Integrating Finite Element Analysis into an Undergraduate Biomechanics Course

Renee D. Rogge, Ph.D.
Mercer University

Introduction

A course in finite element (FE) analysis is offered occasionally to biomedical engineering (BME) students at Mercer University as a technical elective through the mechanical engineering department. However, few BME students take this course. Since FE techniques in industry and academia has become widespread, particularly in the field of biomechanics, it was determined that some discussion of FE techniques was warranted in the senior-level biomechanics course. The FE module was designed to meet the course objectives stating that the students must be able to (1) describe the current uses of FE techniques in biomechanics, (2) apply the FE technique to a biomechanics problem in two-dimensions incorporating appropriate mesh parameters, material properties, boundary conditions and loading conditions, and (3) discuss the problems and limitations of the FE approach in biomechanics research. The integration of a FE module into the biomechanics course also served to reinforce several other course objectives. Through application of the FE technique, basic concepts of stress and strain were reinforced and students gained experience in the prediction of results and in the use of “sanity checks” when evaluating their results.

Student achievement was assessed using in-class assignments, homework assignments, a design project, and final exam questions. Student and instructor satisfaction with the FE module was high and student performance on the homework assignments, design project, and final exam questions was excellent.

Module Contents

Instructional Component

The instructional portion of the module presented the basic concepts of the FE method, including the benefits and drawbacks of the approach. An in-class "pencil and paper" calculation of the displacement of nodes for a three-noded triangle was completed. The stiffness, load, and displacement matrices were developed, requiring discussions of material property specifications, loading conditions, and boundary conditions, respectively. Following the calculation of nodal displacement, other element types and node configurations were discussed.

Commercially available FE codes were discussed and the class went through the steps that would be common to each software package. These steps included implementing an accurate geometry, applying appropriate material properties, determining boundary and loading conditions, understanding mesh requirements, performing convergence tests, and validating model results.

Current biomechanics research using the FE method was discussed and sample models (from journal articles, web sites, personal research, etc.) were shown to the class. This segment of the course really captured the attention of the students and I would recommend actually starting the course with this "real-world" activity. One sample model was chosen at random and the class discussed the approach they would take to create, validate, and use this model. Limitations of the results were also discussed at length.

FE Software

Quickfield (http://www.quickfield.com) provides a free student version of their FE software that may be downloaded and installed on Windows® 95/98/NT. The functional limitations in the student version are (1) a 200 node maximum, (2) triangular elements are the only element choice, and (3) only two-dimensional problems may be analyzed. Quickfield is a complete FE package with pre- and post-processing capabilities. Quickfield provides on-line tutorials and full documentation that may help the instructor learn the software.

Quickfield Tutorial

A step-by-step tutorial was provided by the instructor to help the students learn Quickfield. The class was held in a computer classroom where the students had their own computer and could observe the actions of the instructor as they worked through the tutorial with the instructor. It was very important to go slowly and to reinforce the steps that had been discussed the previous class period. The tutorial involved solving for the maximum displacement of a cantilever beam with a point load applied at the end of the beam.

Students built the beam geometry, input the elastic modulus and Poisson's ratio, and entered the loading and boundary conditions. The next step was mesh generation. Quickfield allows for automatic mesh generation and this feature was utilized. The model was then solved and the results viewed.

The students were asked to validate their model results using beam deflection theory. Upon finding their results were very inaccurate, the students refined their meshes successively until their results matched their calculations. This was an excellent opportunity to stress the importance of accuracy and validity in FE modeling.

In-Class Assignment

The biomechanics students were given an in-class assignment to calculate the stress concentration factor due to the presence of a hole centered in a flat steel plate under uniform tensile loading. The assignment specified plate and hole geometry as well as loading requirements. The objective of this assignment was to reinforce the two previous lectures and to allow each student an opportunity to work at their own pace and ask questions of the instructor or their colleagues. Most of the questions were about the mechanics of the software and "figuring out" the nuances of the program.

Homework Assignments

The first homework assignment required the calculation of the stress concentration factor (SCF) due to the presence of an *offset* hole in a flat titanium plate under uniform tensile loading. The change in location of the defect changed the symmetry conditions of the problem, requiring them to understand how this affects the boundary conditions. The students were asked to turn in a brief report presenting the steps they used to solve the problem, a printout of the von Mises stress plot with the loading and boundary constraints labeled, and a comparison of the theoretical and calculated SCF. Assignments were assessed based on their understanding of the steps needed to complete the assignment and the accuracy of their SCF.

The second assignment asked the students to discuss, in detail, the approach they would take to determine the stresses in the mandible while chewing. The successful completion of this assignment required the students to discuss (1) obtaining the geometry, (2) determining the loading/boundary conditions and material properties, (3) meshing difficulties, (4) convergence testing, (5) validation procedures, (6) possible uses of the results, and (7) limitations of the model and how the limitations might be overcome.

Finite Element Project

A project is standard in biomechanics classes at Mercer University. Following the FE module, a project utilizing the FE method was developed. Students were given a scaled image of a human hip with a cemented implant. The students were asked to create a model from this image and to analyze the current implant. No other information was provided. Students were required to make two design changes to the implant and to report the influence of these changes. The students were also asked to make three changes to loading or boundary conditions based on physiologic evidence. Three material property changes were also requested. The project report required discussions of why the changes were made and how these changes influenced the results.

Project Assessment

The evaluation form for the FE project is shown in Table 1. The FE project was evaluated based on the thoroughness of the project and the quality of the write-up. A concise abstract was required along with a clear and complete introduction. A thorough methods section detailing the procedures taken and a very comprehensive results section were expected, including sufficient figures. The discussion section was also very important, requiring a thorough explanation of the results and the impact of the changes made. Sources of error and future modeling suggestions were expected in the conclusions.

Discussion

The finite element module was very successful. The projects were of high quality and demonstrated a remarkable amount of detail and care. It was obvious while reading the papers that the students were interested in the project and invested a great deal of time and energy into it. Several students performed more analyses than were required just "to see what happened."

It was also rewarding to see their confidence increase when discussing stresses and strains. Even at the senior-level, these terms can still seem abstract, but the visual confirmation provided by the FE software reinforced the concepts. The students became quite adept at predicting the responses of their models. They were also able to adequately discuss FE techniques used in biomechanics.

The software was easy to learn and the students had little difficulty navigating the program. It was limited to 2-D problems, but this was not a major problem for an introductory course. The in-class tutorial and in-class assignment allowed small computer glitches or common operator errors to be identified and corrected either by the instructor or classmates. These exercises reduced student frustration and demand on instructor time.

The homework assignments required students to work independently and iron out the details of the FE method on smaller scale problems with "correct" answers prior to the larger and open-ended project. This also gave the instructor a chance to correct any major problems with theory or application of the technique.

The pace of the module was appropriate for a senior-level class, with three class sessions devoted to the FE method. Student comments were favorable regarding time committed to the module, but a few students requested more class time on the subject.

Although the benefits are numerous, there are a few drawbacks to the module. At least three lectures were devoted to the module, not including the lectures on the application of the FE method in biomechanics. There are many topics to cover in an introductory biomechanics course and the use of three lectures on this module is a large time commitment. A significant amount of time must be spent learning the program if the instructor is not familiar with it. Developing tutorials, assignments, and projects may be equally demanding.

Conclusion

This module will be further developed and implemented in future offerings of biomechanics at Mercer University. The cantilever beam and hole-in-a-flat-plate problems are classic and will be continued. However, a list of common mistakes has been developed that will be given to future courses in an attempt to reduce the difficulty of learning the program. The FE project will be modified to reflect a new modeling subject and to incorporate a section on recommended validation techniques.

Bibliographic Information

RENEE ROGGE is an assistant professor of Biomedical Engineering at Mercer University. She earned a BS in Biomedical Engineering from Tulane University and a Ph.D. in Biomedical Engineering from the University of Iowa.

Table 1. Evaluation form used to assess the FE design project

FE PROJECT EVALUATION

Student:___________________________________

Item	Value	Score
Presentation: page numbers, sections, professional	5	
Writing: grammar, readability, and spelling.	5	
Abstract	5	
Introduction	5	
Methods	10	
3 reasonable loading/boundary conditions? Includes explanation and interpretation of results	15	
Two design changes? Impact of these changes discussed?	15	
Material property changes? Impact of changes?	15	
Conclusions, including use of FE in biomechanics, future modeling suggestions, need for validation?	15	
Appropriate figures?	10	
	RAW NET SCORE	