# Improving Mechanical Design Education using Solid Modeling and Finite Element Analysis Modules

***Hodge Jenkins*[1] *and Jack Mahaney*[1]**

**Abstract** – In mechanical design, engineering students are presented with two main charges. The first of these is to design a component or system for a specified function. The second is to mitigate any mechanical failure during its useful life through analysis and re-design cycles. While engineering curricula tend to focus on analysis in some courses and design in others, it is critical for engineers to see analysis as an integral part of design. .

For many engineering students (and graduate engineers) it is difficult to determine the location of highest stress in a part by inspection, especially if the loading is three-dimensional. In an effort to better prepare students for professional practice, improve visualization of stresses in designs, and increase student interest, engineering application software was integrated into the junior-level mechanics sequence. Course modules using solid modeling and finite element analysis software were included via single laboratory sessions and assignments emphasizing visualization and relationships between design and analysis. The modules reinforce the mechanics and design theory of the classroom without extensive finite element theory being presented. Descriptions of the modules and their learning objectives as well as results of student feedback are presented and discussed.

*Keywords:* Mechanical design, Finite Element Analysis (FEA), solid modeling, mechanics.

## INTRODUCTION

This work is part of an educational initiative by Mercer University School of Engineering to enhance student education and interest as well as readiness for modern engineering practice and graduate research, through the use of state-of-the-art engineering design and analysis software. One educational objective of this initiative is cumulative student learning experiences via common software across the mechanics and design curriculum for students in mechanical engineering. Integration and use of mechanical engineering application software (such as Pro/Engineer and Pro/Mechanica [1]) throughout the solid mechanics courses provides students a continuous learning opportunity for engineering and computing skill advancement, as well as improving student understanding and interest in engineering. Software integration into the solid mechanics and design curriculum is envisioned in Figure 1.

Engineering students specializing in mechanical engineering advance in knowledge and skill throughout several courses. Common software threads of computer aided design (CAD) and finite element modeling and finite element analysis (FEM/FEA) skills build from course to course by integration of engineering application software modules. Students advance their skills with more detailed work as they progress throughout the curriculum. The commitment of the faculty to this approach is an essential component for this effort to succeed.

The importance of advanced CAE software in the practice of engineering has been a major pedagogical concern for engineering educators for some time. A significant learning benefit from employing a CAE approach is the visualization of resulting stresses and displacements of machine elements, not readily seen from the other less visual methods. The primary goal of this supplemental instructional method is to improve student visualization of loading and stress fields. Additional goals include renewing and improving student interest in design, instructor interest, and increasing student time on task [2]. The approach presented here is based on modern, professional, graphically oriented computer aided engineering (CAE) tools for design and analysis. It should be noted that the methods

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described in this manuscript do not preclude other learning approaches including hand derivations and calculation tools such as MathCAD or Excel in the classroom. Previous investigations have had some success using those methods alone [3]. More recent work has followed an approach similar to that described here [4].

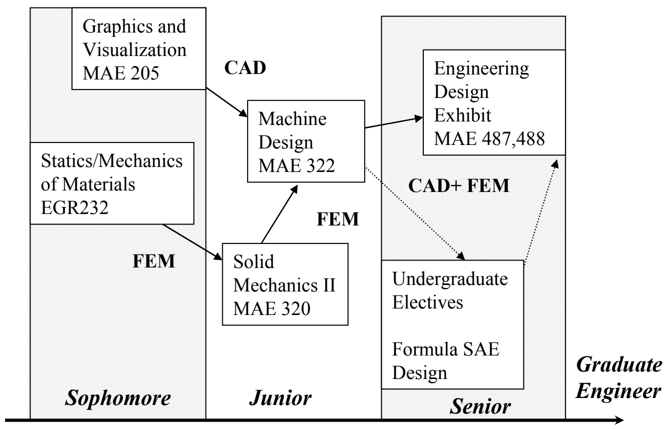


Figure 1. Common Engineering Software Experience Thread in Mechanics and Machine Design Curriculum

## BACKGROUND OF COURSES

The two mechanics courses discussed in this paper are three-credit hours classes at the junior level in mechanical engineering. Both courses are classic lecture and recitation style classes, focusing on manually generated student product consisting of homework, projects, quizzes, and exams. The added software modules present significant departures from lecture classes, increasing student interest and leading the students to explore independently in their design projects. It is important to note that each module is a single class period in duration with an additional homework assignment.

All engineering students at Mercer take a 3-semester-hour course in the sophomore year that combines statics and solid mechanics. Thus mechanical engineering students who take Solid Mechanics II in the fall of the junior year have a background in some of the topics that are normally presented in an introductory course. Our course is thus able to present some topics that are not seen in the typical Solid Mechanics course, and go deeper into other topics. Topics covered in our course include: tension, compression, and shear; axially loaded members; torsion; strain energy; stress concentrations; stresses and deflections of beams; plane stress with applications; and buckling.

The second course in the junior-level mechanics sequence to implement solid modeling/finite element analysis (FEA) modules is Machine Design. Solid Mechanics II is a prerequisite for Machine Design. Machine Design presents static and dynamic failure theories for ductile and brittle materials, and focuses on the safe design of various machine elements, based on these failure theories and other design paradigms. Topics include: shafts, gears, bearings, cams, fasteners, chains, belts, flywheels, springs, brakes and clutches. Students have a semester-long project to apply these new design skills to specific machine.

A word about the finite element method may be in order here. The purpose of these modules is to give the students a visual representation of the stresses and deflections found in some of the classic problems. We hope that this will help them to develop some physical insight. We use ProMechanica because the finite element method applied in the software is pretty transparent. The students learn about loads, boundary conditions, and such, and very little about meshing and element types, as that is done automatically by the software. We wave our hands as necessary to give them an understanding of element order and convergence, but only enough so that they can get reasonable results. Finite element theory is taught in a senior course on that topic.

## MODULE APPROACH

Both mechanics courses, described in this paper, are tightly scheduled because of course subject learning objectives. Thus, the use of class time for software tutorials has been limited in each course to one in-class session per each learning module. Out-of-class assignments and additional tutorial/question sessions were also provided with modules. Each module is described in this text, including learning objectives, methods and assignments. Tutorials and assignments may be found at the web site of the Keck Engineering Analysis Center at Mercer University [5]. Integration of design and analysis is a common theme of the modules and is apparent from the in-class exercises and homework assignments. Students actively participate in the analysis as part of design. In machine design, the term design project (part of the normal syllabus) also emphasizes the use of the solid modeling and FEA software for analysis of complicated designs of component geometry and loading.

One of the difficulties students face is visualization of forces, moments and resulting stress fields of loaded members. This is especially true in combined 3-D loading situations and in 2-D cases with stress concentrations. It is also vital to maintain or increase student interest in learning the subject area. The graphic nature of the modeling software provides a ready means of imaging stress fields and deformation. Through the use of solid modeling and FEA, the modules provide students additional experience in analysis and design, building upon previous courses and software modules in those courses. Basic engineering skills are also enforced through the modules, such as the importance of coordinate systems and unit selection.

**Overall Learning Goals for the Modules:**

- Students will improve visualization skills and gain an ability to rapidly interpret and assess multiple solutions (designs).
- Students will gain insight into stress, strain and deflection analysis, available only through interactive learning.
- Students will see the effects of component geometry discontinuities related to stress concentration.
- Students will increase skills in CAE software for 3-D solid modeling, static force and stress analyses through use and appropriate application (Pro/Engineer and Pro/Mechanica).
- Students will see the connection between design and analysis through an integrated software approach.
- Student will also learn the limitations and potential errors associated with CAE tools.
- Students will see the correlation of theory and hand calculations to the results of CAE tools.

## STRESS CONCENTRATION MODULE

In the first module of the Solid Mechanics II course, students use solid modeling software (in this case, Pro/Engineer) to model a flat bar with fillets and a centered hole (Figure 2). The model is then transferred into a finite element modeling software (integrated Pro/Mechanica) where a 3-D static, stress analysis is performed with the bar under a tensile load. The finite element model was created, using automeshing using P-elements [7]. The point of the assignment is to derive via parametric analyses, a stress concentration factor curve for this particular bar and loading configuration for various hole sizes. Students create a plot of a series of curves for stress concentration vs. hole size for several ratios of fillet radius to hole diameter. The students learn a number of different things with this type of project, while not specifically finite element theory.

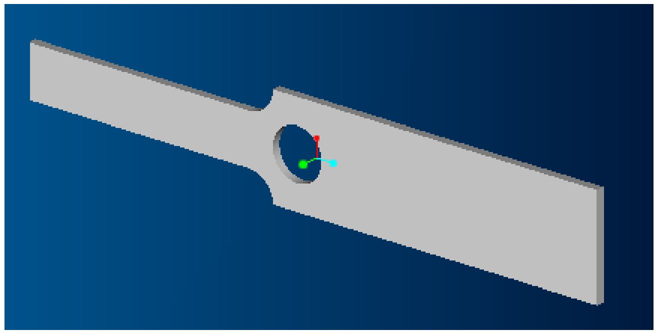

Figure 2.  Solid model of a flat bar with fillets and a centered hole.

First, students get more practice using and applying the solid modeling and finite element software for the various cases.  This builds on the student software experiences from previous courses and modules, as outlined in Figure 1. While some of the students have used the software in previous courses, many have not.  So instruction starts from ground zero.

Secondly, the students learn to plan and execute a software "experiment" using finite element software.  Students must decide on the appropriate number of cases to determine the stress concentration curves.  Additionally students also get practice in graphically displaying data, as well as providing word descriptions in a report.

Lastly, students are presented with an opportunity for increased insight into the determination of stress concentrations in complex situations, which may not always be described in textbooks and reference manuals.

## PLANE STRESS ANALYSIS MODULE

The second module in Solid Mechanics II is the plane stress analysis of a cylindrical pressure vessel.  The students model a quarter-cylinder in Pro/Engineer and then analyze it in Pro/Mechanica for a plane stress analysis. As this is a two-dimensional analysis, axial pressure loads are not considered.  There are several goals in this module.

First, the students learn how to perform a plane stress analysis, using symmetry boundary conditions.  While they have studied plane stress theory in class, modeling it is a new experience.  Symmetry boundary conditions are new, as well.

Additionally, the students learn, via their FEA experiments, the appropriate ratio of radius to thickness for a pressure vessel to be considered thin-walled, versus one that must be considered thick-walled.  This is accomplished by varying the thickness of the wall in several analyses.  The thin-walled case is most often studied in solid mechanics, with the thick-walled cylinder being left for more advanced courses.  By changing the thickness of the cylinder and studying the resulting stress gradients through the thickness, the students get some insight into the thin vs. thick assumption.  Students determine the limits of applicability of the thin-walled solution as a function of the ratio of radius to thickness from graphical displays of the resulting maximum stresses.  Note: Convergence of the FEA solutions is accomplished within the standard program operation using a multi-pass adaptive method for 9$^{th}$ order equations and 2% convergence error on displacement, strain energy and RMS stress.

## THREE DIMENSIONAL LOADING MODULE

A module for the Machine Design course was developed for three-dimensional (3-D) moment loading of members. The module consists of an in-class demonstration problem and a homework assignment that builds on this problem. In class the students use solid modeling software to develop the model of typical bracket [6], depicted in Figure 3. The selection of the simple bracket illustrates to students how the off-center force generates moment and torque at the base of the bracket.   The model construction is rudimentary solid modeling using two extrusions and rounds (fillets).  Stress and deflections are obtained by using the integrated version Pro/Mechanica with the Pro/Engineer model. A finite element model was created, using automeshing using P-elements [7].  A downward load was applied on the outer surface of the brackets as shown in Figure 4.  The software results of this model for a static analysis are shown in Figures 4a and 4b for von Mises stress and total deflection.  These results can be compared to closed form theoretical calculations by hand or using MathCAD.  Differences between the hand calculation and the FEA results for the stress highlight the effect of convergence error. The deflection comparisons between the FEA model and hand calculations are quite good.

A brief discussion of the finite element method was included in the lesson to illuminate how accuracy/solution convergence can be increased by using a finer mesh with traditional H-elements or using higher order polynomial fits for the P-element stress functions with fixed elements. For the analyses described here, a 5% convergence was specified using a multi-pass adaptive method with a maximum 9$^{th}$ order polynomial fit. Note: Node location and spacing may also be adjusted for better results.

A homework assignment provides students with the opportunity to analyze the effects of two designs of a lug wrench in terms of the resulting stresses. In this case students create models of two lug wrenches: a single lever arm and a dual lever arm design for handle. These are depicted in Figures 5a and 6a. Both have the same applied force at the end(s) of the wrench arms. The dual arm total length is the same as the single arm, so both yield the same torque. Students determine the highest load that can be applied without failure using von Mises or maximum shear stress failure theories. A comparison between hand calculations is also made. Stress concentrations at the arm to lug shaft are reduced by adding fillets. A sufficiently large fillet must be applied for the connection point not to be limiting factor. Resulting stresses and deflections illustrate the differences of the two designs, and why the dual arm is the preferred design.

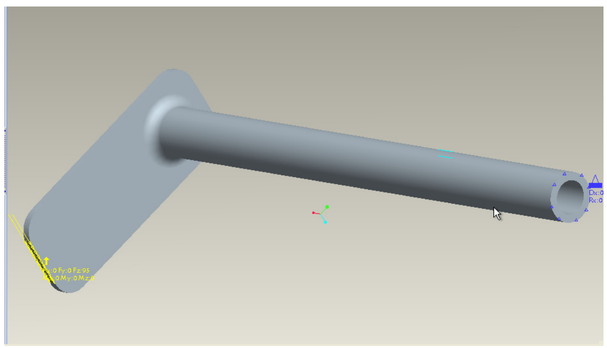

Figure 3. Machine Design Module: Solids Model of a Simple Bracket.

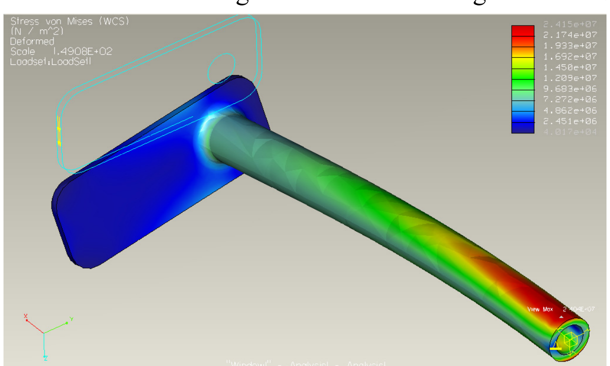


Figure 4a. von Mises Stress for Simple Bracket

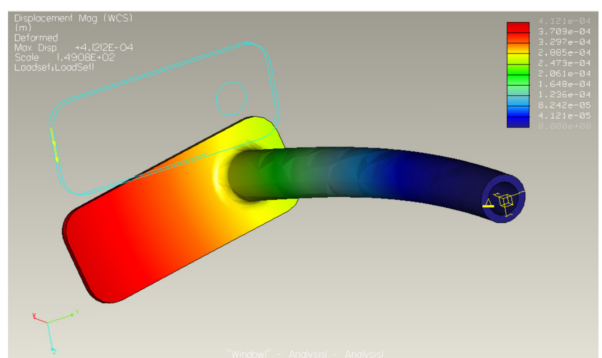


Figure 4b. Displacement for Simple Bracket

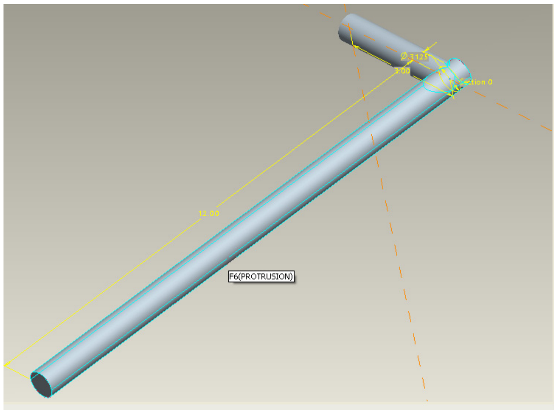

Figure 5a Single Lever Arm Lug Wrench

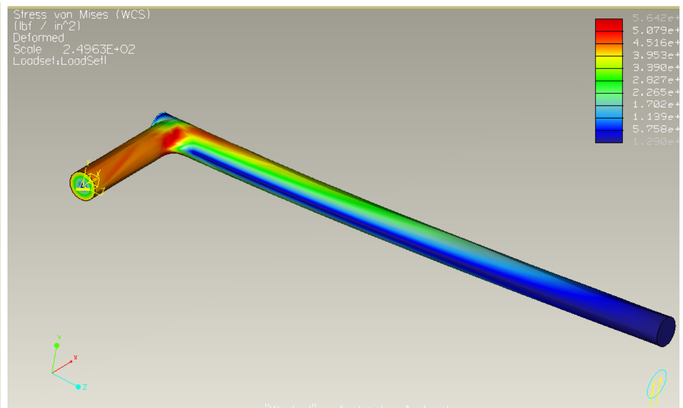


Figure 5b. von Mises Stress Single Lever Arm Lug Wrench

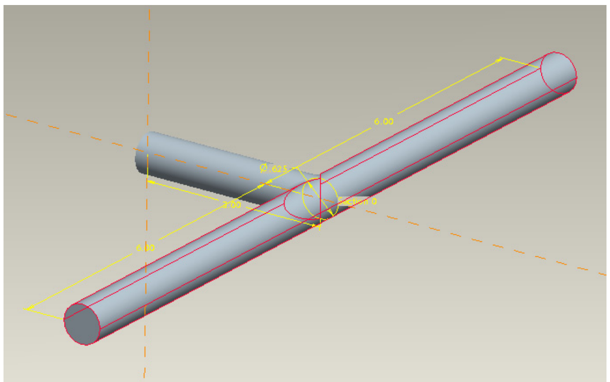

Figure 6a Double Lever Arm Lug Wrench

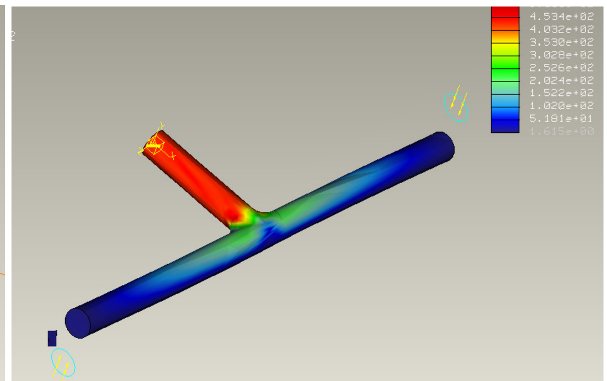


Figure 6b. von Mises Stress for Double Lever Arm Lug Wrench

## RESULTS

Limited results are available from the initial trial of the modules. Surveys of students were taken after completion of all of the modules and the associated homework. Students were asked to self-rank their confidence in their ability on several tasks (using a modified Likert scale from 1 to 5, 5 being very confident, 1 being not confident at all). Summary results are presented in Table 1, for all students.

Students ranked themselves as confident or better (3.0 or higher) in their ability to (1) generate problem solutions, (2) analyze problem results, (3) discuss meaning of results, (4) specify problem details, and (5) understand software capabilities. Students had the weakest confidence in their ability to use UNIX, followed closely by the ability to conduct analysis independently.

**Table 1. Self-confidence in Ability Ranking Survey (1-5)**

| **Ability to: (self-ranked)** | **Rating** |
|---|---|
| Understand software capabilities | 3.11 |
| Specify problem details | 3.33 |
| Generate problem solutions | 3.56 |
| Analyze problem results | 3.44 |
| Discuss meaning of results | 3.33 |
| Conduct analysis independently | 2.78 |
| Use UNIX-based software | 2.50 |

## OBSERVATIONS AND CONCLUSIONS

Many students (not all) enjoyed the modeling and analysis assignments. As members of the 'Digital Generation', they are attracted to most anything that involves computer use, and the more graphical the better. The assignments, however, were not as addictive as games. The ability to create animations of deflections within the software was also an attraction for students.

The students did not, by-and-large, enjoy the more mundane aspects of the assignments, involving analysis, synthesis of results, and writing the report. In addition they have little, if any, experience reading technical papers and reports, so the mechanics of putting together such a document, with figures, equations, and concise explanations, are difficult for many of them. They can only benefit from this exposure.

Our students were more at ease with MS-Windows environments than with the Unix-based graphical environment. This is clearly demonstrated by the survey result indicating that the students felt the least confident in using UNIX-based software of all the abilities questioned. This may also be due in part by the availability of other computer facilities with MS-Windows-based versions of the modeling and analysis software. Students favored the use MS-Windows-based computers. UNIX is not taught outside the Advanced Engineering Computation Center.

### Lessons Learned for Future Offering Considerations

It was difficult, in one class period, to complete both the model creation and analysis. Although it is pedagogically good for the students to create a model in 3-D, it was more expedient to have a pre-made base model (dual handle) available for the homework. In the future, this problem should not occur as students will have had sufficient Pro/E solid modeling in a prerequisite Engineering Graphics course.

The UNIX operating system environment in the computer lab presented additional learning obstacles for students. UNIX was a little cumbersome for the students, as most had not used UNIX prior. Many concepts were foreign to them, such as FTP, and UNIX file manipulation. While UNIX is good environment for students to experience, it is not recommended if it is only used within the module.

Note: the authors found students were very interested in additional faculty-lead homework sessions outside of class to complete the assignment. Having out-of-class homework sessions where students could perform the homework worked well. Students felt more at ease with a faculty member available to ask questions as they did the homework.

While this software effort to enhance student understanding, interest, and preparedness is just beginning, it is apparent that students are gaining benefits.

## FUTURE DEVELOPMENT

The initiative to infuse modern CAE tools into the mechanics and design curriculum via integrated software modules will continue to be developed, adding new modules to courses. Refinements to the modules described in this paper are also planned. Additional modules will include common machine design situations. A gear tooth stress module is planned to examine the effects of rolling contact stress in comparison with the bending stress at the base. Thus, students will see component failures initiated at surfaces. Ideal beam analysis module is also planned to assist students in performing space frame stress and deflection analyses.

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**Jack Mahaney**

Dr. Mahaney is an Assistant Professor in Mercer University's Dept. of Mechanical and Industrial Engineering. A native of Northern California, Jack served eleven years in the Navy as a submarine Missile Technician. After leaving the Navy, he attended Old Dominion University in Norfolk, VA, where he earned the BSME in 1982 and ME in 1985. He left ODU to help found Mercer's School of Engineering in 1985. With an interest in computational mechanics, and particularly finite element methods, it was natural that Jack would pursue his PhD work at the University of Wales Swansea, where he worked with Dr. Richard Wood and Dr. Javier Bonet. He finished in July of 2002, after only five years of part-time work and 16 trips to Wales. His thesis is entitled "Aspects of Large Strain Membrane Analysis Using the Finite Element Method." Today, Dr. Mahaney is a leader in the efforts at Mercer to integrate computational techniques and tools into the ME curriculum.