Teaching Finite Element Analysis in Undergraduate Technology Curriculum

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Session: Tools, techniques, and best practices of engineering education for the digital generation

I. Abstract

Typically, FEA courses are offered at a graduate level, covering the theoretical basis with little or no effort to apply this technology to real problems. In some institutions, this course is offered to seniors, but the content is also mostly theoretical. At Wentworth, we have designed an FEA course based on our industrial experience which could be labeled "Applied Finite Element Analysis". This paper describes the methodology followed in the development of this course, along with its details.

Students are first introduced to the concept of FEA in their "Strength of Materials" course during the sophomore year through a tutorial as part of a laboratory exercise. Some students become more familiar with FEA while taking "Machine Design", which is a technical elective course, offered during the junior year. The formal introduction to FEA, offered in the last semester of the student's curriculum is given with two hours of lecture and four hours of laboratory per week. The first lecture reviews the concept of FEA, without involving any theoretical development. Subsequent lectures cover practical modeling and analysis techniques usually not available in FEA textbooks. The laboratory component allows students to practice what was covered in lecture through solving problems designed by faculty and assigned to them. Each assignment includes hand calculations to verify the FEA solution. This also helps students debug their solution in case of a mismatch between the two solutions.

II. Introduction

As practicing engineers, the authors recognize the value of FEA in the product design and development cycle. Increasingly, companies are utilizing FEA to reduce their product design cycle, so why is it that most institutions suffice by introducing a theoretically based FEA course? If industry requires a certain skill, why do we not include this skill in the student's training? If a student is not planning to attend graduate school, what is the value of a theoretical FEA course? The authors have also come across situations where an employer expected a new hire, fresh out of undergraduate school to perform FEA, just because he/she had an FEA course on their transcript.

In the Mechanical Engineering Technology (BMET) program at Wentworth, we decided to re-engineer an existing upper level CAD course to eliminate this deficiency. To do this, the authors of this paper formed a working group and designed the course based on their combined experience in industry. Once the course was designed, the best tool for the course had to be selected. Requirements for this tool were two fold. The tool needed to be state of the art, and the tool needed to fit the overall pedagogy of the program. For these reasons, SolidWorks/CosmosWorks package was chosen. The tight integration of solid modeling and FEA in this package, along with positive response from our Industrial Advisory Partners was also instrumental in this selection. Students utilize SolidWorks in their sophomore year to understand spatial modeling and fit. Because of this course and use in other courses, by the time the “Applied FEA” course is taken in the senior year, they have become quite familiar with solid modeling.

In the BMET program, students are first introduced to the concept of FEA in their “Strength of Materials” course during their sophomore year through a tutorial as part of a laboratory exercise. Their next exposure is in the “Heat Transfer” course in the senior year, where CosmosWorks is used to solve conductive and convective problems as well as fin design and compare results to hand calculations. Some students become more familiar with FEA while taking a “Machine Design” course, which is a technical elective course in the junior year.

The formal introduction to FEA is offered in the last semester of the student’s curriculum with two hours of lecture and four hours of laboratory per week. The first lecture in this course reviews the concept of FEA, without involving any theoretical development. Subsequent lectures cover practical modeling and analysis techniques usually not available in FEA textbooks. The laboratory component allows students to practice what was covered in lecture through solving problems designed by faculty and assigned to them. Each assignment includes hand calculations to verify the FEA solution. This also helps students debug their solution in case of a mismatch between the two solutions.

III. Course Specifications

Before designing the course, the following specifications were laid out:

- The main goal is to familiarize students with the concepts involved in solving real world problems, and not to teach the theory of FEA.
- The software package used in the course is only a tool to help convey the information. Hence the course should be independent of the software package.
- Home work problems should include hand calculations for ball park verification. There are two reasons for this requirement:
    - Students have completed their major technical courses by this time and simplifying real world problems for hand calculations is a beneficial new skill that needs to be further developed.
    - To further emphasize the numerical nature of FEA and its susceptibility to give a totally incorrect answer due to modeling or input errors, even though the problem ran and “pretty pictures” were generated as output.

- Emphasize that a one semester course in applied FEA does not qualify students as experts and further on the job training/experience is required before they are competent to solve problems without supervision.
- Students should be exposed to a wide variety of problems in Stress, Deflection, Vibration, Heat Transfer, Thermal-Stress, and optimization.
- All course material including lectures, labs, homework assignment, exams and projects are designed by faculty and are available to students through Blackboard, Wentworth's online learning platform.

IV. Course Layout

This required (vs. elective) four credit hour course is offered in the last semester of the BMET program. Faculty have the option of scheduling two one hour lectures or one two hour lecture per week. There are also two lab sessions, two hours each per week. Although the lectures and labs are designated as such, the distinction between lecture and lab at times is blurred since all students have laptops (Wentworth Laptop Program/Wireless Campus). The authors routinely cover lecture material and in the same session assign related lab work and homework. Students work on the lab material first, which consists of tutorials, simple conceptual problems, etc. and if they finish the work they have the option of moving to the homework. Students are assigned two homework problems per week.

Since we have no BMET graduate programs, and therefore no teaching assistants, all lecture and lab sessions are taught by faculty. Although it was mentioned earlier that this course is not about the tool, in order for students to become familiar with the tool, a portion of some lectures is devoted to explaining the menus, options, etc. in CosmosWorks.

V. Topics Covered

In the 13 weeks of the summer semester when this course is offered, the following topics are covered.

Week 1- Introduction to CosmosWorks- Plate in tension, plate in bending

- Topics such as mesh generation, boundary conditions and loads as well as post processing are covered.

Week 2- Static Analysis & Convergence

- The H method, convergence threshold, and mesh refinement are discussed. It is greatly emphasized that a single run is FEA is not meaningful and multiple runs are required to achieve acceptable results.

Week 3- Shell elements vs. Solid elements

- The advantages of using shell elements in thin structures are explained.

Week 4- Displacement Loads, Symmetry, Cyclic Symmetry

- The concept of applied non-zero boundary conditions as load is covered along with advantages of using symmetry boundary conditions to reduce modeling and run time. Also, cyclic symmetry for a specific subset of problems, such as rotating equipment is discussed.

Week 5- Re-entrant Corners and Singularities

- The concept of singularity is discussed and demonstrated through the use of stress concentration tables as well as FE analyses of filleted and non-filleted L brackets.

Week 6- Assemblies and Contacts

- Contacts, their definition and use in assemblies are covered along with limitations and precautions in using this type of joint to model assemblies. Other topics include mesh generation of contact pairs and interpretation of results of contact region. A typical problem is presented in section VI.

Week 7- Bolted Assemblies and reaction forces

- Connectors, particularly bolted joints are discussed and different methods including the use of temperature change in bolts to simulate preload are explain. The bolt feature in CosmosWorks does not require an actual bolt model, somewhat different from other applications such as ANSYS Workbench. Since this is a relatively new feature in the FEA technology, students are cautioned in their use.

Week 8- Hydrostatic Loads

- Use of hydrostatic loading is examined and two homework problems related to this topic are assigned.

Week 9- Frequency Analysis and resonance issues

- Modal analysis and resonance is covered at this point in the course. Fine tuning of simple structures is conveyed through a simple homework problem. A typical problem is presented in section VI.

Week 10- Conductive and Convective Heat transfer

- Thermal analysis including conduction and convection are covered and simple problems with both concepts are given as homework.

Week 11- Thermal Stresses

- Thermally induced stresses are discussed as a two step solution, where first the temperature map is determined and then used as input into the stress analysis in the second step.

Week 12 and 13- Shape Optimization

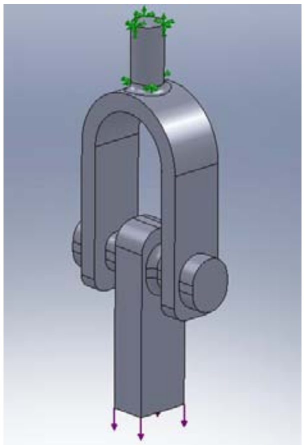
- Shape optimization is discussed and simple parts requiring optimization based on both stress and frequency design specifications are assigned for homework.

VI. Typical Homework Problems

Example 1: **Assembly and Contacts**

a) **<u>Pre-processing</u>**:

- Download the two part files and one assembly file models for HW#10.
- Define Study with solid mesh.
- The U shaped part material is AISI 304 and other part is made of AISI cold rolled steel.
- Define all contact pairs.
- Use a mesh size of 0.2" to start (if you get errors, try refining fillets).
- Apply a tensile force of 5000 pounds to the bottom of assembly and a fixed support to the top and cylindrical faces as shown.



b) Run Analysis:

- Refine mesh until a 5% convergence is achieved (Von-Mises).

c) Post-Processing:

- Record peak Maximum Principal and Von-Mises stresses for each component.

d) Hand Calculations:

- Simplify the problem as a short beam-bending for one arm with a fillet and apply the appropriate load and boundary conditions. Use a closed form solution to find maximum principal stress in fillet.

e) Report:

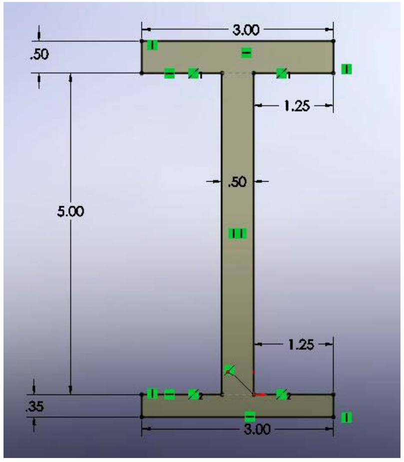
- Tabulate your runs and show results for all parts.
- Plot Von-Mises stress for each component, ensuring the stress range is defined for that component.
- Determine the factor of safety for the assembly. Show all run statistics in the table and detailed hand calculations.
- How does your hand calculation compare to FEA results?

Example 2: Vibration and Resonance

You are to optimize the cross-section dimensions of a beam to support a motor that weighs 250 pounds and is running at 700 RPM.

a) <u>Pre-processing</u>:

- Create a solid model of the beam with cross section as shown and length of 36”.
- Create a frequency study called “Beam-Motor Natural frequency”.
- Apply material property for 1020 steel.
- Apply fixed BC to left end.
- Right click on study, select properties:
  - Make sure Number of frequencies is set to 6 in the options tab.
- Apply a distributed “mass” of 250 pounds to the right end face. The software converts this weight to mass units for analysis purposes.



b) <u>Run Analysis</u>:

c) <u>Post-Processing</u>:

- Determine the first three distinct natural frequencies for the beam.
- Examine the beam bending frequencies and record their values.
- Use a 10% of motor running speed for an avoidance zone envelop.
- Determine if there is a potential for resonance with any of the frequencies above.
- If so, first change the 5” height dimension to 6” and run the problem to check for resonance.
- If problem persists, go to the original dimensions and increase the flange width (3”) in increments of one inch and run until resonance is eliminated.

d) <u>Report</u>:

- Tabulate the results of your runs and show unique frequencies from FEA and hand calculations.
- Which frequency or frequencies had the potential for resonance with engine speed?
- What was the effect of increasing the web dimension and why? Explain.
- What was the effect of increasing the flange dimension and why? Explain.
- Plot all frequencies in above table.
- Include your hand calculations, per equations below. Make sure you use correct units.

$$\omega^2 = \frac{20EI}{mL^4 + 5ML^3 + 20I_d L}$$

$$N = \frac{\omega}{2\pi}$$

Where:

N = Bending Natural frequency of beam

E = Modulus of elasticity

I = Moment of inertia of cross section of beam

L = Length of the beam

m = Mass of the beam per unit length of beam

M = Mass of the motor

I_d = 1

VII. Conclusions

Through the last eight years, the Mechanical Engineering Technology program faculty at Wentworth Institute of Technology have designed and implemented an undergraduate course in Applied Finite Element Analysis. The course addresses the issues relevant to the practice and use of FEA in industry and has evolved to its present format, as presented in this paper. It is our opinion that this is an effective method for teaching FEA in undergraduate technology curriculum.

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