Finite Element Analysis in a Mechanics Course Sequence

William Edward Howard, Joseph C. Musto, Vincent Prantil
Milwaukee School of Engineering

Abstract

Finite element analysis has evolved from a specialized task to a mainstream design tool over the past decade due to faster and cheaper computer hardware and user-friendly software. As a result, teaching the finite element method to a greater number of undergraduate students has become a priority for many engineering departments. At Milwaukee School of Engineering, a finite element analysis course in the Mechanical Engineering department has been redesigned to take advantage of PC-based FE and solid modeling software, while providing a solid introduction to finite element theory. The course covers element formulations for 1-D spring and 2-D truss, beam, and triangular structural plate elements by direct equilibrium and energy methods. A simple heat transfer element is also considered. Lab exercises are designed to complement the lecture material, and the project culminates in a design project. Solid modeling software is introduced during the course, and is used by the students to make quick design iterations for their projects.

This course will be required for all mechanical engineering students at Milwaukee School of Engineering within two years. Therefore, topics typically included in other mechanics courses (energy methods, stress concentrations, failure criteria, torsion of non-circular shafts, etc.) can be incorporated into this course where appropriate. The authors discuss plans for the integration of the course into the required mechanics course sequence, as well as opportunities for inclusion of finite element analysis in subsequent courses.

I. Introduction

Finite element analysis (FEA) gained widespread use in specific industries, most notably the aerospace industry, in the 1960's and 70's. A mainframe computer was required to run the programs, so the use of FEA was generally restricted to larger companies. The role of the stress analyst was fairly specialized. Finite element models typically required days or weeks to create, and the lack of a graphical interface made the task of interpreting results difficult. Proper element selection and meshing of a model were critical to obtaining good results.

During the 1980 and early 90's, as personal computers became widespread, FEA software evolved to the point that a reasonably powerful PC could be used to perform relatively complex analysis. Graphical user interfaces streamlined the tasks of model creation, meshing, and result interpretation so that a competent engineer with good computer skills could become proficient at FEA without devoting full time to the task.

With the rapid growth of solid modeling in the mid-to-late 1990's, FEA has become an integral part of the design process for many companies. Rather than creating a model from scratch with the FEA program, the same solid model that is used for creating 2-D manufacturing drawings, rapid prototype model files, and tool paths can be used as the starting point for the FEA model. The ability to quickly change dimensions on the solid model enables analysis runs of many different configurations to be performed in a short period of time. In the iterative design process, then, FEA can be used in selecting the best design configuration.

As a result of the rapid evolution of solid modeling and finite element software, the distinctions between the roles of design engineer, stress analyst, and draftsman have become increasingly blurred. At Milwaukee School of Engineering (MSOE), a survey of our recent mechanical engineering graduates showed that the most common job category was mechanical design. As a result, we strongly encourage upperclassmen to add finite element analysis and solid modeling as two tools they should have when seeking employment. Beginning in the fall of 2002, seniors will be required to take one FEA course.

Traditionally, university courses in FEA have fallen into one of two categories: 1) mathematically rigorous theory courses that are targeted toward researchers who will create their own codes, and 2) courses primarily focused on learning to use a specific FEA program with minimal theory. Other universities have experimented with using FEA in basic mechanics courses. Of particular note, Brinson et al.[1] describe the incorporation of the finite element method as early as the first course in mechanics (statics) at Northwestern University. This course also includes instruction in matrix algebra, and the inclusion of rod and truss elements is seen as a practical application of both traditional topics (unit vectors and direction cosines) and matrix math.

In the Mechanical Engineering Department at MSOE, we set out to create a course that would provide enough theory for a practicing engineer to have a sufficient understanding of the workings of a code. At the same time, we wanted to provide enough experience working with a commercial program so that the student completing the course can feel that FEA is a tool that he/she is comfortable using in the design process. These goals were made based on the assumption that this course would be most students' only study of FEA before graduation.

II. FEA Course at Milwaukee School of Engineering

The software that we chose is the Algor® finite element analysis program and the SolidWorks® solid modeling program. Algor® was chosen because it works well as both a stand-alone program and working with a solid modeling interface. SolidWorks® was chosen primarily because of its ease of use and its widespread commercial use in our region. We chose not to use an FEA program that is completely integrated into the solid modeling program, as we wanted students to use a variety of element types.

The class structure of the course is two hours per week in lecture and two hours per week in a computer laboratory. The class is 10 weeks long (one quarter). The relatively short amount of time in lecture has led us to prepare extensive note packets to hand out every class, with many details to be filled in during the lecture periods. This technique allows for more material to be covered in a single class period then would otherwise be practical. A week-by-week summary of the course follows:

Week 1
Lecture Topics: Introduction, Steps in FEA, review of matrix operations and Gaussian elimination.
Lab Exercise: Introduction to ALGOR and SuperDraw.

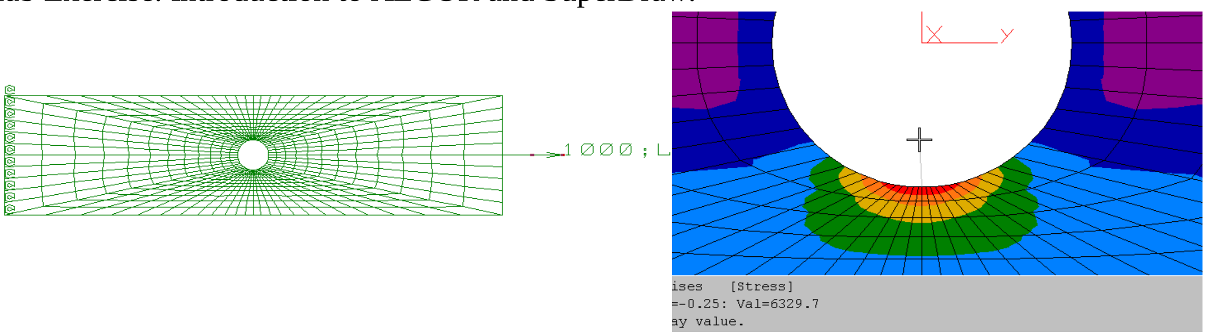

Figure 1 Week 1 Exercise - Stress Concentration Factor Model and Stress Results

The first week's lab exercise leads the students through the steps of creating a finite element model with ALGOR's SuperDraw program. A plate with a circular hole is modeled and analyzed for axial loading. Students build the model two different ways. In the first model, an automatic grid generator is used. In the second, the student has control over the mesh geometry. The plate model is shown in Figure 1.

Week 2
Lecture Topic: Spring elements
Lab Exercise: Modeling with SolidWorks®

The lecture classes begin with the formulation of a one-dimensional spring element using direct equilibrium. A simple assemblage of springs is analyzed with the finite element method. Since this spring assemblage can be easily evaluated with methods from statics, it is easy for students to understand the steps of the FEA process through this simple analysis. A homework problem for the students to work through a spring assemblage by hand is assigned this week.

Students begin working with SolidWorks® in lab this week. Two step-by-step tutorials lead students through the creation of the bracket and flange shown in Figure 2. Students will also have the lab period of week 4 to complete these tutorials.

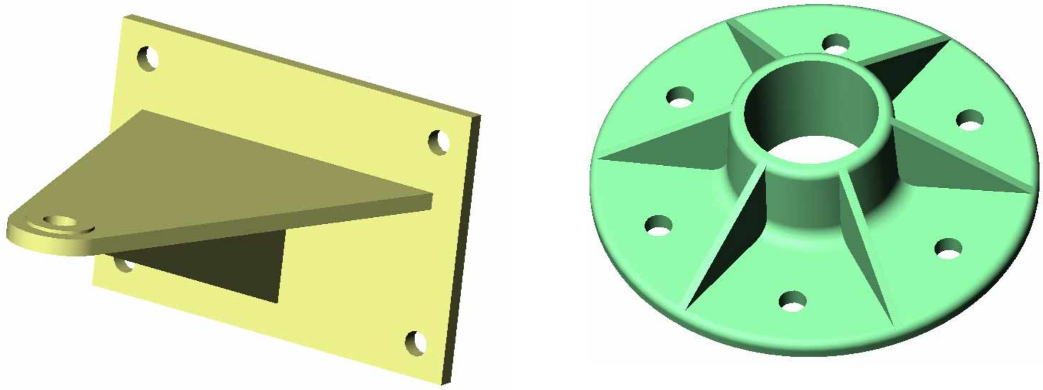

Figure 2 Components Modeled with SolidWorks Weeks 2 and 4

Week 3
Lecture Topic: Truss elements
Lab Exercise: 2-D and 3-D truss analysis

2-D truss elements are formulated this week during the lecture, again by direct equilibrium. Truss elements are very similar to spring elements, but require the transformation of quantities between local and global coordinate systems. A homework problem to analyze a simple four-member truss is assigned.

In the lab, the same four-member truss is analyzed with ALGOR®, and then a fifth member is added to make the truss statically indeterminate. The 3-D truss shown in Figure 3 is also analyzed.

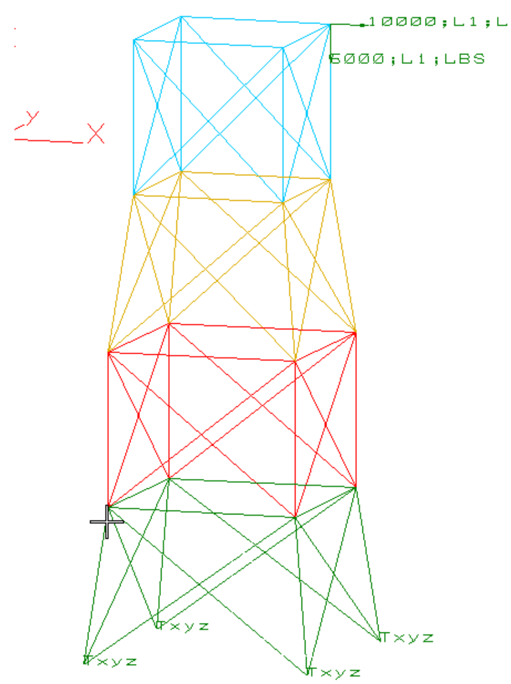

Figure 3   Week 3 Truss Analysis Exercise

Week 4
Lecture Topics: Energy methods, formulation of truss element equations with principle of stationary potential energy, begin beam element formulation
Lab Exercise: Continuation of SolidWorks® tutorials

An energy formulation of the truss element, which has already been formulated by direct equilibrium, is a good introduction to energy methods. The truss is subjected to axial stresses only, so the formulation is straightforward and easy for the students to grasp.

Week 5
Lecture Topics: Formulation of beam element
Lab Exercises: Simple beam analysis, mixed-element model

The potential energy formulation of the truss element provides a good starting point for the derivation of the beam element. This element is of particular importance, as the student is dealing for the first time with an element for which stress and strain vary within the element. After analyzing a simple beam by hand and with ALGOR®, the students analyze a steel table with combined beam and plate elements as shown in Figure 4.

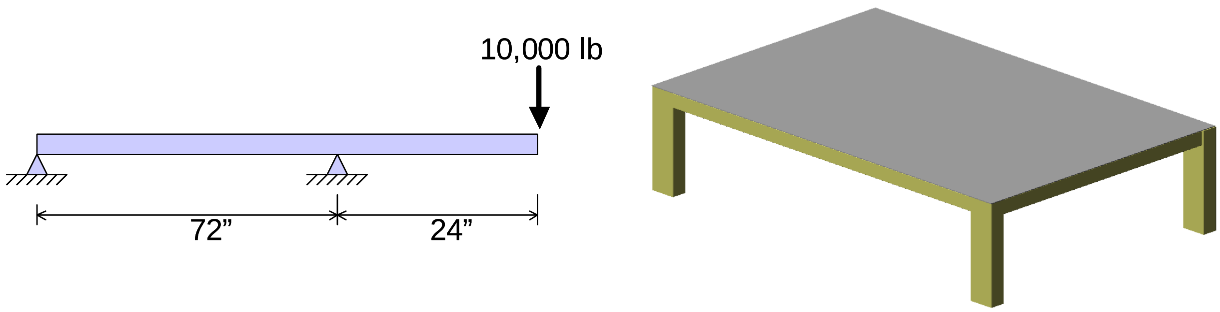

Figure 4 Week 5 Exercises - Simple Beam and Beam/Plate Table Model

Week 6
Lecture Topics: Mid-term exam, begin constant-strain triangle element formulation
Lab Exercise: Plane stress analysis – thin-wall pressure vessels

Two thin-wall pressure vessels, one with a hemispherical head and the other with a relatively flat toro-spherical head, are analyzed during the lab this week, as shown in Figure 5. The use of symmetry to reduce the model size is emphasized.

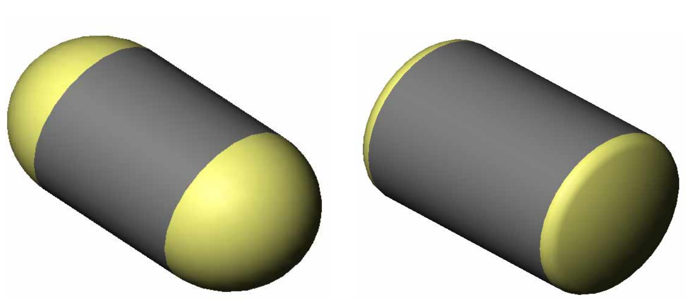

Figure 5 Week 6 Exercise Pressure Vessels - Spherical and Toro-Spherical Heads

Week 7
Lecture Topics: Constant-strain triangle element
Lab Exercise: Solid element analysis with SolidWorks® and ALGOR®

A flange with bolt holes and a seal groove is modeled with SolidWorks®, as shown in Figure 6. This flange is meshed with ALGOR®'s solid model interface and transferred to ALGOR® for analysis. This flange is the baseline for the design problem that the students will work on for the rest of the quarter. Given a set of design requirements and material properties, the students are to redesign the flange with the goal of minimizing weight.

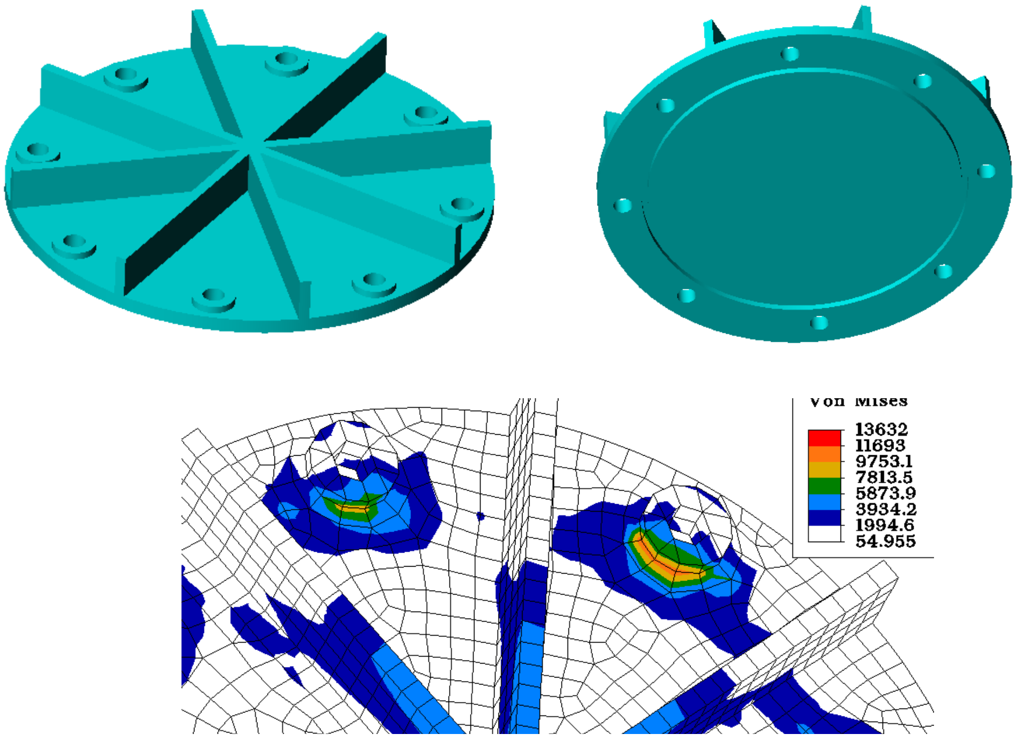

Figure 6   Flange with Seal Groove Modeled with Solidworks and Analyzed with ALGOR

Week 8
Lecture Topics: Finish Constant-strain triangle element, begin 2-D heat transfer element
Lab Exercise: Precision exercise

Since the examples using the constant-strain triangle presented during lecture are quite simple (more than 2-4 elements become impractical to work by hand), the subject of precision naturally fits in this week. By examining the relative difference between the average stress calculated at a node and the stress at the same node calculated for a specific element, students are able to get feel for the accuracy of the finite element method. During the lab, a simple structure is modeled with constant-strain triangle and higher-order quadrilateral elements. Precision values for various mesh densities are compared.

Week 9
Lecture Topics: Heat transfer element
Lab Exercise: Heat transfer analysis with conduction and convection

Although this course is predominately focused on structural problems, the inclusion of a heat transfer problem illustrates the application of the method to other problems (this addition was also requested by our Industrial Advisory Committee). The simple geometry of the model allows for several variations of the model to be analyzed, examining the effects of different materials and convection coefficients. In the future we plan to include a simpler problem, such as an annulus with distinct convection coefficients on the inner and outer surfaces, for which an exact solution can be found for comparison.

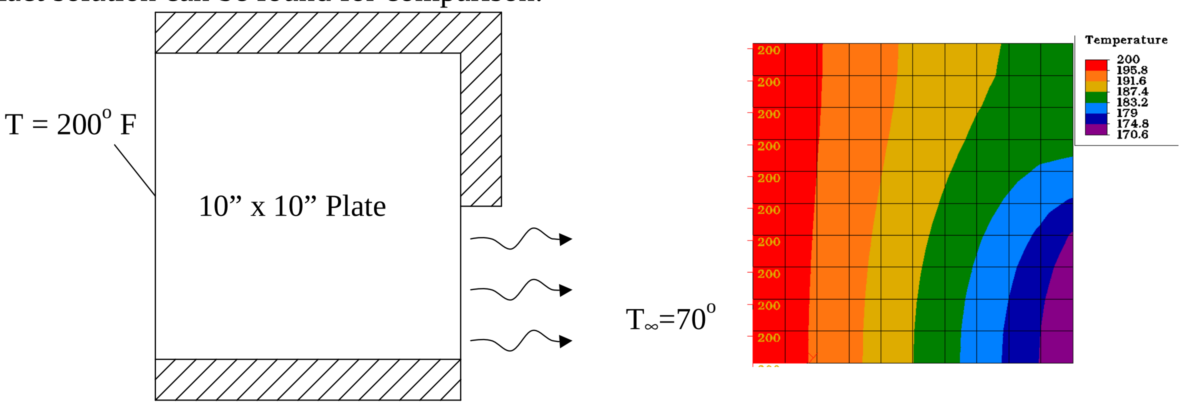

Figure 7 Heat Transfer Model and Results

Week 10
Lecture Topics: Advanced topics, review for final exam
Lab Exercise: Complete flange design problem

The inclusion of geometric and material non-linearities in FEA is discussed this week. Also, time-dependent analysis is introduced. The goal of discussing these topics is to stimulate a desire in the students to learn more about FEA.

The FEA class as outlined above was taught for the first time in spring 2000. Student response to the class was very positive. Most of MSOE’s upperclassmen have held intern positions with local companies, and they recognize the value of being familiar with modern design and analysis tools.

III. Further Integration of FEA into the Mechanics Course Sequence

The course described above is currently an elective. In the fall of 2002, the course will be required for all seniors. It will represent the final required course in our mechanics course sequence, as illustrated in Figure 8. Once the course is required for all students, it is possible to rearrange some of the topics covered.

For example, torsion of non-circular shafts is briefly covered in the second mechanics of materials course. Because the derivation of the stress solution is beyond the scope of the course, the coverage tends to be minimal. However, the modeling of a square cross-section shaft under torsion is easy to accomplish with solid elements. This and other non-circular sections have stress distributions that are well known. Analysis of such sections could lead very naturally into a discussion of the application of failure criteria. Static failure criteria are covered in both the second mechanics of materials course and the machine components course. The FEA class offers a good opportunity to reinforce the teaching of failure criteria, since it is easy to have stress results displayed as principal stresses, Von Mises effective stress, or maximum shear stress. On the other hand, introducing energy methods and FEA theory during the second mechanics of materials course allows more topics to be covered during the FEA class. In particular, introduction of energy methods in the context of a full course on solid mechanics allows its application to topics in heat transfer in a much more straightforward manner.

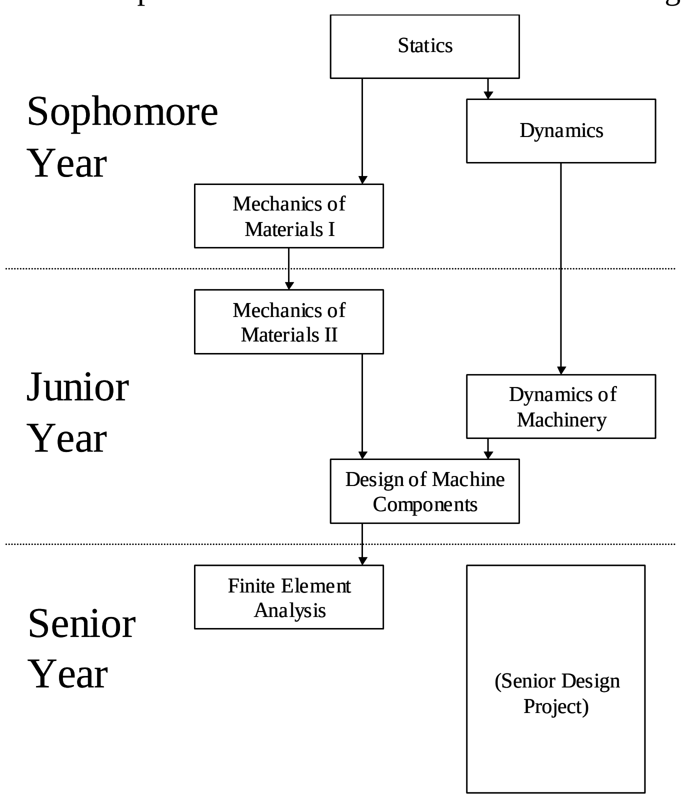

Figure 8 Mechanics Course Sequence

IV. Conclusion

Finite element analysis is now a tool that is used by a large percentage of design engineers. Therefore, the teaching of the finite element method has taken on greater importance. It should be held in mind, however, that FEA is not an independent subject but rather an extension of basic mechanics principles made possible by the revolution in computing during the last 20 years. Therefore, opportunities exist to help students' understanding of basic mechanics at the same time they are learning a valuable skill for the workplace. What we have outlined here is a way to accomplish this by coupling the course with a required course sequence in mechanics.

Bibliography

[1] Brinson, L., Belytschko, T., Moran, B., & Black, T. "Design and Computational Methods in Basic Mechanics Courses", Journal of Engineering Education, April 1997.

WILLIAM EDWARD HOWARD
Ed Howard is an Assistant Professor in the Mechanical Engineering Department at Milwaukee School of Engineering. He holds a B.S. in Civil Engineering and an M.S. in Engineering Mechanics from Virginia Tech, and is currently a PhD candidate at Marquette University. He has 14 years of industrial experience in the design and analysis of composite structures.

JOSEPH C. MUSTO
Joseph C. Musto is an Associate Professor and Mechanical Engineering Program Director at Milwaukee School of Engineering. He holds a B.S. degree from Clarkson University (Potsdam, NY), and an M.Eng. and Ph.D. from Rensselaer Polytechnic Institute (Troy, NY), all in Mechanical Engineering. His industrial experience includes engineering positions with Eastman Kodak Company (Rochester, NY) and Brady Corporation (Milwaukee, WI).

VINCENT PRANTIL
Dr. Prantil received his BS, MS and PhD in Mechanical Engineering from Cornell University. His research interests lie in microstructural material modeling, finite element and numerical analysis. He was a senior staff member at Sandia National Laboratories in the Applied Mechanics and Materials Modeling departments for ten years. He joined the mechanical engineering faculty at MSOE in September 2000.