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Theory and Commercial Software - Finding the Balance in a Finite Elements Course

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Abstract

The mechanical engineering curriculum at California State University Chico includes a required course in Finite Element Analysis (FEA). The course has traditionally concentrated on the theory of the method and its formulation from fundamental governing equations. Assignment problems have included rigorous hand-work such as assembling stiffness matrices, as well as computer based solutions through non-specific computational software such as Excel or MATLAB®. The course traditionally has not included any exposure to, or instruction in, the use of commercial FEA software.

Past feedback from advisory committees, capstone sponsors, senior exit surveys, and other anecdotal evidence clearly indicated a problem with the curriculum's approach to finite elements. While program graduates may be well versed in the theory, there is strong evidence that they are not skilled its proper application through the use of commercial FEA software. Common observations included poorly posed problems, unnecessary computational rigor, meaningless results, or indeed the inability to obtain a solution at all.

In response, the FEA course has been modified to include some basic instruction in the proper use of commercial FEA software. Each segment of theory-based discussion and traditional homework assignments is followed by exploring the same concepts within the context of commercial software. Emphasis is placed on its proper use, underlying assumptions, limitations, and validity of results.

A Brief History of FEA and CAD Software

Development of the finite element method pre-dates computers by a wide margin, and its early formulations were to applied to engineering problems as early as the 1950s.[1] But the computational rigor of the method prevented its widespread use until the necessary computing power became available. FEA saw its first extensive use in the 1970s, employed on mainframe computers in the automotive and aerospace industries. Software of that time was command-line based, and required highly specialized training for its use and interpretation.

The 1980s moved computing from the mainframe to the desktop, and saw an explosion of specialized software, including many packages designed specifically for FEA. While these early programs were explicitly built to solve engineering problems, they were not at all user friendly (by today's standards), and still required specialized training in their proper use.

The rapid expansion of desktop computing power in the 1990s enabled solution of more and more complex problems through FEA. But these more computationally intensive models were often associated with increasingly complex geometries, and most FEA software did not include sophisticated tools for model construction.

Parallel to the advancement of FEA software was the emerging sophistication of computer aided drafting or design (CAD) software. Initially created as a tool to replace board drafting, CAD quickly evolved from a 2D drafting tool to a 3D modeling tool capable of capturing design intent through parametric associations. This led many FEA users to create the geometry in the more robust and user-friendly CAD programs then transfer the models to the FEA software for analysis.

Recognizing this trend, and the growing ubiquity of FEA as a design tool, several makers of parametric modeling software incorporated FEA capabilities into their products, allowing the engineer to perform model construction and analysis within a single interface. This trend has also significantly increased the access to, and ease of use of, FEA as a design and analysis tool (for better or for worse). This seamless integration of molding and analysis tools is now available in several commercial solid modeling software packages. Three commonly in use today are SolidWorks from Dassault Systèmes, Pro/ENGINEER from PTC, and Inventor® from Autodesk.®

A Brief History of FEA and CAD Courses

Through this evolution of FEA and CAD software, engineering curricula have made significant changes as well. As FEA took hold as a tool in industry, FEA courses began to appear in many engineering and technology programs.[2] The courses were initially taught only at the graduate level or perhaps as an advanced undergraduate elective. As FEA became more common in the workplace, FEA courses became more common in engineering programs and more commonly appeared at the undergraduate level.

Similarly, as CAD swept into industry, engineering programs underwent parallel changes, with computer aided drafting replacing board drafting, 3D CAD replacing 2D CAD, and parametric modeling becoming a standard course for most mechanical engineering programs.

At our institution, and no doubt at many more, students now gain reasonable proficiency in parametric solid modeling software fairly early in the curriculum. This also gives them easy access to commercial FEA tools long before any such concepts have been taught in the classroom. Since they will likely be exposed to these FEA tools in the workplace, or even be expected to have competency in them, it is imperative that they have an understanding of their proper application, and limitations, in the solution of engineering problems. As others have stated,[3] it's not exactly clear what should be taught in today's FEA course.

The Traditional FEA Course

The FEA course at California State University Chico is preceded by two prerequisite courses in technical computing. The first, *Introduction to Technical Computing*, is a foundation course that introduces basic programming along with exposure to non-specific computational software such as Excel and MATLAB.® The second course, *Equation Solving Techniques*, covers numerical analysis, analytical methods, and equation solving techniques for mechanical engineering design. It utilizes MATLAB® in a less structured environment, relying more on student-written programs.

The FEA course has traditionally concentrated on the theory of the method, focusing on the development of the finite element formulation from fundamental governing equations. Students learn (or are exposed to) the stiffness method, Galerkin's method, isoparametric formulation, and the work-energy method. Application areas include elasticity, vibration, and heat transfer, but most application problems necessarily lack complexity so that they can be solved by hand or through non-specific computational software. The course traditionally has not included any exposure to, or instruction in, the use of commercial FEA software.

Some Disappointing Observations

Students typically complete the FEA course in the spring of their junior year before beginning the two course Capstone Design sequence in the senior year. One of the major tenets of the capstone program is for students to utilize competencies gained in their first three years of study in the solution of a real-world engineering design problem. Application of the finite element method in general, and the use of commercial software in particular, are often expected of students working on these design projects.

Substantial anecdotal evidence from capstone faculty advisors, sponsors, and design reports, along with data from senior exit surveys, advisory committees, and employer feedback, all point to the same conclusion. That is, while our students may be well versed in the theory of finite elements, they are not skilled its proper application via commercial software designed specifically for the purpose.

While most students with basic modeling skills can produce a Von Mises stress plot of a simple, stand-alone part, there is scant evidence that they have any true understanding of the effects of boundary conditions, load profiles, or the underlying assumptions of material behavior (i.e. the infinitely linear stress-strain curve assumed in a linear static analysis). They have no concept of mesh quality, control, or refinement, since most current software hides those steps from users by default. They also do not have a good understanding of time dependency, or the ability to model transient problems.

Moreover, they struggle significantly when attempting to model multiple parts in an assembly, often producing completely unrealistic results, or more commonly, no results at all due to modeling errors that prevent the software from obtaining a solution. They do not understand the need for model simplification, and have no idea that computational rigor can be reduced by simulating connections instead of modeling hardware such as nuts, bolts, and washers. They do not know how to specify different element types or utilize 2D assumptions for plane stress, plane strain, or axisymmetric problems. They do not understand that many 3D members can (and should) be modeled as weldments, beams, or trusses, again significantly reducing computational effort.

Finally, when reporting results within design reports, they do not address underlying assumptions, boundary conditions, the validity of assumed loads, or the overall accuracy of the solution. They do not address stresses other than Von Mises, rarely report displacements, and frequently report results to six or more significant figures with no discussion of the accuracy of the solution based on assumed loads and/or boundary conditions. They also do not relate design decisions to the analysis results, but that in itself is more an issue with design methodology than with specific FEA modeling skills.

The New FEA Course

In response to the many observations detailed above, the FEA course has been modified significantly to include basic instruction in applying the method via commercial software. While others may disagree, it is still strongly held by department faculty that proper application of FEA requires some level of understanding of the underlying theory, and that the FEA course should not be turned into a training course for a specific brand of software. Commercial FEA software should also not be treated as a "black box" tool, but instead be used with intelligence and understanding about its powerful features, but also its limitations.

So while the theory-based approach to the topic remains, the content has been augmented to include instruction in the appropriate use of commercial software (SolidWorks Simulation in this case). As all instructors are aware, content cannot simply be added to a course without removing something else, so there has been an inevitable reduction in the amount of theory taught. But an attempt has been made to retain the most important theoretical concepts while allowing the introduction of commercial software techniques, hopefully striking an appropriate balance between the two.

The course is taught over a single fifteen-week semester with three fifty-minute class meetings per week. A two-hour comprehensive exam is scheduled in the sixteenth week. Both the old and new versions utilize a traditional lecture that includes three segments of material, each about five weeks in length that are followed by a written exam. Lectures are presented in traditional chalkboard format and include background, theory, and example problems. Homework assignments require hand-based work, such as the formulation of stiffness matrices, and often include problems of very simple geometry that are solved using non-specific computational software such as MATLAB® or Excel.

Most traditional lecture based courses of this type have a natural void after the completion of the material that will appear on an upcoming test. Time is typically allowed for assignments to be worked, submitted, graded, and returned, which can span several class meetings. Rather than moving on to the next "testable" section of material, these voids are now utilized to examine the topics just covered in the context of their application through commercial software.

Lectures delivered during these voids are of a totally different style. PowerPoint is utilized to give an overview of the procedure, and screen captures from FEA software are shown to illustrate various panels and buttons that are used to access particular features and commands. The presentation is followed by a live demonstration of the FEA software, where the instructor runs through the basic steps involved in a particular analysis. Separate homework assignments for these sections are to be accomplished with commercial FEA software and are not the subject of a future written test. As an example, one problem might be to repeat a homework assignment from the text that was initially solved by hand to compare solution results. Another might be a problem of the same classification, but with complex geometries that could not reasonably be solved by hand.

To further illustrate, plane stress and plane strain elements are a standard topic in most any FEA course. The elements are presented in a traditional theoretical manner, with hand-based homework problems that might require development of the local and global stiffness matrices for a simple problem with straightforward geometry and a small number of elements. The theoretical instruction also provides an understanding of the types of problems for which those elements are applicable. The topic is then presented again in the context of its application via commercial software. That is, students are shown how to perform a 2D plane strain or plane stress analysis which includes specification of the proper element type for the problem at hand.

Tips, Traps, and Techniques in Commercial FEA Software

In addition to exploring topics specifically tied to FEA theory, such as the use of truss, beam, or axisymmetric elements, instruction is also given on some of the more general competencies associated with proper use of commercial FEA software. Topics covered include:

- Units
- Material properties
- Meaning of various boundary conditions in the context of FEA theory (i.e. limiting or prescribing nodal displacements)
- Use of weldment structural members
- Model simplification
- Mesh generation and controls
- Mesh inspection and refinement
- Symmetry
- Assembly modeling (contact, connections, friction, interference detection, …)
- Thermal loads and boundary conditions
- Displaced and non-displaced shapes
- Reporting stresses other than Von Mises
- Factor of Safety and Design Insight plots
- Edge Plots
- Significant Figures
- Accuracy of solution
- General guidelines for reporting results

A final change to the course is the addition of a final project, an open ended FEA modeling assignment. Students select an object and/or application of their choosing, then build the models, run appropriate analyses, and document the results. Key competencies expected from the projects include simplifying models for analysis, applying realistic loads and boundary conditions, choosing relevant results in post processing, and reporting appropriate conclusions from the analysis. The specific rubric used to grade the final reports is included in Appendix A.

Specific details of topics covered throughout the course are presented in Appendix B. PowerPoint presentations used in the commercial FEA software portions of the class are made freely available to any interested party by contacting the author.

Assessing the Changes

The modified FEA course was first taught during spring 2012. Since the course is normally taken in the spring of the junior year, many students that took the final unmodified version of the course in spring 2011 were still available for survey a year later. Identical surveys were given to both sets of students, the group that took the final unmodified course in spring 2011 and the group that took the modified course in spring 2012.

The survey (Appendix C) solicited standard Likert scale[4] responses to six questions, and also provided room for written comments. The survey questions are shown in Table 1 below.

Table 1 – Survey Questions

Lead in	After completing the Finite Elements course, I …
Q1	have a fundamental understanding of the underlying theory of finite element analysis (FEA).
Q2	clearly understand the advantages of FEA over traditional analysis techniques.
Q3	clearly understand the underlying assumptions and limitations of FEA, and what factors contribute to the validity of an FEA analysis.
Q4	understand the basics of the derivation of FEA equations, i.e. the stiffness matrix, for various element types.
Q5	I can formulate and solve simple FEA problems by using spreadsheet software such as Excel and/or code based software such as MATLAB®.
Q6	I can formulate and solve complex, real world FEA problems using commercial software such as SolidWorks Simulation and/or Adina.

The "before" survey was completed by 11 of 51 students in the class. This result rate is unfortunately small, but is a function of implementing it nearly a year after the students took the course. Figure 1 shows the percent of students responding in each Likert category.

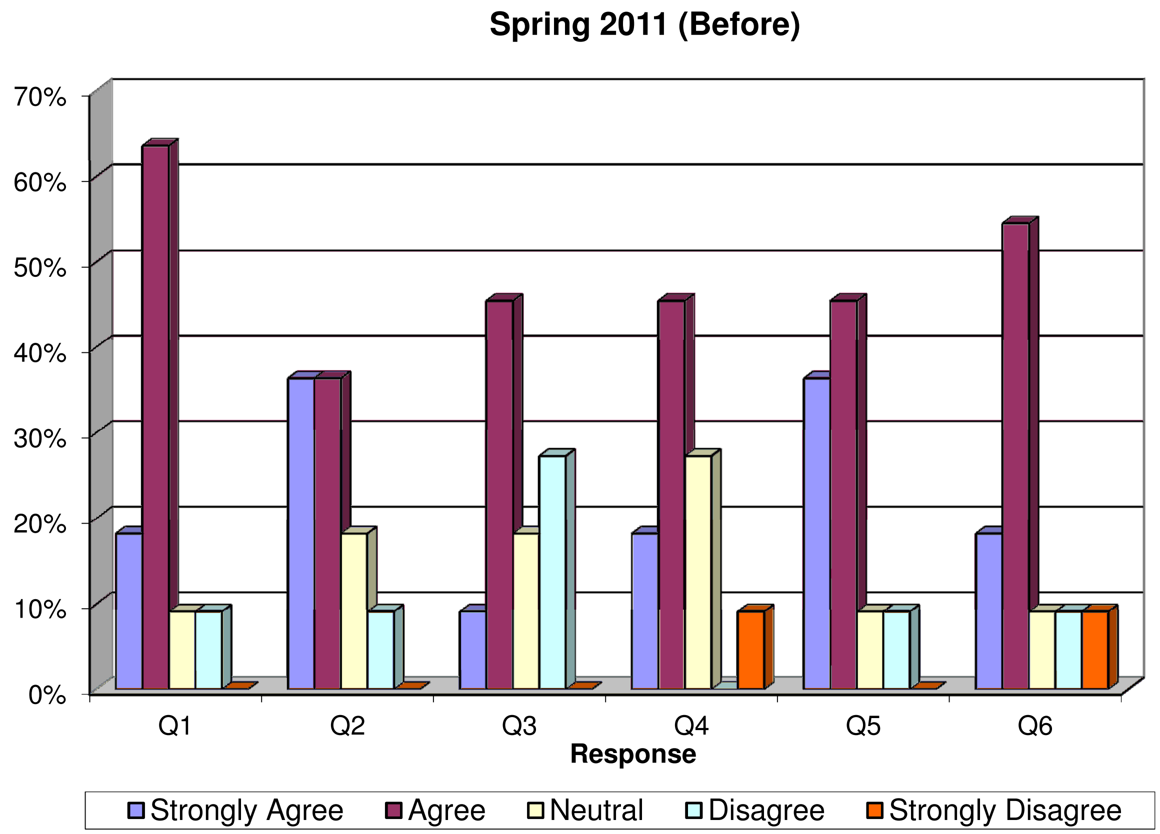

Figure 1 – Percent of Responses for each Likert Category Before the Course Change

While the data show a general satisfaction with the course, the strongest positive responses relate to understanding the underlying theory of the method and applying it with non-specific computational software rather than commercial software designed specifically for the purpose.

In addition to the Likert responses, students were also given the opportunity to provide written comments. A sampling of comments about the course before the changes were implemented is included in Table 2 below.

Table 2 – Written Comments from Student Surveys Before the Course Change

- How, not why
- Very tedious derivatives with no relation to big picture
- More of an understanding of Excel than anything
- Too much theory, not enough application
- I learned from a text that was not required for the class
- Still need some practice to fine tune my ability to use SolidWorks for FEA

The "after" survey was completed by 44 of 49 students in the class. The response rate is much higher due to the "captive audience" resulting from the survey being administered immediately at the conclusion of the course. Figure 2 shows the percentage of students responding in each Likert category.

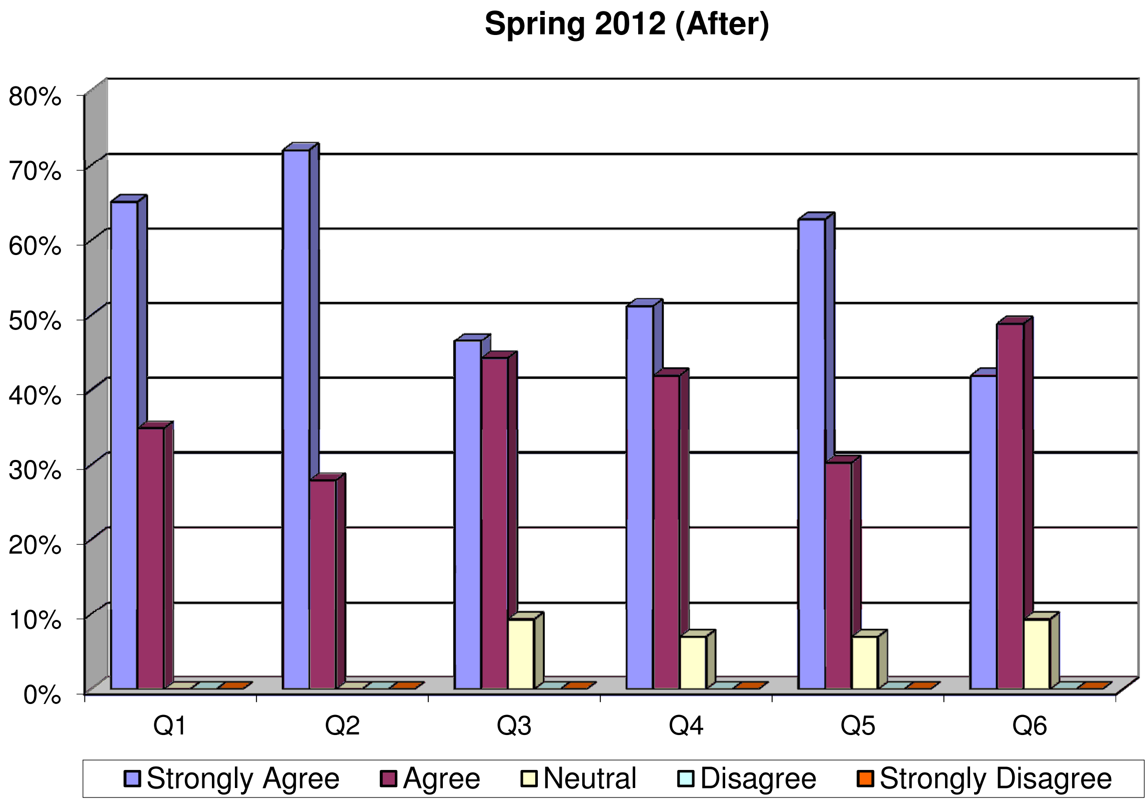

Figure 2 – Percent of Responses for each Likert Category After the Course Change

The data from the student surveys show a very high satisfaction with the course in general, with the most positive response relating to understanding the advantages of FEA over traditional analysis techniques. There is also strong evidence of the student's confidence in the appropriate use of commercial FEA software.

In addition to the Likert responses, students were also given the opportunity to provide written comments. A sampling of comments about the course after the changes were implemented is included in Table 3.

As a final measure of comparison, the Likert data from both surveys was scored from 5 to1, with 5 = *Strongly Agree*, 4 = *Agree*, 3 = *Neutral*, etc. The data from both surveys are shown in Figure 3.

Table 3 – Written Comments from Student Surveys After the Course Change

- Brought the theory from other classes together
- Great class; learned a lot
- Knowing what FEA software is doing in a simulation is very important
- Great teaching structure
- The final project was a great contribution to my overall knowledge
- It really helped me understand why software is useful
- The SolidWorks assignments were awesome
- Learned what is going on inside the computer
- Used for other classes on top of this one for analysis
- The class is set up in a way that made learning the material very easy
- This is something all mechanical engineers need to know how to do

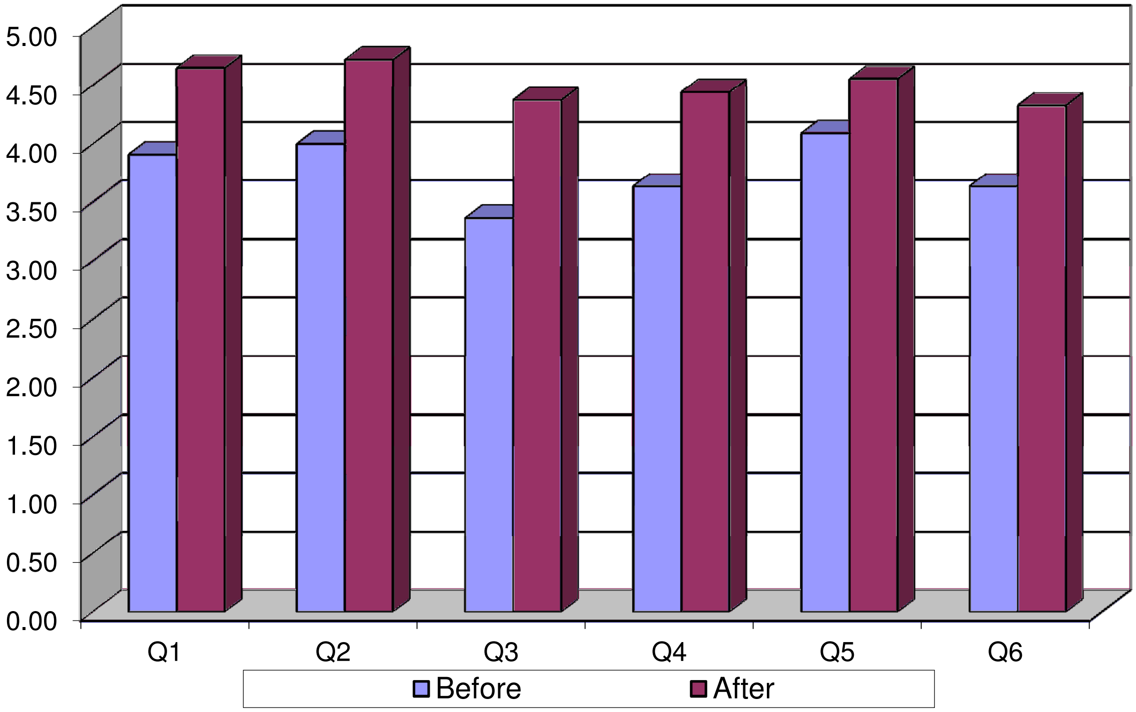

Figure 3 – Before and After Likert Scores

The before and after data show an increased satisfaction on all responses, with the most improvement shown in question 3, which relates to clearly understanding the underlying assumptions and limitations of FEA.

Conclusion

While the student survey data and written comments clearly show an improvement in the course, it is not taken as a final referendum on the issue. The effectiveness of the course modifications will continue to be monitored through advisory committees, employer feedback, senior exit surveys, and capstone advisors and sponsors.

References

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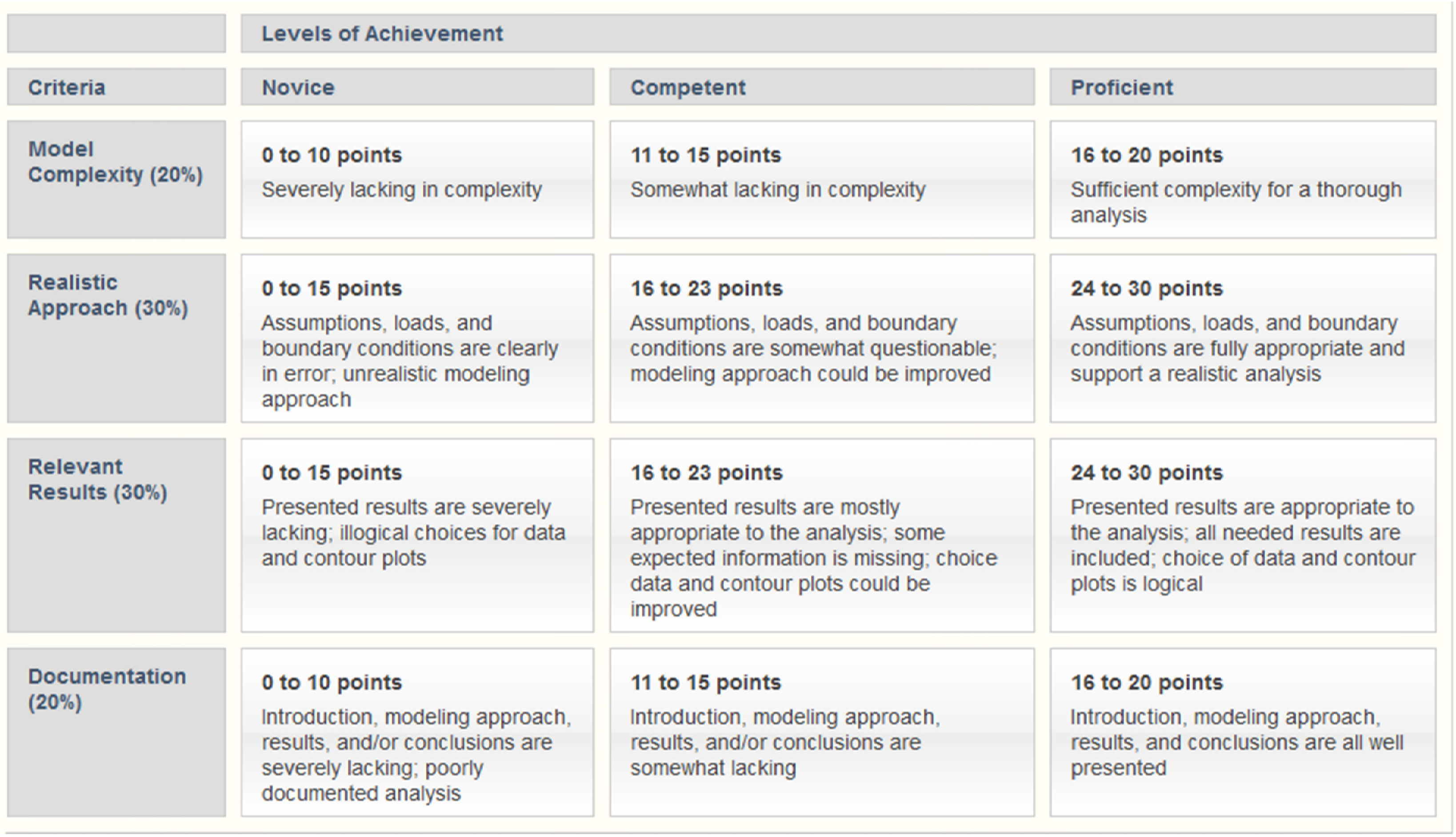
5. Logan, D. L., A First Course in the Finite Element Method, 5th Edition, Cengage Learning, 2012

Appendix A – Final Project Grade Rubric



	Levels of Achievement		
Criteria	**Novice**	**Competent**	**Proficient**
Model Complexity (20%)	**0 to 10 points** Severely lacking in complexity	**11 to 15 points** Somewhat lacking in complexity	**16 to 20 points** Sufficient complexity for a thorough analysis
Realistic Approach (30%)	**0 to 15 points** Assumptions, loads, and boundary conditions are clearly in error; unrealistic modeling approach	**16 to 23 points** Assumptions, loads, and boundary conditions are somewhat questionable; modeling approach could be improved	**24 to 30 points** Assumptions, loads, and boundary conditions are fully appropriate and support a realistic analysis
Relevant Results (30%)	**0 to 15 points** Presented results are severely lacking; illogical choices for data and contour plots	**16 to 23 points** Presented results are mostly appropriate to the analysis; some expected information is missing; choice data and contour plots could be improved	**24 to 30 points** Presented results are appropriate to the analysis; all needed results are included; choice of data and contour plots is logical
Documentation (20%)	**0 to 10 points** Introduction, modeling approach, results, and/or conclusions are severely lacking; poorly documented analysis	**11 to 15 points** Introduction, modeling approach, results, and/or conclusions are somewhat lacking	**16 to 20 points** Introduction, modeling approach, results, and conclusions are all well presented

Appendix B – Details of Course Content

The following table gives a general list of topics for the modified FEA course. The type is identified as being either traditional theory-based (TB) or geared towards the use of commercial software (CS). The approximate number of 50 minute class meetings for each topic is also included (not included in the listing are class meetings for taking exams and going over them afterwards). The theory-based discussions and homework are based on the required textbook for the class by Logan.[5] The commercial software modules were developed by the author. PowerPoint presentations used for the commercial software modules are freely available by contacting the author.

Topic	Type	Duration
Introduction	TB	1.5
Spring elements, direct stiffness method	TB	2.5
Truss elements, coordinate transformations	TB	2.5
Stress in bar elements	TB	1.5
Bar elements in 3D space, symmetry	TB	2.0
Review for Test I	TB	0.5
Truss Analysis in SW Simulation	CS	2.5
Beam equations	TB	2.0
Distributed loading, comparison to exact solutions	TB	2.0
Beam elements	TB	1.5
Plane stress and plane strain elements	TB	2.5
Review for Test II	TB	0.5
Beam Analysis in SW Simulation	CS	2.0
2D Analysis in SW Simulation	CS	2.0
Axisymmetric elements	TB	2.0
3D stress analysis	TB	1.5
1D heat transfer element	TB	3.0
2D heat transfer element	TB	2.0
Review for Test III	TB	0.5
Axisymmetric and Thermal analysis in SW Simulation	CS	1.5
3D Models and Assemblies in SW Simulation	CS	2.0
Review for Final Exam	TB	1.0

Appendix C – Survey Instrument

The purpose of this survey is to assess outcomes from curricular changes made to the Finite Element Analysis course. Please circle your agreement with the statements below. Feel free to add comments to clarify your answers as needed.

After completing FEA during the spring 20____ semester, I …

1. Have a fundamental understanding of the underlying theory of finite element analysis (FEA).

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

2. Cleary understand the advantages of FEA over traditional analysis techniques.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

3. Cleary understand the underlying assumptions and limitations of FEA, and what factors contribute to the validity of an FEA analysis.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

4. Understand the basics of the derivation of FEA equations, i.e. the stiffness matrix, for various element types.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

5. I can formulate and solve simple FEA problems by using spreadsheet software such as Excel and/or code based software such as Matlab.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments:

6. I can formulate and solve complex, real world FEA problems using commercial software such as SolidWorks Simulation and/or Adina.

   Strongly Agree Agree Neutral Disagree Strongly Disagree

   Comments: