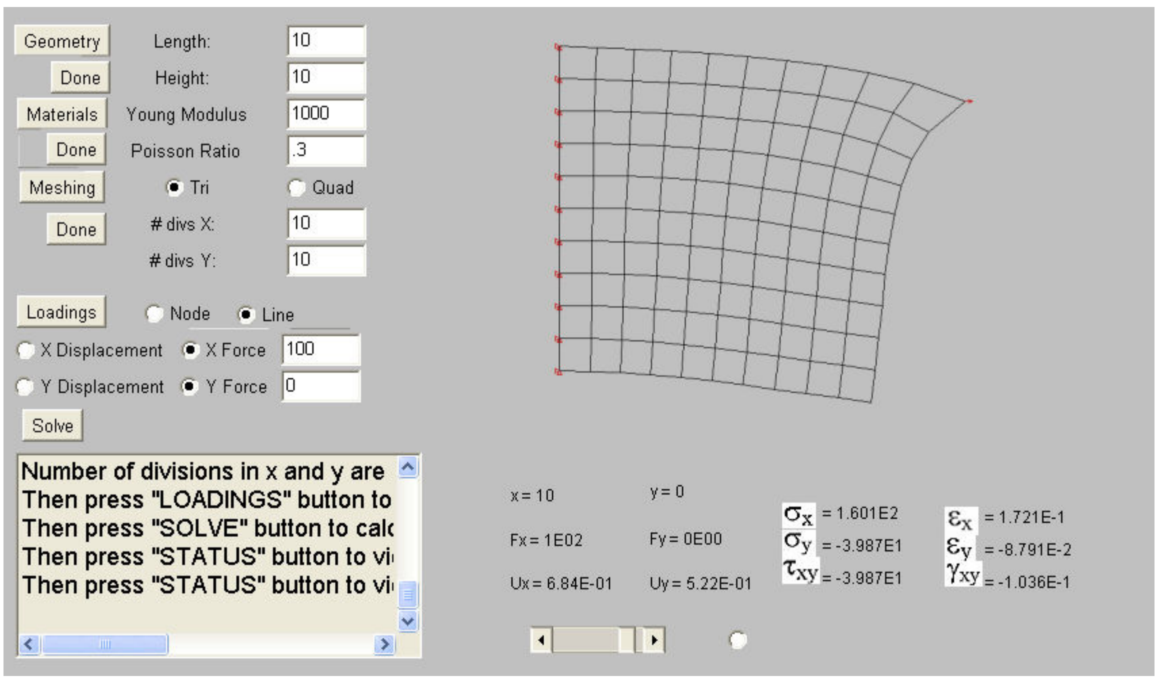

Figure 1. Single Screen Graphical User Interface for Web Based FEA Program.

Use of Program in Class

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.

<u>Examples of pre-defined problems for demonstration in class</u>
In each of the examples below, we draw the problem on the left and show the deformed mesh as predicted by the finite element program.

This example illustrates the fundamental, but difficult to comprehend, idea of internal force:

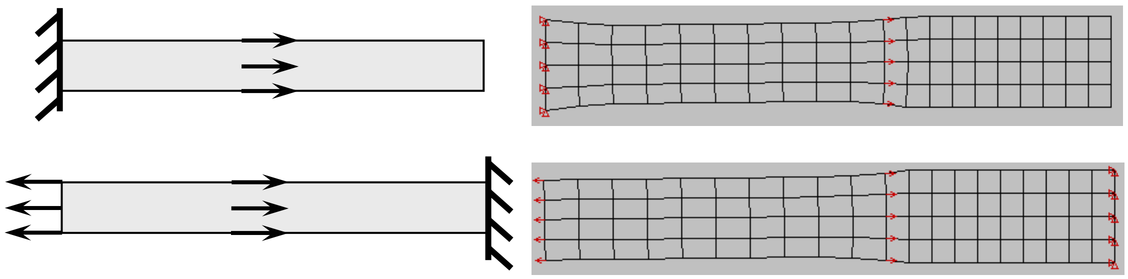

Figure 2. In-class demonstration of concept of internal force.

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

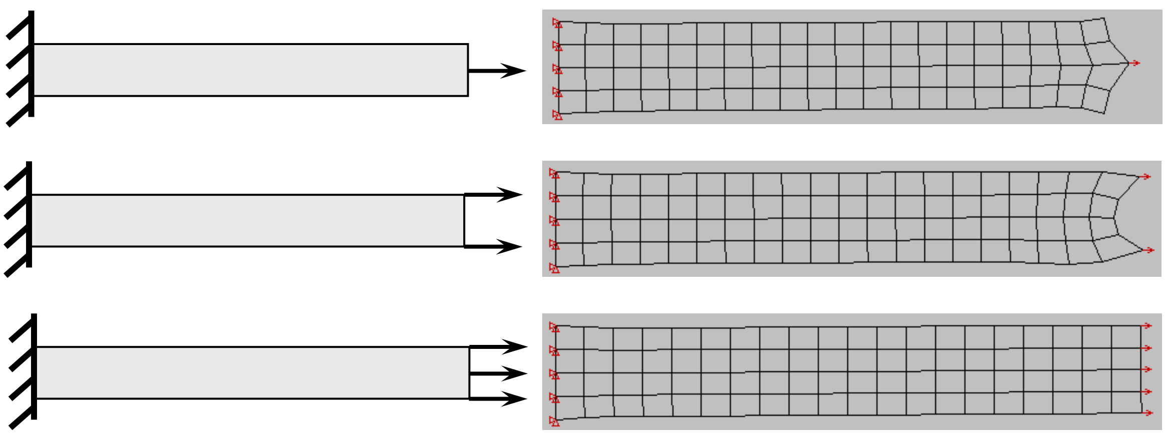

Figure 3. In-class demonstration of St. Venant's principle.

This example illustrates the effect of applying an axial force off the center-line of a bar:

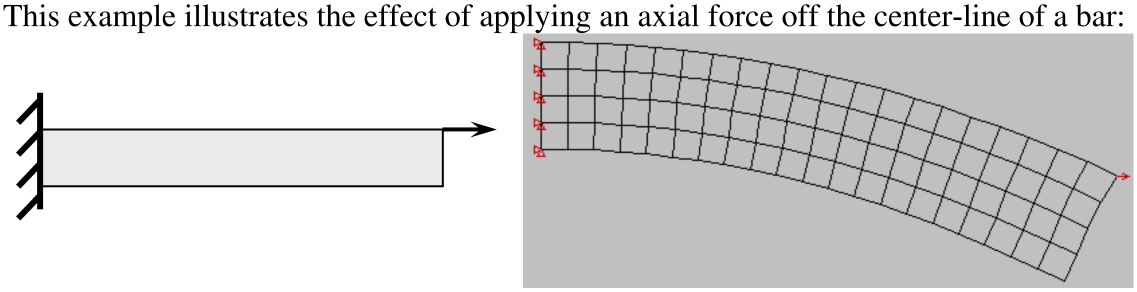

Figure 4. In-class demonstration of effect of an axial force applied off center.

Examples of Assignments For Students

One goal is for students to translate from the usual notation for loads in strength of materials into FEA input. It can be argued that students benefit from an alternative view of even the simplest problems treated in strength of materials, a view that can be obtained by doing a finite element analysis. For example, the following type of problem is commonly treated in strength of materials. Students might be asked to determine stresses and displacements at several points, using the traditional methods they have learned. These quantities are often computed in a rather routine manner, without their physical significance appreciated (fully or at all). For example, it is not easy to grasp the concept that the segment to the right of the 60 N force feels no stress, or the segment to the left of the 20 N force feels a stress due to 40 N, not 20 N. However, once they solve this problem in FEA and view the distorted mesh, then the results take on more reality.

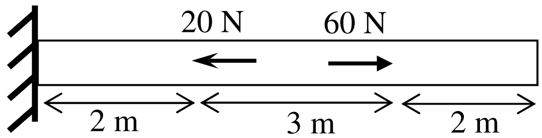

Figure 5. Homework assignment addressing axial loading.

One conceptual difficulty students have is seeing the support as applying a force, to be treated just like the other forces in determining internal forces and stresses. As an additional problem, students can replace the support at the left end with a 40 N force and specify displacements to be zero elsewhere (at, say, the right end). Students will see the same shape change and same stresses as before, but now the body is shifted.

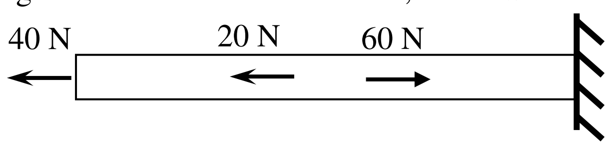

Figure 6. Homework assignment complementing that of Figure 5, showing how similar internal forces can lead to different variations in deflection.

More sophisticated problems can be addressed, once students have begun learning beam theory. For example, they can be asked how they would translate the loads and supports as drawn in beam theory into finite element input. Being able to express a distributed load or an applied moment in the form of individual forces on nodes is some indication of a higher-level understanding of these loads. Students can also be asked to carry out the analysis in FEA and compare with calculations from beam theory. (The roller could be removed, if a statically determinate problem is preferred.)

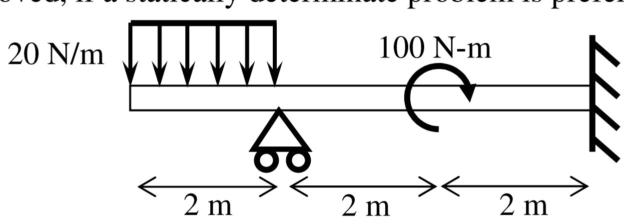

Figure 7. Homework assignment requiring students to convert boundary conditions as portrayed in beam problems into finite element input.

Another goal is to be able to compare FEA results with a simpler, more approximate analysis (i.e., strength of materials). Consider the following problem, with displacements prescribed at three points and a force at a fourth point. Even if the body is not very long compared to its height, beam theory can give at least rough estimates of the level of stresses.

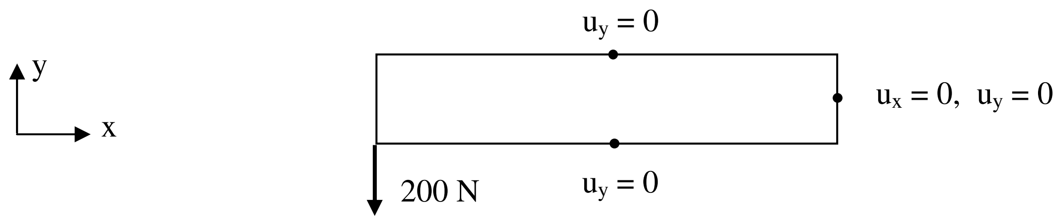

Figure 8. Homework assignment requiring students to boundary conditions from elasticity into a beam problems.

Initial Experience With Pilot Version Of Program In Class

A pilot version of the FEA program was used as a basis for assignments in a mechanics of materials class in the Department of Mechanical Engineering Carnegie Mellon University in the Spring 2003 semester. This class consists of mechanical engineering majors, most of whom were second-year students. During that semester, there was a total of 7 homework problems were assigned using the program. An example of one of the problems is as follows. (This was the second of two problems. The first problem dealt with uniform uniaxial tension, and included the idea of applying forces to the nodes across one end so as to produce uniform tension.)

This problem is to be analyzed both using the techniques you learned in axial loading and with the simple FEA program. Use a mesh which is 4 divisions in y and 60 divisions in x. Take E = 1000 and Poisson ratio = 0.3. Fix the ends completely against x- and y-displacement. Apply the forces (equal to 60 and 20) across their respective cross-sections, so as to simulate a uniform stress (equal forces applied to the central nodes, half those values applied to the upper and lower nodes).
From the FEA calculate the deflections in the x direction and the stress in the x-direction at the cross-section 35 from the left end. Compare those FEA results with the results of hand calculation from axial loading.

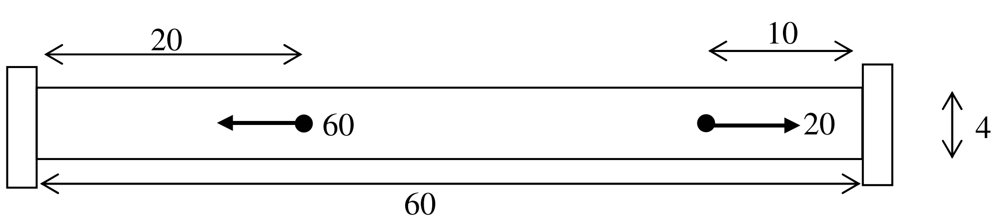

Figure 9. Homework assignment used in pilot testing of program.

Students were surveyed near the middle of the semester regarding various aspects of the course, including use of the simple FEA program. By this 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

As this program was still in a very preliminary form, and this was our first experience in framing assignments for its use, no assessment of the quantitative impact on specific learning objectives were conducted. Still, the reaction of students to this very tentative exploration was positive enough to warrant further exploration of this idea.

Summary

There is a need to integrate exposure to CAE tools into the undergraduate engineering courses. In addition, in some instances, one can harness that exposure to directly benefit learning of the core concepts of the subject. Here we have argued that a simple to use FEA program, with its ability to display deformed shapes, can serve the important goal of improving understanding the fundamental concepts of displacement and deformation. To this end, we have developed such a program, with two uses in mind: for instructors who wish to use demonstrate certain key points in lecture, and for students to use to do homework assignments. Preliminary testing of this idea in a sophomore mechanics of materials course has been conducted, with encouraging response of students.

Bibliographic Information

1. National Research Council. (1996). *From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology.* Report of a Convocation. Washington, DC: National Academy Press.
2. National Science Foundation. (1996). *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology.* (NSF 96-139) Arlington, VA: National Science Foundation.
3. Committee on Undergraduate Science Education, (1999). *Transforming Undergraduate Education in Science, Mathematics, Engineering and Technology*, National Academy Press, Washington, D.C.]
4. http://www.abet.org/images/Criteria/E1%2003-04%20EAC%20Criteria%2011-15-02.pdf (accessed June 3, 2003).
5. Hardy, S. J., (1985). Teaching programme for finite element analysis *International Journal of Mechanical Engineering Education*, v 13, n 3, p 191-194.
6. Brown, David K., (1986) on the teaching of the finite element method of stress analysis using basic on micros *International Journal of Mechanical Engineering Education*, v 14, n 4, p 221-234.

7. Gessel, G. R., Rieder, W. G. & Tennyson, S. A., (1987). Integration of microcomputer based finite element analysis into the undergraduate mechanical engineering curriculum, *Computers in Education Journal.* v 7, n 2, p 7-10)
8. Carr, J.B., Pilkington, D.F. & Barlow, M.I., (1989). Design and implementation of a finite element system for educational use, *International Journal of Mechanical Engineering Education*, v 17, n 4, p 265-276.
9. Sadiku, M. N. O., Makki, A. Z. & Agba, L. C., (1991). A further introduction to finite element analysis of electromagnetic problems, *IEEE Transactions on Education*, v 34, n 4, p 322-329
10. Jensen, D. & Pramono, E., (1998). Method for teaching finite elements which combines the advantages of commercial pre- and postprocessing with student-written software, *Computer Applications in Engineering Education*, v 6, n 2, p 105-114.
11. Brinson, L.C., Belytschko, T., Moran, B. & Black, T., (1997). Design and computational methods in basic mechanics courses, Journal of Engineering Education, v 86, p 159-166.
12. Boronkay, T. G. and Dave, J. "Introduction of Finite Element Methods in the Lower Division Mechanical Engineering Technology Curriculum" Proceedings of the 1997 American Society for Engineering Education Annual Conference & Exposition, 1997.
13. Cronin, P.J. " A simple problem which students can solve and check using an inexpensive calculator ", Proceedings of the 2000 American Society for Engineering Education Annual Conference & Exposition, 2000.
14. Baker, J. R., Capece, V. R., Lee, R. J. "Integration of Finite Element Software in Undergraduate Engineering Courses" , Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition, 2001.
15. Pike, M. "Introducing Finite Element Analysis in Statics", Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition, 2001.
16. Hestenes, D., Wells, M. & Swackhammer, G., (1992). Force Concept Inventory, The Physics Teacher, Vol. 30, pp. 141-151.
17. Laurillard, D. (1993). Rethinking University Teaching: A Framework for the Effective Use of Learning Technologies, Routledge, London.
18. Steif, P.S. and Dollar, A., "A New Approach To Teaching And Learning Statics", Proceedings of the 2003 American Society for Engineering Education Annual Conference & Exposition, Nashville, TN, June 22-25, 2003.
19. Steif, P.S. and Dollar, A., "Collaborative, goal-oriented, Manipulation of Artifacts by Students during Statics Lecture", 33rd ASEE/IEEE Frontiers in Education Conference, Boulder, Co., November 5-8, 2003.
20. Bransford, J.D. & Stein, B.S. (1993). *The IDEAL Problem Solver (2nd. ed.),* New York, Freeman.

Biographical Information

PAUL S. STEIF
Professor, Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, Pa
Degrees: Sc. B. 1979, Brown University; M.S. 1980, Ph.D. 1982, Harvard University.
Research area: solid mechanics and engineering education.

EDWARD GALLAGHER
Associate Engineer, Bechtel Bettis Inc., Charleston, SC
Degrees: B.S. 2003 Carnegie Mellon University