A TECHNICAL ELECTIVE COURSE IN MODELING AND SIMULATION - TEACHING THE CAPABILITIES AND LIMITATIONS OF PROFESSIONAL LEVEL SOFTWARE

Gregory K. Watkins
Mechanical and Mechatronic Engineering and Sustainable Manufacturing
California State University - Chico

Abstract

The mechanical engineering program at California State University Chico includes a required junior level course in Finite Element Analysis (FEA). Students learn the theory of the method and receive some basic instruction in the proper use of commercial software, SolidWorks Simulation in this case. Due to time constraints and the necessary instruction in FEA theory, the exposure to commercial software is limited to basic linear elastic studies. While important concepts such as element choice, mesh quality, and appropriate boundary conditions are covered, no advanced capabilities, such as nonlinear analysis, time dependency, impact, buckling, or fluid flow are explored.

The demand for a continuation course on the subject has become increasingly clear over the past several years. Commonly, a significant portion of the students completing the required course have expressed a direct and forthwith desire to learn more about the subject. Industrial partners, both advisory committee members and Capstone Design Program sponsors, have communicated the desire for additional competencies in recent graduates. Finally, several years' mentorship of Capstone Design Projects has made clear the frequent opportunity for students to perform more advanced modeling and simulation analyses.

In response, a technical elective course titled Modeling and Simulation was developed. The course carries pre-requisites of solid modeling, fluid mechanics, heat transfer, finite elements, and machine design. The primary intent of the course is to explore the advanced capabilities of professional level simulation software while importantly understanding the underlying assumptions and limitations of the various analysis techniques. Outcomes include giving students wide exposure to advanced simulation tools they are likely to encounter in the workplace while equipping them with sufficient understanding of their proper use and limitations.

The Existing Course in Finite Element Analysis

The mechanical engineering curriculum at California State University Chico includes a required junior level course in Finite Element Analysis (FEA). Yearly enrollment averages about one hundred students. Prerequisites include completion of the standard calculus and differential equation course sequence, as well as Statics, Strength of Materials, and a numerical methods based course called Equation Solving Techniques.

The FEA course has recently been completely redesigned [1] to augment the traditional theory-based content with some basic instruction in the proper use of commercial software. At regular intervals throughout the course, theory-based instruction is followed by exploration of the same concepts in the context of commercial simulation software.

The topics covered in each segment are summarized in Table 1. They are grouped into roughly 1/3 increments, each of which is followed by a written exam that tests theoretical topics with "by hand" problems that are straightforward enough to be solved with a scientific calculator.

Table 1 – Content Summary of Existing FEA Course.

Theory Based Instruction	Commercial Software Augment
Spring elements, direct stiffness method, truss elements, coordinate transformations, stress in bar elements, bar elements in 3D space	Analysis of trusses including: Initial set-up, truss geometry, section properties, study properties and settings, boundary conditions, loads, meshing, solving, post processing
Beam equations, distributed loading, comparison to exact solutions, beam elements, plane stress and plane strain elements	Beam elements, section properties, geometry creation, weldments, fixtures, loads, mesh controls, stress in beam elements, plane stress, plane strain, 2D simplification, mesh quality
Axisymmetric elements, 3D stress analysis, 1D heat transfer elements, 2D heat transfer elements, thermal stress	Axisymmetric problems, 3D analysis, symmetry, adaptive mesh refinement, assembly modeling, contact, friction, limitations of linear static FEA, thermal

The Case for Additional Instruction in Modeling and Simulation

While the redesigned FEA course has been very well received by students, capstone sponsors, advisory board members and other faculty in the department, it has actually helped create demand for additional instruction in the topic. This was especially true when clarifying the assumptions behind the linear static finite element analysis, and the limitations of the technique under different model conditions.

Arguably the most important assumption for undergraduates to fundamentally understand is the assumed linear relationship between stress and strain. During the development of the various element models, students see directly how Young's Modulus (E) contributes to the stiffness matrix, and the common assumption that E has a constant value for a given material. Most common commercial codes, when operated with default settings, assume a constant relationship between stress and strain forever, regardless of the magnitude of the applied forces or the stresses predicted in the geometry. Figure 1 shows a favorite graphic used in class to illustrate this point.

Students hopefully grasp the concept that a linear static analysis that predicts von-Mises stress in excess of the material's yield strength really only tells them two things; that the material's yield strength has been exceeded and that plastic deformation will occur. All other results, such as nodal displacements, element stresses, deformed shape, etc., are useless.

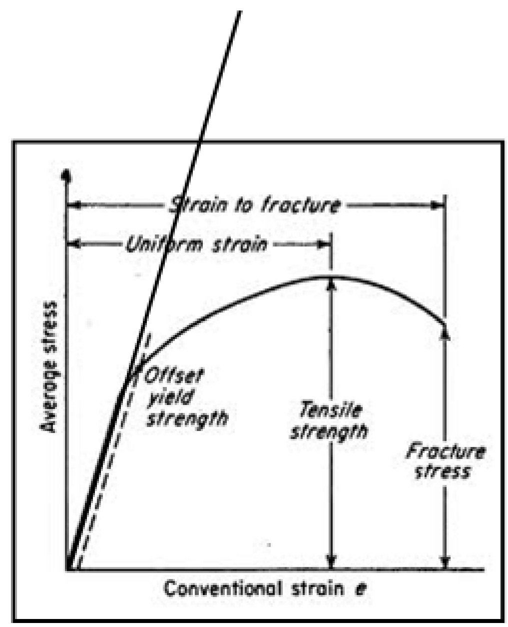

Figure 1 – The Infinite Stress Strain Curve.

But when the point has been made and the concept fully grasped, the natural next question from students is, "so how are those situations modeled?" This leads to a brief discussion of non-linear analysis, which is simply too complex a topic to be covered in an already busy single-semester course. Similar observations and discussion regularly occur around the topics of large displacements, buckling, time dependency, rigid body motion, impact, fluid flow, and fluid-solid interaction.

Though certainly not all, a significant percentage of students who complete the required FEA course express a strong interest in a continuation course. In addition, the university's industrial partners, both advisory committee members and Capstone Design Program sponsors, have communicated the desire for graduates to have additional competencies in simulation. Finally, students in the senior level Capstone Design course frequently have the opportunity to perform advanced simulation as part of their senior project. A recent example is a project sponsored by the NASA Jet Propulsion Laboratory that focused on their land-based 70m deep space antenna. They wanted to understand the phenomena behind the observed loosening of bolts that join sections of the bearing surface that supports rotation of the antenna. They specifically requested a detailed, time dependent, non-linear finite element analysis of the joint assembly under transient loading conditions. Students would not have been able to approach the problem in any realistic way without significant additional instruction.

While a similar course dedicated to advanced modeling techniques has not been located in the pedagogical literature, a course has been proposed [2] at a peer institution. The literature does show numerous applications of advanced simulation techniques in other advanced subjects such as vibrations, [3] fatigue, [4] and design of experiments. [5]

An Advanced Undergraduate Course in Modeling and Simulation

This demand led to the development of a technical elective course titled *Modeling and Simulation*. The senior level course is offered in the fall semester and is designed to be taken concurrently with the first semester of the capstone design course. The new course has prerequisites of Solid Modeling, Fluid Mechanics, Heat Transfer, Finite Element Analysis, and Machine Design.

The primary intent of the course is to explore advanced simulation techniques and demonstrate how they are implemented in professional level software. For each technique, underlying assumptions and limitations are explored, giving the student an understanding of what the software is trying to do while also providing insights into how the results may be interpreted.

While the course is defined as undergraduate (400) level, it is taught more as a graduate class. There is a single, three hour meeting per week. Instruction in the first hour or so introduces the topic at hand and explains how it differs from a standard (default) FEA simulation. To the extent that it is practical, assumptions and algorithmic steps taken by the software are explained. Basic procedural steps are covered, including various software options and their respective meanings.

Instruction proceeds with a live demonstration of an analysis of the type just presented. Models are prepared ahead of time, along with common set-up tasks to speed up the demonstrations. Saved solutions are utilized for analyses that take a significant amount of time to run.

The students are then given a "warm-up" assignment. All students work on the same, pre-determined problem. Depending on the particular assignment, well defined models are often provided that will facilitate successful completion of the analysis in a reasonable amount of time. Results of the analysis are provided so that students can verify that they have correctly solved the problem.

With the warm-up assignment complete, students then perform the same type of analysis on a problem of their choosing. They are encouraged to opt for something in their areas of interest, which adds a meaningful element to the assignment. This also leads them to discover one of the common pitfalls of open-ended assignments, problems that aren't "well behaved" and may or may not be solvable based on the student's choice of set-up and other parameters.

In their out-of-class time, students finish up the analysis and interpret the results. A key element here is validation of their analysis through comparison to some form of a simplified analytical analysis (hand calculation). In most cases, a preliminary analysis with simplifying assumptions and/or simplistic geometry is required to determine a "ball park" value for the expected results which is used to verify the validity of the solution. Students choose which results to present and how to present them. They are expected to explain the meaningful outcomes of the analysis while also pointing out spurious results that are not meaningful. Homework is submitted in the form of a technical memo that summarizes the application, assumptions, analysis, and results. The format is intended to represent what a working engineer would generate for an internal client such as a boss or technically competent manager in industry.

Two commercial software packages are utilized in the course, SolidWorks Simulation Professional and ADINA (Automatic Dynamic Incremental Nonlinear Analysis). SolidWorks is chosen due the students' existing knowledge of its modeling capabilities from earlier courses in engineering graphics and computer aided design (CAD), along with its strong presence in industry. Adina is introduced as a highly advanced simulation code more typically utilized in research settings, with significant capabilities beyond most commonly used commercial software options.

The course does not utilize a textbook, but much of the lecture material and some of the demonstration assignments have been developed based on material from a collection of texts, [6-9] all of which are recommended for those that may be interested in developing a similar course.

Course Topics

The course explores numerous topics beyond the standard linear static analyses that are the primary focus of the required junior level course. Weekly topics from the course are briefly summarized here along with representative samples of example and demonstration assignments. Detailed PowerPoint based lectures are freely available to any interested parties by contacting the author.

Week 1 – Linear Static FEA, is primarily a review from the required junior level course. A representative assignment is an analysis of the U-Clamp shown in Figure 2, which was taken from Bertoline. [9] This assignment explores single-part versus assembly modeling and the associated (and sometime unrealistic) boundary conditions required by the simpler approach.

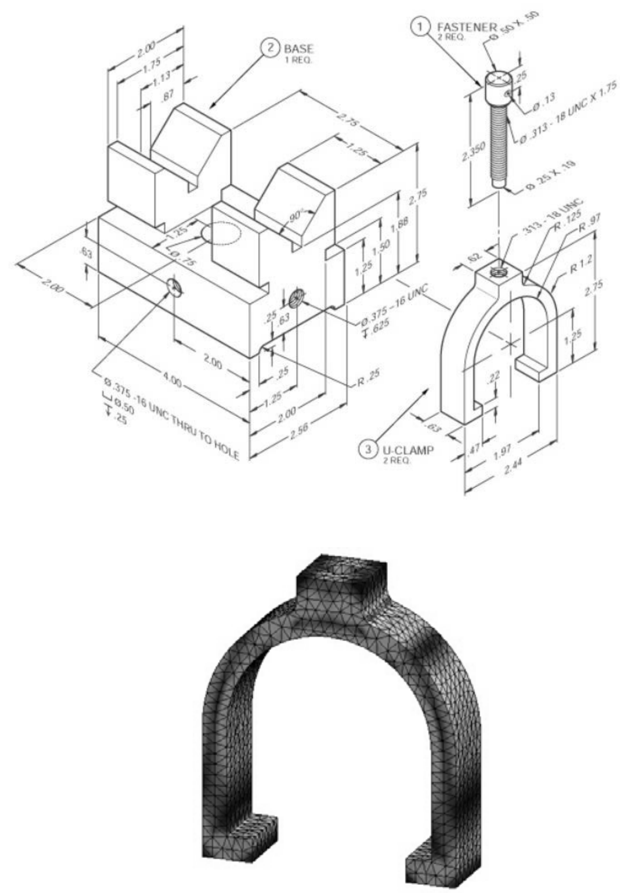

Figure 2 – Linear Static FEA.

Week 2 – Design Optimization introduces variables, constraints, and sensors in the context of determining an optimum design configuration. An example problem, taken from Steffen [7] and shown in Figure 3, minimizes the weight of a part by varying three of its dimensions within upper bounds of von Mises stress and deflection.

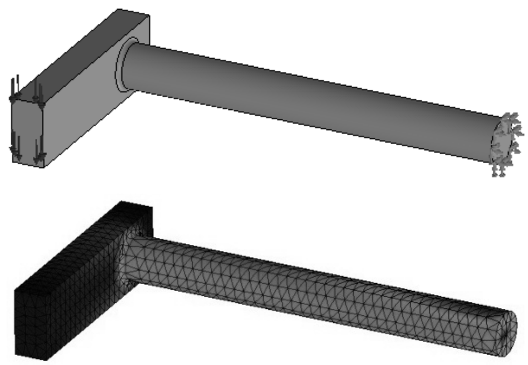

Figure 3 – Optimization Problem.

Week 3 – Assembly Modeling introduces multi-part analysis and the concepts of contact, friction, and connections. Utilization of symmetry is also introduced. A representative problem of a shaft, hub, and key, generated by the author, is shown in Figure 4. Of particular note in this problem are the vastly different results obtained when frictional vs. bonded contact is specified.

Week 4 – FEA Simulation from Motion Studies reviews the generation of motion studies, including motors, springs, contact, gravity, forces, dampers, and data plots. Data plots are then utilized to determine when maximum loads occur within a motion study. Students are then shown techniques to extract loads from motion studies at specific times and apply them to individual parts. A demonstration assembly taken from a SolidWorks tutorial, along with data plots and part analyses, is shown in Figure 5. In this example, loads for part analysis are extracted at the instant of maximum motor torque.

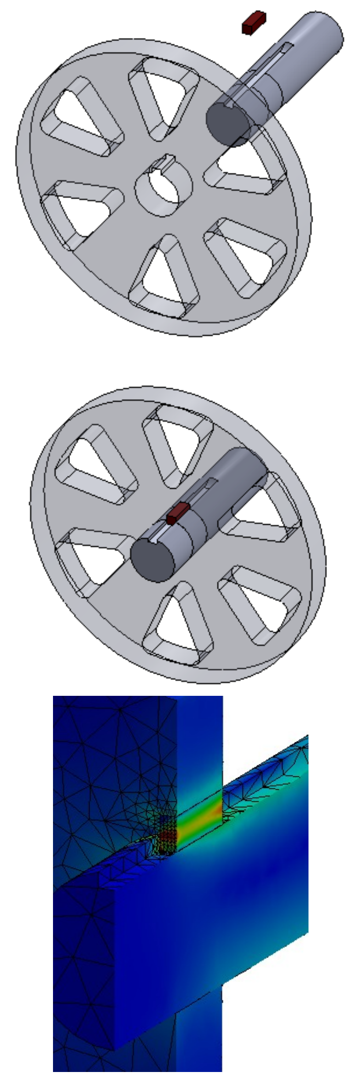

Figure 4 – Assembly Modeling.

Week 5 – Nonlinear Analysis introduces the multiple sources of non-linearity and explores the various means of simulating non-linear behavior. Specific instances detailed include changes in model shape as well as non-linear material behavior. The specific case of plastic deformation and residual stresses are demonstrated. A sample large displacement model and a sample non-linear material model, both taken from Kurowski, [6] are shown in Figure 6. The first model demonstrates large displacements without exceeding the material's yield strength while the second explores residual stresses after plastic deformation has occurred.

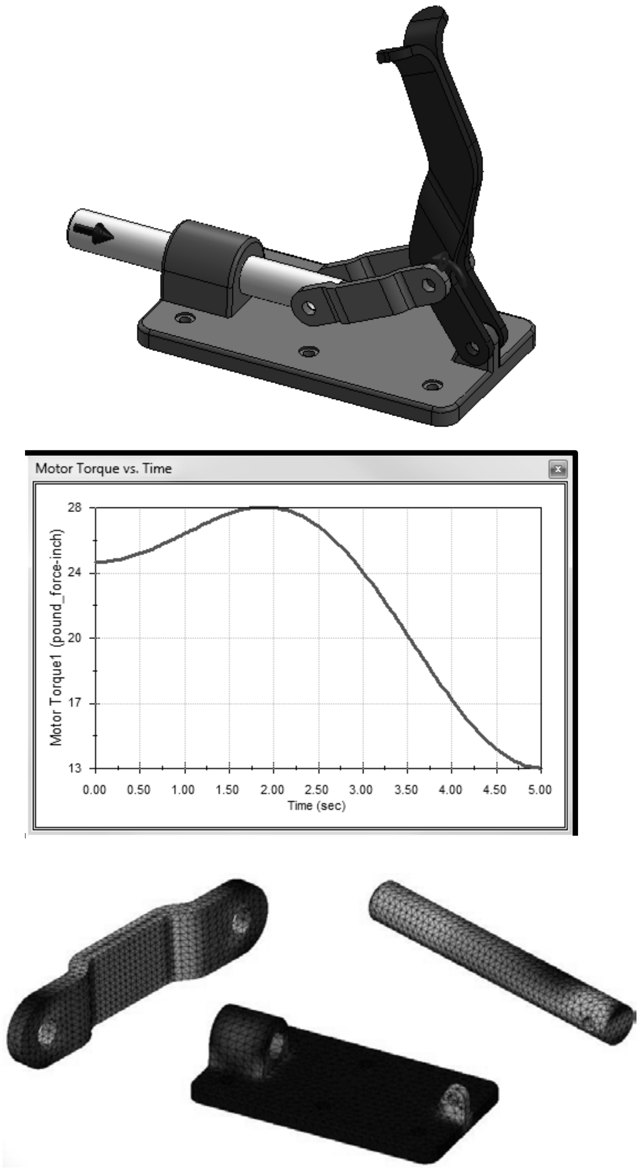

Figure 5 – Simulation Loads from Motion Studies.

Week 6 – Buckling and Drop Test introduces both topics. Buckling analyses predict a load where buckling will occur, while drop test simulates an impact load resulting from dropping an object from a specified height onto a floor with specified rigidity. A sample buckling problem and a sample drop test model, both taken from Kurowski, [6] are shown in Figure 7. The curved I-Beam buckles long before the material's yield strength is reached, while the ring's time-dependent stresses resulting from impact are determined.

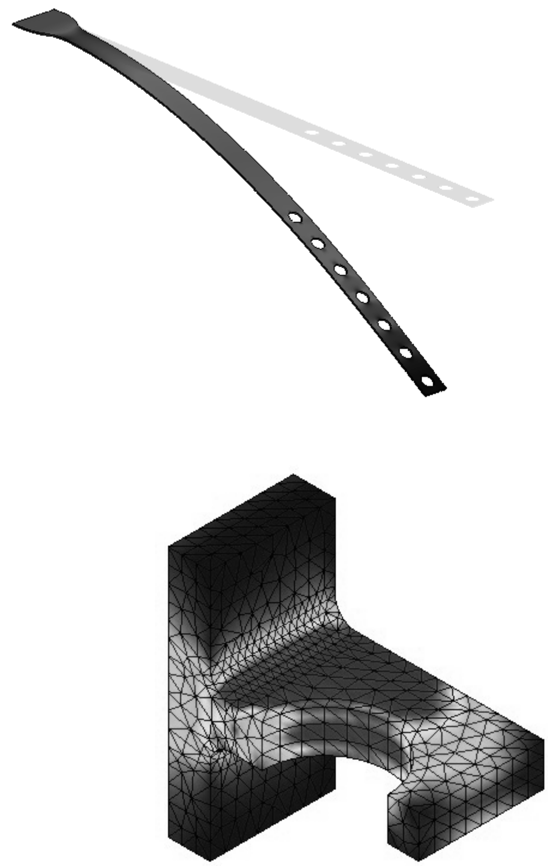

Figure 6 – Non-Linear Analysis.

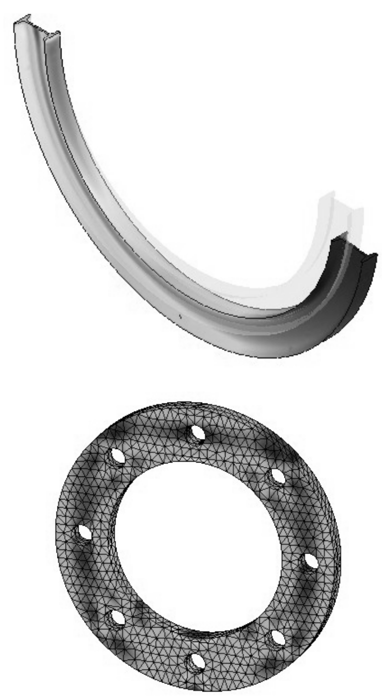

Figure 7 – Buckling and Drop Test Analyses.

Week 7 – Modal Analysis explores resonance frequencies and their respective mode shapes. An example problem of a tuning fork, taken from Kurowski, [6] is shown in Figure 8. The various mode shapes and their associated frequencies are determined. The model also illustrates a practical application in harmonics.

Week 8 – Thermal Analysis introduces simulation of steady state heat transfer problems, including contact resistance in assemblies. The section also introduces thermal stress. An example multi-body heat transfer model, as well as a thermal stress analysis, both created by the author, are shown in Figure 9. The first model illustrates the safe handle design of a wood burning stove while the second shows contact stresses generated from the temperature change in dissimilar materials.

Week 9 – Transient Thermal Analysis introduces time dependency in thermal simulations. Topics include time stepping, initial temperature, unsteady loads, and time history post processing. A sample problem of a heat source and radiator, taken from Kurowski, [6] is shown in Figure 10. The problem illustrates the transient thermal response of a radiator as well as the contact resistance between the radiator and source.

Figure 8 – Modal Analysis.

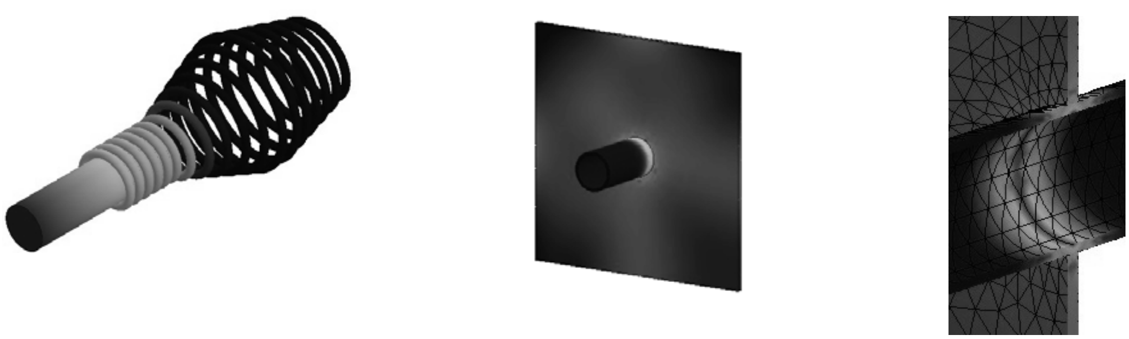

Figure 9 – Steady State Heat Transfer and Thermal Stress.

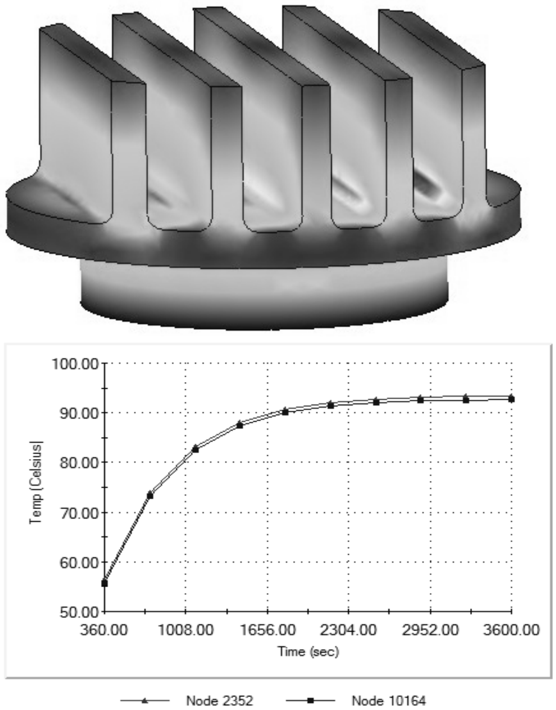

Figure 10 – Transient Thermal Analysis.

Week 10 – Computational Fluid Dynamics (CFD) introduces internal and external flow problems. Internal flow analysis is demonstrated through a valve body taken from a SolidWorks tutorial and is shown in Figure 11a. External flow is demonstrated over a car body with geometry taken from 3D Content Central [10] and is shown in Figure 11b. The internal flow model illustrates the effects of a partially closed valve while the car body problem explores determination of lift and drag.

Week 11 – Thermal CFD and Time Dependency introduces thermal aspects and time dependency to flow simulation problems. A demonstration model of cooling of an electronics enclosure, taken from a SolidWorks tutorial, is shown in Figure 12a. A time dependent thermal simulation of a mixing elbow developed by the author is shown in Figure 12b. The first model includes simulation of a cooling fan taken from a library while the second shows the transient response of introducing a warm liquid into cool liquid flow.

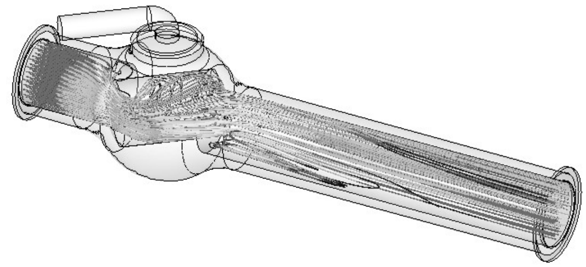

Figure 11a – Computational Fluid Dynamics.

Figure 11b – Computational Fluid Dynamics.

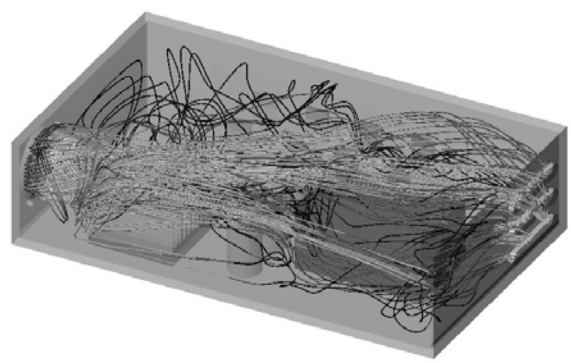

Figure 12a – Thermal CFD and Time Dependency.

Figure 12b – Thermal CFD and Time Dependency.

Week 12 – Adina Overview introduces the alternative, and much more capable software package Adina. A linear static FEA of the same U-Clamp taken from Bertoline [9] is introduced and shown in Figure 13.

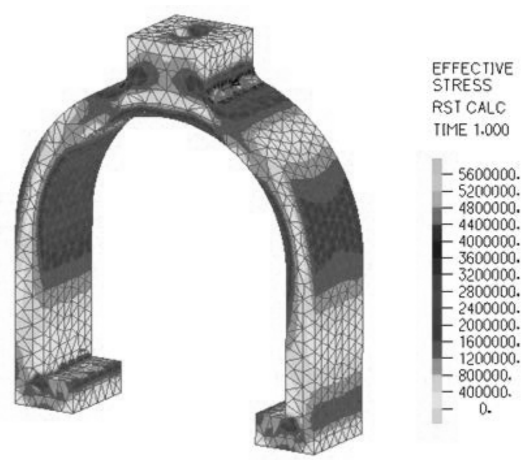

Figure 13 – Linear Static FEA in Adina.

Week 13 – Adina CFD and FSI introduces the software's capabilities in CFD and also Fluid Solid Interaction (FSI). Figure 14 shows a demonstration problem of 2D flow through a channel with an obstacle that is first modeled as fixed and then as flexible. The model was created by the author. The problem explores the effect that the displacing body has on the flow field.

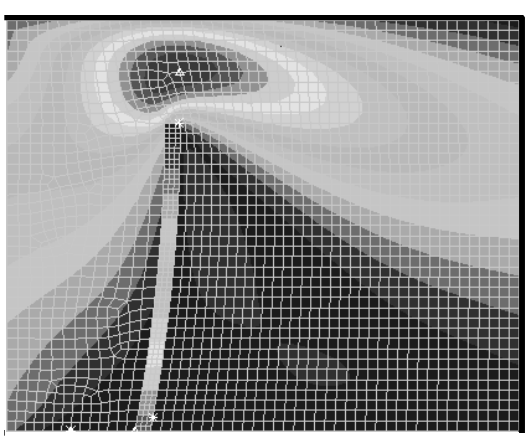

Figure 14 – CFD and FSI in Adina.

Week 14 – Sliding Mesh introduces another FSI capability within Adina. A demonstration 2D sliding mesh model of a spinning turbine blade, taken from an Adina tutorial, is shown in Figure 15. The model illustrates a transient FSI problem as the turbine blade begins at rest and then rotates in response to the introduced flow.

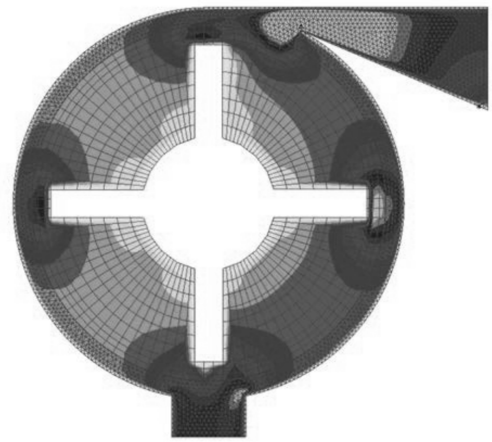

Figure 15 – Sliding Mesh CFD.

Conclusion

The technical elective course has now been offered twice, and is on an every-other-year rotation within the department. Positive anecdotal feedback about the class has been received from multiple department stakeholders. Students who have taken the class, while acknowledging the significant amount of work, have generally praised the class and commented about the significant additional knowledge developed in modeling and simulation. Selected student comments include:

- *The simulation class has absolutely helped me understand how to do proper FEA and how to document the results.*
- *I thoroughly enjoyed this course. (The professor) did a great job showing what was possible in the software and showing the weakness/limitations.*
- *I feel that this class helped prepare me to go into the working world and apply my simulation knowledge effectively and intelligently.*
- *I wish that this class would be required for the degree so that all students can build up the knowledge and idea of the reliability and accuracy of simulation software.*

The course is also a strong selling point with potential capstone sponsors, who have expressed praise (and surprise) at the abilities of the students in the program. Many department faculty, all of whom regularly supervise capstone design projects, have offered positive feedback on the additional skills and capabilities that students from the class were applying to their senior projects.

Not only are modeling and simulation tools becoming more and more common in today's engineering workplace, their sophistication and capabilities continue to expand as well. Today's graduates need to have competency not just in the fundamental theory of FEA, but of its proper application, and limitations, to advanced applications common in today's workplace.

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Biographical Information

Gregory Watkins received a B.S. in Mechanical Engineering from North Carolina State University, a Master of Engineering Management from Old Dominion University, and a Ph.D. in Mechanical Engineering from the University of North Carolina at Charlotte. He is a Professor in the department of Mechanical and Mechatronic Engineering and Sustainable Manufacturing at California State University Chico. He previously taught in the Engineering Technology department at UNC Charlotte and the Engineering Technologies Division at Central Piedmont Community College. He also has nine years of industrial work experience.